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Compressive Strength of Geopolymer Concrete: A Review of Alkali/Binder Ratio, Binder Type and Curing Conditions

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ABSTRACT

This study systematically reviews the impact of key parameters such as alkali/binder ratio (ABR), binder type, curing temperature (CT), and curing time on the compressive strength (CS) of sustainable geopolymer concrete (GPC). The analysis reveals that CS increases as the ABR decreases, with a ratio of 0.25 representing a critical level for optimizing both workability and strength. An evaluation of different binders, including fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin (MK), silica fume (SF), and ferrochromium slag (FS), showed that GGBS delivered superior strength performance. A complete replacement of FA with GGBS resulted in a CS increase of up to 397%. Conversely, adding FA, SF, or MK to GGBS-based mixes reduced CS by 41%, 52%, and 58%, while increasing the initial setting time by up to 200%, 180%, and 120%, respectively. The optimal curing conditions for most GPC mixes were identified as a temperature between 75 and 90°C, maintained for 24 to 48 hours. Notably, ambient temperature curing was found to be unsuitable, especially for Class F FA-based GPC, underscoring the necessity of thermal activation for achieving practical strength development.

Keywords: alkali/binder ratio, binder type, compressive strength, curing temperature and time, geopolymer concrete.

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1. Introduction

Today, concrete production is rising in parallel with population growth and housing demand. Cement and aggregate components of concrete are also affected by this increase. Reportedly, the annual cement production worldwide reached 4-5 billion tons in 2014 and has been increasing by approximately 5% per year (Gök and Kılınç, 2017; Ma et al., 2024). Based on the European Cement Association's 2024 Activity Report, global cement output in 2023 was estimated at approximately 4.03 billion tons, of which Türkiye contributed approximately 2% (The European Cement Association, 2025). According to 2023 data, China ranks first in the world with 2.023 billion tons of cement, while Türkiye ranks fifth, with 81.5 million tons of cement (The European Cement Association, 2025). Accounting other components of concrete, global annual concrete consumption is estimated to reach 30 billion tons (Bertoldo et al., 2023; Gök and Kılınç, 2017).

Concrete production accounts for a significant percentage of the world's greenhouse gas emissions, the most prevalent of which is carbon dioxide (CO_2). Cement production emits approximately 0.9-1 ton of CO_2 per ton of cement produced, which corresponds to 5%–8% of the world's anthropogenic CO_2 emissions (Cao et al., 2017; Frangieh et al., 2022; Naqi and Jang, 2019; Nawaz et al., 2020; Tekle et al., 2020).

In light of these environmental concerns, alkali-activated materials (geopolymers) have been proposed as environmentally friendly substitutes for traditional cement. The chemical processes involved in geopolymerization can lead to significantly lower greenhouse gas emissions, and improved mechanical properties and workability (Srinivasa et al., 2024). It is important to emphasize that the high resistance of geopolymer mixtures usually demands the inclusion of sodium silicate (Na_2SiO_3) in its composition, demonstrating a compromise between sustainability and mechanical properties (Malathy et al., 2022). Geopolymers offer reductions in carbon emissions and possess advantageous mechanical and thermal properties, making them suitable for numerous construction applications. Material development through geopolymers involves activating pozzolanic materials with high strength and durability properties comparable to OPC at an equal environmental cost (Okeyinka et al., 2019). Moreover, geopolymers can incorporate a wide range of thereby providing substantial resource savings and enhancing structural sustainability (Bourzik et al., 2024; Huynh et al., 2020). The reactivity of geopolymers stems from their unique, highly amorphous microstructure, which enables them, when applied as binders, to effectively bind fine aggregates and increase their cohesive strength (Bujang et al., 2023). Studies have shown that geopolymers exhibit superior long-term durability and resistance to environmental agents compared to traditional cement-based materials (Sadat et al., 2016). Existing studies report that geopolymers are used not only in new construction but also for the rehabilitation of existing concrete structures, offering a multipurpose technique to enhence sustainability in the built environment (Frangieh et al., 2023; Maras, 2021).

Geopolymer concrete (GPC) has, in recent decades, attracted considerable interest as a substitute for OPC because of its environmental benefits and improved mechanical properties, particularly under varied curing conditions. The compressive strength of GPC can reach only 20 MPa after a curing period of 4 h under room temperature, and even up to 100 MPa at the age of 28 days, indicating that it can be used where rapid hardening is necessary (Adeleke et al.,2023; Tang et al.,2021).

Experimental observations examining the impact of material composition and curing conditions on the strength and durability of GPC have confirmed these assertions. According to Wallah and Rangan, an FA-based GPC blend incorporating an 8-molar NaOH solution achieved a CS of approximately 58 MPa when dry-cured at 60°C and 56 MPa when steam-cured (Razak et al., 2022). Increasing the molarity from 6 M to 10 M can increase compressive strength by 100% (Rawat et al., 2024). Most notably, GPC exhibited reduced creep and improved resistance to acids and sulfates compared to ordinary OPC concrete, thereby solidifying its long-term performance advantages in aggressive environments (Yang et al., 2021). The use of diverse source materials in GPC and the performance of GPC across various environments remain under investigation (Malacatus et al., 2024; Marathe et al., 2025; Safari et al., 2024; Thumrongvut et al., 2022).

The use of other materials also contributed to improved performance. Park et al. (2016) investigated the effects of crumb rubber particles and calcium oxide on FA and found that CS exhibited wide variation depending on the type of FA used; the highest value, 42.5 MPa, was recorded in mixes without crumb rubber particles (Kim and Park, 2014). Güzelküçük and Demir (2019) also demonstrated that changes in NaOH molarity, curing time, and curing temperature had a significant influence on CS values, with optimal conditions yielding a CS of 46.76 MPa at a molarity of 15.5 and 110°C after 24 hours of curing.

Further studies supported the multifunctional performance of GPC. The architectural application of GPC has also been realized, exemplified by the Institute of Global Change Building at Queensland University, which demonstrates its use and long-term durability in real-world contexts (Yang et al., 2021).

This study investigated the effects of alkali/binder ratio (ABR), binder type, CT and curing time on the mechanical and durability properties of GPC. The effect of factors on the strength of the GPC was determined by analyzing findings from previous studies.

2. Literature Review

To conduct this review, a comprehensive search of the literature was performed in major scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search covered studies published between 2011 and 2025, with the majority of the selected publications coming from the last decade, ensuring up-to-date coverage. Keywords and their combinations were used such as: "geopolymer concrete (GPC)", "alkali/binder ratio (ABR)", "compressive strength (CS)", "binder type", "curing temperature (CT)", and "curing time". Only peer-reviewed journal articles and conference papers written in English were included. The final set of studies considered in this review comprises those that directly address the effects of ABR, binder type, CT, and curing time on the CS of GPC.

The effects of ABR, binder type, CT and curing time are critical to the mechanical and durability properties of GPC. In this study, the effects of the following factors on the mechanical and durability properties of GPC were investigated: ABR (0.25–0.94); source material (binder) type (FA, bottom ash (BA), GGBS, FS, SF), and MK; CT (ambient temperature to 120°C); and curing time (0–48 hours).

2.1. Alkali/binder Ratio (ABR)

ABR is the ratio of the total alkaline liquid used in GPC to the binder used as source material. Based on experience gained from previous studies, the use of ABR, which usually ranges from 0.30 to 0.45, is recommended (Deb et al., 2014; Midhin et al., 2024; Pham et al., 2023; Ramesh and Srikanth, 2020; Sangi et al., 2023). Figure 1 shows CSs obtained from GPC specimens produced by multiple researchers using different ABRs.

Hadi et al. (2017) sought to determine, using the Taguchi Method, the optimum mixing ratios of GGBS-based GPC cured under ambient conditions. For this purpose, the effects of the binder amount (ABR), the ratio of Na_2SiO_3 to NaOH, and the molarity of NaOH in GPC were investigated. 9 different concrete mixes were prepared by varying the binder amounts (400, 450, and 500 kg/m3), ABR (0.35, 0.45, and 0.55), the ratio of Na2SiO3 to NaOH (1.5, 2.0, and 2.5), and the molarity of NaOH (10, 12, and 14 M). The highest 7-day CS (60.4 MPa) was obtained from the concrete mixture with a binder content of 450 kg/m3, an ABR of 0.35, a Na2SiO3-to-NaOH solution ratio of 2.5, and a NaOH solution molarity of 14. An increase in ABR decreased the CS of GPC. The 28-day CS averaged 55.8 MPa at 0.35 ABR and 38.09 MPa at 0.55 ABR. Based on the 7-day CS, an ABR level of 0.35 is the optimum value, and ABR is the parameter with the greatest impact on the CS of GPC, with an impact level of 71.23%.

Reddy et al. (2018) aimed to develop a rational design method to produce F-class FA and GGBS-based GPCs cured under ambient conditions. For this purpose, the absolute volume method was used in OPC concrete mixture calculations, together with the water-cement ratio and gradation curves. Five ABRs were used in the study: 0.4, 0.5, 0.6, 0.7, and 0.8. The highest 28-day CS (66.23 MPa) was obtained from the mixture with 0.4 ABR; the lowest 28-day CS (32.73 MPa) was obtained from the mixture with 0.8 ABR. An increase in ABR to 0.8 resulted in a 50% decrease in CS. On the other hand, as ABR increased, the slump value rose from 40 mm to 160 mm. The increase in slump value and the decrease in CS with increasing ABR indicate that the behaviour of GPC is similar to that of OPC concrete. In addition, with an increase in ABR, changes occur in the dissolution percentages and mineral phases of essential elements, such as silica (Si), alumina (Al), calcium (Ca), and sodium (Na) in the mixture, which affects the strength of the GPC.

Olivia and Nikraz (2012) aimed to determine the optimal values of factors affecting the mechanical and durability properties of F-class FA-based GPC using the Taguchi Method. Four parameters were studied: aggregate amount, ABR, the ratio of Na_2SiO_3 to NaOH, and the curing method. In the experimental study in which 0.30, 0.35, and 0.40 ABR were used, the highest 28-day CS (54 MPa) was obtained from the mixture containing1896 kg/m^3 aggregate, 0.30 ABR, a Na_2SiO_3-to-NaOH ratio of 2.5, 70°C CT, and a 12-hour curing time. The increase in ABR from 0.30 to 0.40 caused a 21.4% decrease in CS. In addition, the slump values of the optimum mixtures with respect to CS ranged from 180 to 250 mm.

Pan et al. (2011) examined the properties of GPC and mortar, such as fracture energy and ductility, across various parameters. ABR (0.45, 0.5 and 0.58), Na_2SiO_3 to NaOH ratio (2.5, 2.9 and 1.1) and curing time (18, 72, and 168 hours) were studied. All concrete mixtures obtained using these parameters were dry-cured at 60 °C. The 28-day CSs were 69.8, 72.1 and 77.9 MPa for 0.45, 0.5 and 0.58 ABR, respectively. Contrary to previous studies, Figures 1 and 2 show that CS increases as ABR increases. As shown in Figure 1, increasing ABR from 0.4 to 0.58 resulted in a 12% increase in CS. In addition, it has been determined that the CS of GPC is slightly higher that of OPC concrete. Among other findings reported in this study, the presence of soluble silicates contributes to the geopolymerization process and leads to rapid strength development in concrete. It has been demonstrated that the fracture energy of GPC is lower than that of OPC concrete, that it is more brittle.

Diaz-Loya et al. (2011) examined the CS, flexural strength, Poisson ratio and elastic modulus of 25 different GPC mixtures using 25 FAs, sources which were obtained from other sources; 12 were C-class and 13 were F-class. In the study of various ABR levels, CSs of up to 80.37 MPa were obtained from GPC produced using C-class FA. In F-class FA-based GPC, the lowest CS was observed in the mixture with 0.78 ABR (10.34 MPa), and the highest CS (49.24 MPa) was observed in the mixture with 0.68 ABR. As shown in Figure 2, there is no consistent decrease in CS with increasing ABR; moreover, the CS (46.79 MPa) of the concrete mixture with 0.40 ABR is lower than the CS (49.24 MPa) of the concrete mixture with 0.68 ABR. Using FA with varying chemical composition and particle-size distribution is considered effective in this situation. The highest CS in C-class FA-based GPC was 80.39 MPa at the 0.4 ABR level. As in F-class FA-based GPC, C-class FA-based GPC also exhibits serious inconsistencies in CS at the same ABR levels. The chemical composition and particle-size distribution of FA are responsible for this observation. The densities of the concrete specimens ranged from 1890 to 2371 kg/m3, and their flexural strengths ranged from 2.24 to 6.41 MPa.

Xie and Ozbakkaloglu (2015) investigated the behaviour of GPC produced with FA and BA with low CaO content, cured at ambient temperature in the laboratory. In that study, CS values close to zero were observed in BA-based GPC specimens, which included BA-based GPC, FA-based GPC, and BA-FA mixture-based GPC. The highest CS at 28 days was 30.4 MPa, while the strength at 70 days reached 48.2 MPa. In general, lower CSs were obtained with increasing ABR. This can be explained by the increase in water content in the reaction medium that accompanies rising ABR; the higher water content reduces friction between particles and thereby decreases CS (Hardjito et al., 2011). This observation is in line with the view that the CS of coal ash–based GPC decreases with increasing ABR (Choeycharoen et al., 2022; Hardjito et al., 2011; Shilar et al., 2022). The CSs of the FA-based GPC for ABR values of 0.25, 0.30, and 0.35 were 30.4 MPa, 34.3 MPa, and 27.2 MPa, respectively. The lower CS observed at the 0.25 ABR level can be explained by insufficient workability at this rate. Thus, problems arise during the concrete settlement process and negatively affect CS. It was found that the slump values of BA-based GPC, FA-based GPC, and BA-FA mixture-based GPC varied from 150 to 160 mm, 60 mm to 260 mm, and 165 to 220 mm, respectively.

2.2. Source Material (Binder) Type

In GPC, source materials (binders) generally include industrial wastes such as FA, GGBS, SF, and rice husk ash, as well as materials of geological origin such as red mud, clay, and kaolin. Materials to be used as binders should be rich in silica and alumina. In this part of the study, previous studies using FA, GGBS, SF, MK, and FS as binders were compiled and analysed.

Studies in which binders such as FA, GGBS, SF, MK, and FS were used individually or in combination were included.

Gök and Kılınç (2017) replaced FA with 4%, 10% and 20% GGBS in GPC, based on a mixture of F-class FA and GGBS; the mixtures were cured in the laboratory using a total of 670 kg of binder. When the 4% GGBS ratio was taken as the reference, adding 20% GGBS increased the CS of GPC by 177% to 42.70 MPa. In addition, the study compared the effects of laboratory and outdoor curing conditions on the CS of concrete produced using GGBS at 15% and 25% of the total binder content. Based on their 28-day CS measurement, concrete specimens under laboratory conditions exhibited substantially higher CS than those under outdoor conditions.

Hadi et al. (2017) aimed to determine the optimum values of the factors affecting the strength of GGBS-based GPC cured under ambient conditions using the Taguchi method. The setting time of the GGBS-based GPC produced using the optimal values has been observed to be very short. The start and end times of the setting were 25 and 55 minutes, respectively. GGBS was partially replaced by F-class FA, SF, and MK at replacement levels of 0%, 10%, 20%, 30%, 40%, 50%, and 60% to achieve a setting time suitable for structural applications. All pozzolans replaced with GGBS have increased the GPC's initial and final setting times. If FA is replaced by 60% GGBS, the initial and final setting times increase from 25 to 75 minutes and from 55 to 105 minutes, respectively. When MK is replaced with 60% GGBS, the initial setting time increases from 25 to 55 minutes, and the final setting time increases from 55 to 90 minutes. When SF is replaced with 60% GGBS, the initial setting time increases from 25 to 70 minutes and the final setting time increases from 55 to 100 minutes. In GPC, where only GGBS is used, the short setting time is thought to be caused by the high CaO content of GGBS. Moreover, with the addition of FA, SF, and MK, the slump of the concrete mixes increased. This situation is thought to be caused by the addition of spherical FA and SF particles into GPC, in contrast to the irregularly shaped GGBS particles. When the GGBS was replaced with UK, SF and MK at 60%, the CS of the GPC decreased by 41%, 52%, and 58%, respectively. The decrease in strength is attributed to a reduction in CaO content, which results from a lower amount of GGBS with high CaO content. The reduction in CaO content causes a delay in the polymerisation reaction and prevents the formation of amorphous Ca-Al-Si gel.

Özcan (2018) investigated the resistance of FS and GGBS-based GPC against acid, sulfate, and salt effects by replacing Elazig FS with 0%, 25%, 50%, 75% and 100% GGBS. The highest 28-day CS was 61.53 MPa from the concrete mixture containing 100% GGBS. The lowest CS was obtained, 17.35 MPa, from the concrete mix with 100% FS. There is a decrease in CS with the increase of FS in all concrete mixtures. As with CS, after holding GPC in 5% sodium chloride (NaCl) and 5% magnesium chloride ($MgCl_2$) salt solutions, the highest and the lowest performance was obtained from the concrete mixture with 100% GGBS and 100% FS, respectively. The minor size change, a reduction, among the concrete mixtures in 5% sodium sulfate (Na_2SO_4) solution was found to be 0.045% in the concrete mix with 100% FS.

Kurtoğlu et al. (2018) examined the mechanical properties of F-class FA-based GPC, GGBS-based GPC, and OPC concrete and found that the highest CS (99.3 MPa) occurred in the GGBS-based concrete mixture. FA-based GPC exhibited a minimum CS of 49.5 MPa, attributable to FA's low activity and low CaO content. As shown in Figure 3, the CS of GGBS-based GPC was twice that of FA-based GPC. In addition, GGBS-based GPC has shown superior performance compared with FA-based GPC and OPC concrete against seawater, sulfate, and acid attacks.

Memon et al. (2013) examined the effect of SF on the properties of F-class FA-based self-compacting GPC. Replacing FA with SF at replacement levels of 0%, 5%, 10%, and 15% resulted in a 6.9% increase in the CS of GPC at the 10% SF replacement level. The highest CS, 55.02 MPa, was recorded for the GPC mixture with 10% SF. Adding 10% SF increases GPC tensile and flexural strengths by 12.8% and 11.5%, respectively. The slump-flow of the GPC decreased by 4.3% with the addition of 10% SF.

Okoye et al. (2017) examined changes in the weight and CS of the specimens after exposure to 2% sulfuric acid (H_2SO_4) and 5% sodium chloride (NaCl) solutions in GPC containing different amounts of both SF and OPC. After 90 days of exposure to a 2% sulfuric acid (H_2SO_4) solution, a 36% loss of CS was observed in OPC concrete. The GPC containing 20% SF and 80% F-class FA exhibited an 8% loss in CS. After 90 days of exposure to a 5% sodium chloride (NaCl) solution, OPC concrete exhibited an 18% loss of CS, whereas GPC containing 20% SF and 80% F-class FA exhibited almost no strength loss.

Rajini and Rao (2014) examined the mechanical properties of this concrete at 7, 28, 56, and 90 days by curing the GPC produced using F-class FA and GGBS as source materials at ambient temperature. Figure 3 shows that, among the concrete mixtures in which GGBS was replaced by FA at 0%, 25%, 50%, 75%, and 100%, the highest CS at 28 days was observed in the mixture containing 100% GGBS (60.23 MPa). When 100% FA replaced the GGBS, there was an 80% reduction in CS. As the ratio of FA in the mixture increased, the CS consistently decreased. For comparison, OPC concrete (51.39 MPa), designed according to IS 10262: 2009 and IS 456: 2000 standards, showed lower CS than GGBS-based GPC, but higher CS than FA-based GPC. In addition, when the 28-day CSs are taken as a reference, the maximum increase in the 90-day CS (112%) was observed for the concrete mixture containing 75% FA and 25% GGBS. This indicates that the FA-based GPC should be cured for a longer period. The decrease in the tensile strength of GPC with an increase in FA ratio in the mixture, similar to its effect on the CS, coincides with the results of existing studies in the literature (Deb et al., 2014)

2.3. CT and Curing Time

CT and time are essential factors affecting the strength of GPC. Since the polymerisation occurring in GPC is a chemical reaction, it is affected by reaction temperature and duration. This situation affects GPC strength. Therefore, CT and curing time are of great importance in the process applied to GPC. In the current literature, GPC is generally used for ambient, dry, or steam curing. In this part of the study, research on GPC, cured at different CTs, is compiled and analysed. For this purpose, the effects of CTs, from ambient temperature to 120°C, and of varying curing times on the strength of GPC were investigated.

Nagral et al. (2014) investigated the effects of CT and curing time by applying CTs of 80°C, 90°C, and 100°C and curing times of 12 and 24 hours to F-class FA and GGBS mixture-based GPC. As shown in Figure 5, the highest 7-day CS (76.53 MPa) was observed in specimens cured at 90°C for 12 hours. CT above 90°C caused a decrease in the CS of concrete cured for both 12 and 24 hours. Moreover, increasing curing time at temperatures above 90°C resulted in a loss of CS in the GPC. During the curing period, water evaporates from the concrete, forming voids that decrease the CS. Increased CT contributes to the polymerisation process and transforms two-dimensional polymeric chains into a three-dimensional structure with stronger bonds. The slump value of GPC was zero at a water/geopolymer solid ratio of 0.201 but increased to 170 mm at a ratio of 0.40.

Vora and Dave (2013) examined factors affecting the CS of F-class FA-based GPC and investigated the effects of 60°C, 75°C, and 90°C CTs. The 7-day CS of GPC at CTs of 60°C, 75°C, and 90°C were 38 MPa, 46 MPa, and 49 MPa, respectively. CTs exceeding 75°C produced only minimal increases in the CS of GPC. In the study, the slump of fresh FA-based GPC increased from 170 mm to 240 mm as the percentage of superplasticisers in FA-based GPC rose from 2% to 4%. Small decreases in CS have been reported when the percentage of superplasticisers exceeds 2%. The workability of fresh concrete increased as additional water was added to the mixture.

Al Bakri Abdullah et al. (2012) produced a C-class, FA-based, lightweight GPC using a foaming agent. The 28-day CSs of the concrete mixtures at ambient (room) and 60°C CTs were 18.1 MPa and 18.2 MPa, respectively. The density of the concrete mix cured at ambient temperature was 1650 kg/m3, and that of the mix cured at 60°C for 24 hours was 1667 kg/m3.

Tuyan et al. (2017) investigated the mechanical properties and resistance to elevated temperatures of C- and F-class FA-based GPCs. They cured C-class FA-based GPC with a water-to-binder ratio of 0.52 under separate conditions at 70°C and at ambient temperature (25°C). As shown in Figure 5, 30 MPa CS was obtained from the concrete mixture cured at 70 °C for 120 hours, whereas 35.1 MPa CS was obtained from the concrete mixture cured at ambient temperature for 28 days. The F-class FA-based GPC with a 0.38 water-to-binder ratio was cured at 70 °C for 120 hours, resulting in a CS of 40.3 MPa. They cured the mixed FA-based GPC (50% C-class and 50% F-class) with a 0.46 water/binder ratio at ambient temperature and found its CS to be 25.1 MPa. It has been determined that the CS of GPC with 50% C-class FA and 50% F-class FA by weight is lower than that of concrete obtained using C-class FA or F-class FA separately. The reason was that F-class FA could not develop binding properties because it did not react at ambient temperature. The study found that F-class FA-based GPC was more resistant to elevated temperatures than OPC concrete. In contrast, C-class FA-based GPC was less resistant than OPC concrete.

Noushini and Castel (2016) investigated the effect of heat curing on the conduction properties of F-class FA-based GPC. The concrete mixtures produced were cured at ambient temperature, 60°C, 75°C and 90°C CTs for 8, 12, 18 and 24 hours. Figure 5 shows the 28-day CS of concrete mixtures cured at ambient temperature, 60°C, 75°C and 90°C CTs for 8 and 24 hours. The 28-day CSs of the concrete mixtures cured at 60°C, 75°C and 90°C CTs for 8 hours of curing time were respectively 27.4 MPa, 44.8 MPa and 52.2 MPa, while the 28-day CS of the concrete mixture cured at ambient temperature was 41.7 MPa. The CSs of the concrete cured at 60°C, 75°C and 90°C for 24 hours of curing time were found to be 50 MPa, 62.3 MPa and 60.7 MPa. When 60°C CT is taken as the reference, the CSs of concrete mixtures, subjected to 8 and 24-hour curing times at 90°C, increased by 91% and 21%, respectively. It has been revealed that the long curing time reduces the difference caused by different temperatures on the CS of the GPC. Previous studies have stated that some of the aluminosilicates in the source material in hardened GPC cannot react without applying a certain CT, and thus, they will remain unresolved. It is stated that the amount of these undissolved solids can only decrease with high CTs (Cai et al., 2020; Yu et al., 2025). In addition, the optimum strength in longer heat curing times (18 and 24 hours) was obtained at 75°C CT. This result is consistent with the studies indicating that subjecting GPC to a longer curing time at high temperatures (such as 90°C) weakens its microstructure and causes lower CS (Nadelman and Kurtis, 2014). The highest CS for 28 days was found at 62.3 MPa from concrete specimens applied at 75°C CT and 24 hours curing time. However, it has been demonstrated that curing for 18 hours at the same temperature results in only a slight decrease (4%) in CS. Therefore, the optimum economic curing condition for F-class FA-based GPC can be accepted as 18 hours at 75°C. On the other hand, it has been revealed that the 1-day CS of GPC cured at ambient temperature has a very low value, like 3 MPa, and the strength development rate is very slow. This situation revealed that ambient temperature curing is unsuitable and practical for F-class FA-based GPC. Therefore, heat curing is essential for F-class FA-based GPC. Other studies have reported similar results (Tuyan et al., 2017).

Saleh (2018) aimed to determine the optimum mixing ratios of F-class FA-based GPC for different CSs. To examine the effect of CT, the concrete mixtures were cured at 30 °C and 70 °C, and tested for CS at 3, 7, 28, 56, and 90 days. For this purpose, they cured the concrete mixtures at 30°C and 70°C and measured the CSs at 3, 7, 28, 56, and 90 days to investigate the effect of CT. Figure 5 shows the 28-day CS of concrete mixtures cured at 30°C and 70°C. Considering their 3-day CS, concrete cured at 30°C did not attain a particular strength, whereas concrete cured at 70°C exhibited a CS of 36.05 MPa. The 28-day CSs of concrete cured at 30°C and 70°C were 16.37 MPa and 41.11 MPa, respectively. These results showed that concrete specimens cured at or below 30 °C exhibited a slower rate of strength development and lower strength than specimens cured at higher temperatures. In contrast, the 90-day CS of specimens cured at 30°C increased by 85% compared with the 28-day CS, whereas specimens cured at 70°C exhibited almost no change in CS. Because the specimens cured at temperatures close to ambient (e.g., 30°C) gain strength slowly, the 90-day strength of F-class FA-based GPC should also be examined. These findings are consistent with previous studies reporting that the silica and alumina components in F-class FA-based GPC cured at ambient temperature are not fully dissolved, and thus concrete gains strength slowly and to a limited extent (Cai et al., 2020; Rajini and Rao, 2014; Tuyan et al., 2017; Yu et al., 2025). In the study, increasing the added water in the concrete mixture from 10 to 50 kg/m^3 increased the slump value of GPC from 51 mm to 114 mm.

Haddad and Alshbuol (2016) investigated the mechanical properties of GPC obtained using Jordanian natural pozzolan, a basaltic tuff. At ambient and at 40°C, 80°C, and 120°C CTs, the 3-, 7-, and 28-day strengths of GPC mixtures were determined after 24 and 48 hours. Figure 5 shows the 28-day CS of the specimens subjected to these CTs and curing times. Increasing the CT from 40°C to 80°C for both 24- and 48-hour curing times caused only slight increases in the CS of the GPC. Increasing the CT from 80°C to 120°C caused the CS of concrete mixtures to decrease by 22% and 31% for 24- and 48-hour curing times, respectively. For the materials and parameters used in the study, the optimum temperature for short curing times was 80°C. In the SEM examination of GPC at 80°C, the aluminosilicate gel that formed appeared dense, with continuous but limited microcracks, contributing to a significant increase in the CS of the concrete. In addition, the 28-day CS of GPC cured at ambient temperature ranged from 9 to 24.1 MPa.

3. Analysis and Evaluation of Literature Studies

3.1. Analysis of ABR

Based on a compilation of studies by various researchers, Figure 1 shows the CS values of GPC designed at different alkali-to-binder ratios (ABR). A graph showing the correlation between ABR and CS of these studies, constructed using the data in Figure 1, is shown in Figure 2. When the results in Figures 1 and 2 are considered together, the CS of GPC generally decreases as ABR increases. However, an ABR of 0.25 is considered a critical threshold for the workability of GPC. Since workability cannot be achieved at this rate, concrete cannot be placed, leading to voids. This adverse situation reduces strength. High CSs are generally obtained in the range 0.35–0.6 ABR, whereas CSs decrease significantly above 0.6 ABR. However, Diaz-Loya et al. (2011) achieved an excellent strength of 49.24 MPa even at an ABR level of 0.68 using F-class FA. The study suggests that variation in FA chemical composition may explain the lack of a consistent decrease in CS with increasing ABR. Figure 2 shows that the low correlation coefficient (0.61) between ABR and CS in that study indicates how significant changes in the chemical composition of the binder are for CS. Among the studies, the correlation coefficient between ABR and CS ranged from 0.61 to 1.0. The correlation coefficients were generally equal to 1, which reveals the importance of the effect of ABR on the CS of GPC.

Among other results obtained in the studies, the presence of soluble silicates contributes to the geopolymerization process and leads to rapid strength development in concrete. The increase in ABR causes a change in the dissolution percentages and mineral phases of essential elements such as silica (Si), alumina (Al), calcium (Ca), and sodium (Na) in the mixture affect the strength of the GPC (Reddy et al., 2018). It has been revealed that the increase in ABR has a negative effect, generally causing a decrease in strength; however, this can be compensated by increasing the applied curing time, and even higher CSs can be achieved.

High-calcium binders such as GGBS or Class C FA tend to react more readily under alkaline conditions; therefore, moderate increases in ABR may enhance CS by accelerating dissolution and gel formation. In contrast, low-calcium binders (for example, Class F FA and MK) are less reactive; consequently, excessive ABR often results in excess free alkali and reduced CS. This explains why opposite ABR–CS trends are reported depending on the binder type.

Finer binders (for example, SF and highly ground FA) facilitate faster geopolymerization even at lower activator levels, while coarser or less reactive ashes require stronger activators or elevated CTs. The differences in fineness and reactivity therefore account for variability in outcomes observed when ABR is adjusted.

The concentration of NaOH (8–10 M, and in some cases up to 14–16 M) and the Na2SiO3/NaOH ratio strongly influence gel chemistry (e.g., N–A–S–H and C–A–S–H). Higher alkalinity may initially increase CS, but can also cause microcracking, shrinkage, or premature precipitation at high ABR, leading to divergent results across studies.

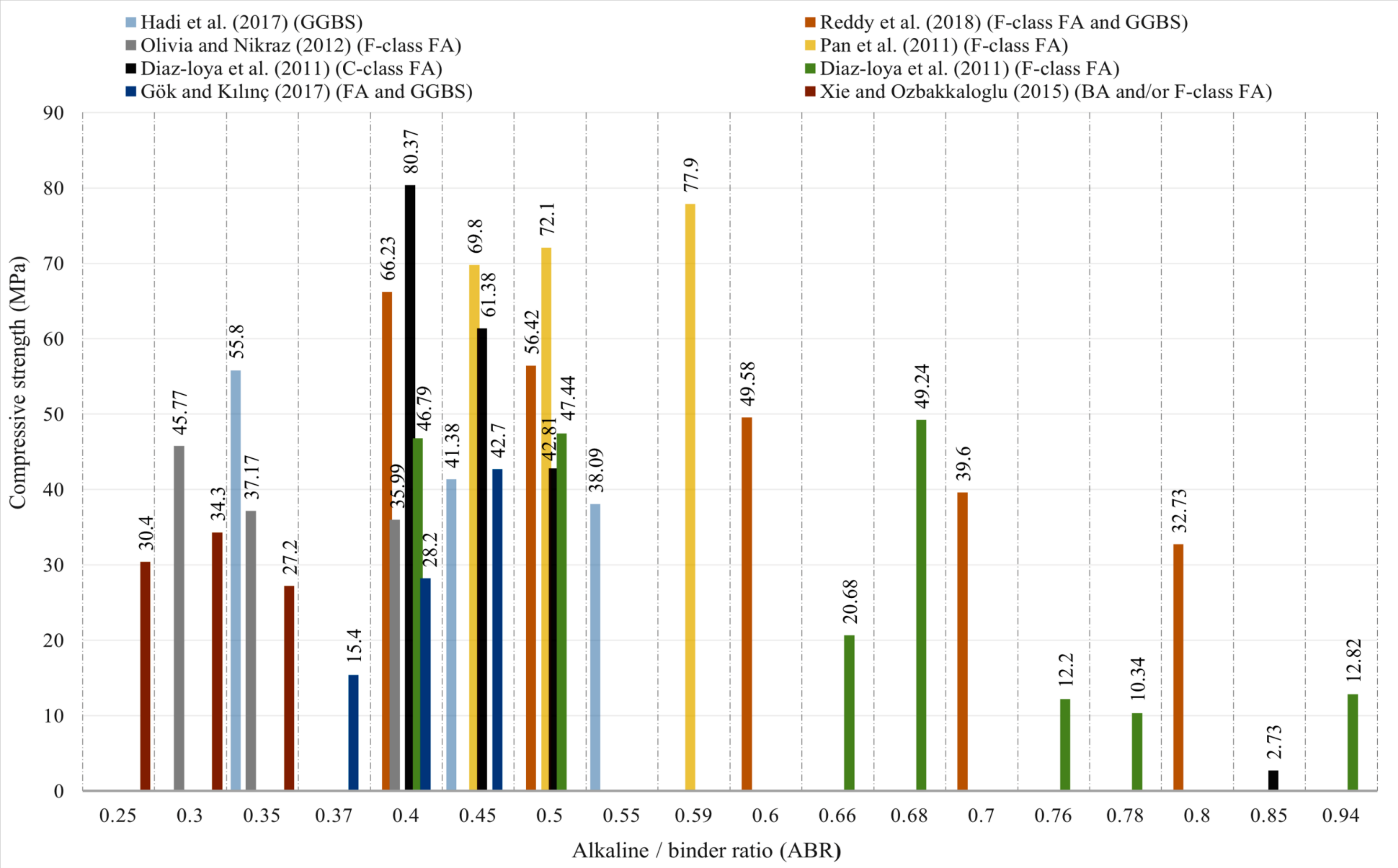

Figure 1. CS values of GPC with different ABR.

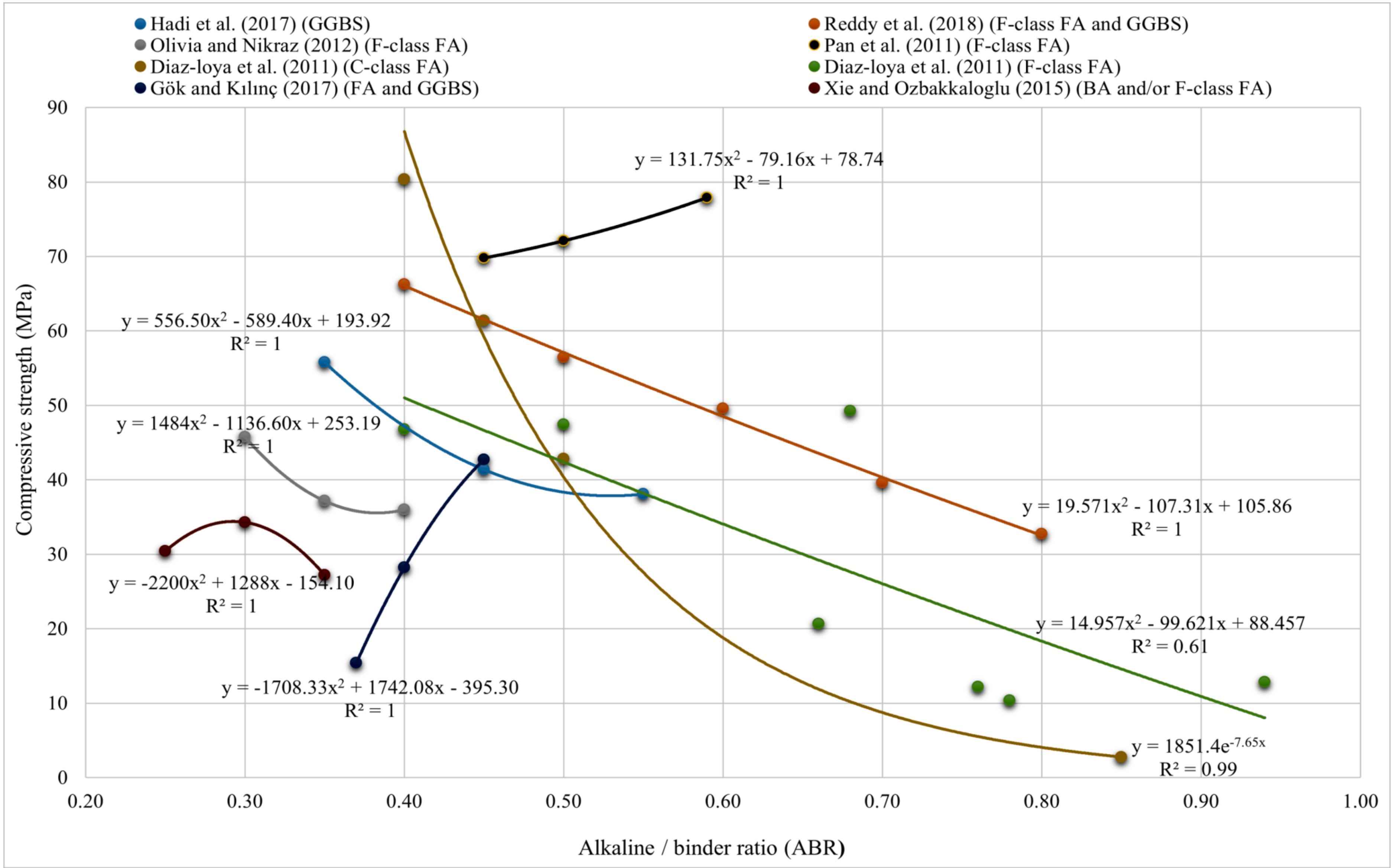

Figure 2. Correlation coefficient value and equation between ABR and CS.

Extremely low ABR values (for example, 0.25) reduce workability and create voids, lowering CS despite a higher concentration of activators. Conversely, high ABR values improve fluidity but dilute the reacting system, reducing strength. The balance point is therefore mixture dependent.

3.2. Analysis of Binder Type

Figure 3 compiles studies by various researchers and shows the CSs of GPC obtained using different binders. Evaluation of the studies indicates that GGBS yields the best results among binder types in GPC. GGBS-based GPC also exhibited superior durability. Adding FA, SF, MK, and FS to GGBS-based GPC has reduced its CS. However, with the addition of FA, SF, and MK to the GGBS-based GPC, the setting times and slump values of the concrete mixtures increased. Studies that show the setting time and workability of concrete decrease with the addition of GGBS to FA-based GPCs support this result (Aliabdo et al., 2016; Nath and Sarker, 2014).

Adding FS to GGBS-based GPC resulted in a 72% reduction in CS. Unlike GGBS, increasing the percentage of FS increases CS when FS is used together with FA (Nath, 2018). When GGBS was partially replaced by 60% MK, the CS of GPC was reduced by 58%. This finding is consistent with other studies in the literature. In addition, the literature states that the degree of reaction decreases as the percentage of MK increases (Kumar et al., 2018).

F-class FA-based GPC generally exhibited low CS. The CS of F-class FA-based GPC is low because F-class FA exhibits low activity and low CaO content. Other researchers reported similar findings (Chi and Huang, 2013). However, it has emerged that improved strength can be obtained when F-class FA-based concrete and mortar are cured at higher CTs (Atiş et al., 2015). When FA was replaced with 100% GGBS, the CS of GPC increased by 397%. While the addition of 10% SF to FA-based GPC provided a 6.9% improvement in the CS of the GPC, it yielded a substantial improvement in durability properties, specifically resistance to acid, sulfate, and chloride attack. Generally, C-class FA-based GPC exhibited superior mechanical properties than F-class FA-based counterparts. FA's chemical content and particle size distribution have an essential role in the strength of GPC. Strengths close to zero were obtained from BA-based GPC. Other researchers have reported that BA yields lower strength in GPC because of a low degree of polymerisation (Aneja et al., 2021; Hosseini et al., 2021; Jin et al., 2021; Osholana et al., 2020; Zhang et al., 2024).

In the literature, there are studies on GPC or mortars obtained using binder types, such as pumice, perlite, and clay (Güzelküçük and Demir, 2019; Muhammad Faheem et al., 2012; Okoye et al., 2015). Faheem et al. (2012) stated that clay-based geopolymer bricks can be manufactured. Still, the CS of clay-based geopolymer bricks is lower than that of geopolymer bricks produced using other waste materials, such as FA.

Okoye et al. (2015) investigated the mechanical properties of FA/kaolin-based GPC. Replacing 50% of FA with kaolin improved the geopolymerization process. The CS was much higher than that of OPC concrete. In addition, the CS of GPC, consisting of 50% FA and 50% kaolin, increased with temperature up to 100°C but decreased at 120°C. The correlation coefficient and the equations describing the relationship between the percentage of binder and CS are shown in Figure 4. Figure 4 shows the relationship between the ratio of added to total binder material, and the CS. For example, Gök and Kılınç (2017) used a total of 670 kg of binder material in the FA-GGBS mixture-based GPC; GGBS was added at 4%, 10%, and 20%. The percentage of GGBS in the total binder material of the mix is expressed as the ratio GGBS/(GGBS + FA) and is shown in Figure 4. When the results shown in Figure 4 are examined, a strong relationship is observed between the binder percentage and the CS of the GPC. The correlation coefficients between these two variables ranged from 0.92 to 1.00.

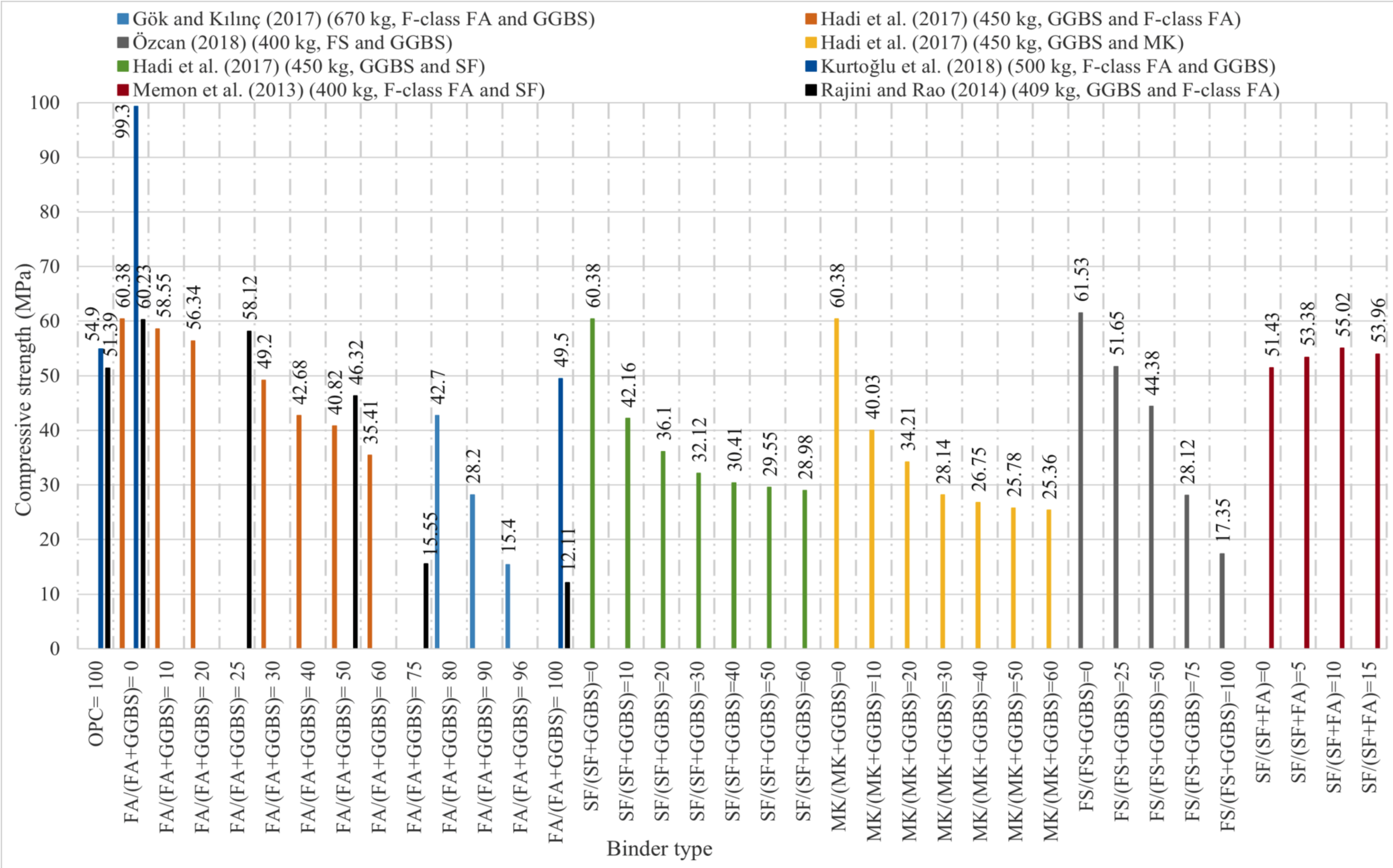

Figure 3. CS values of GPC produced with different binder types.

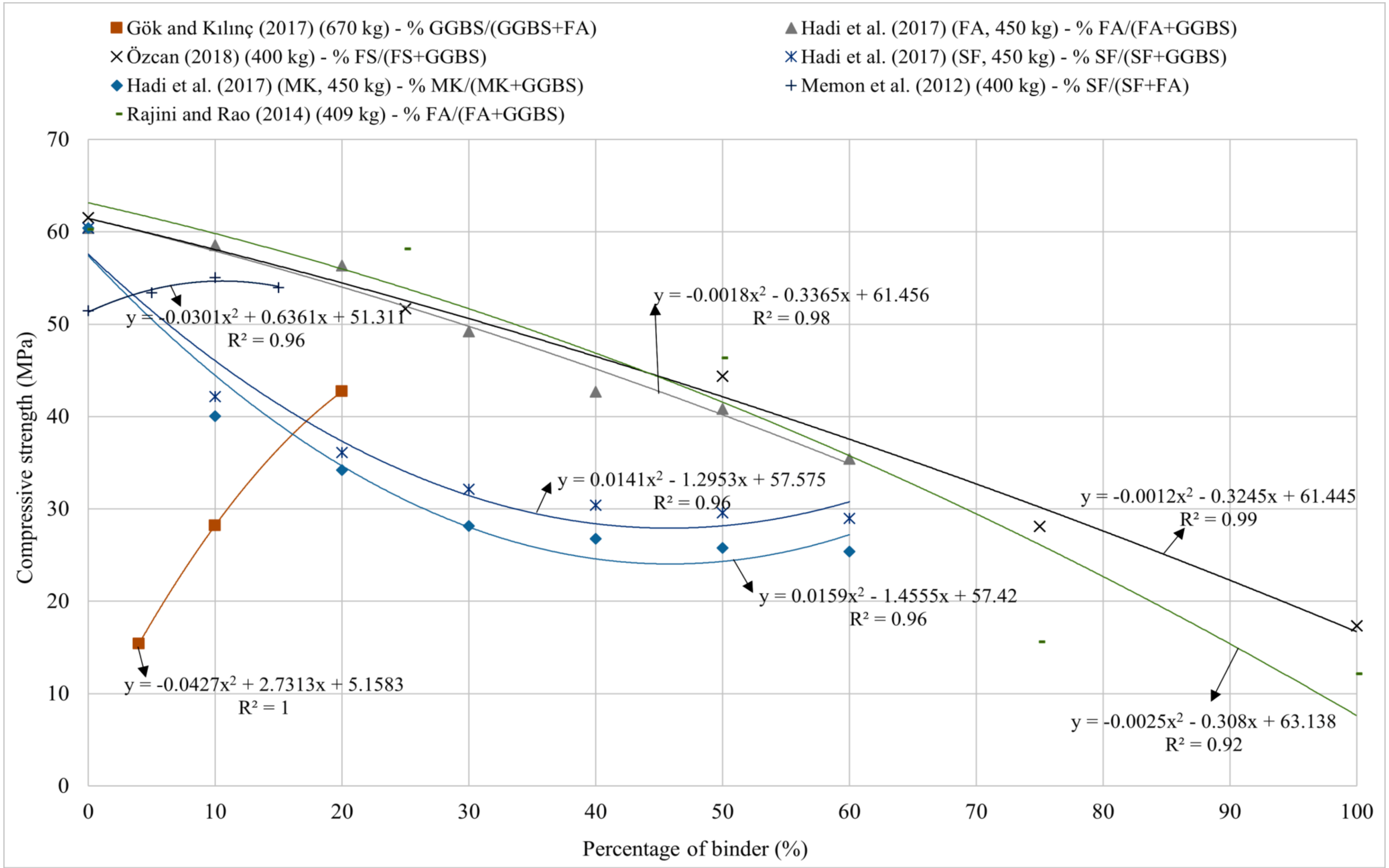

Figure 4. Correlation coefficient value and equation between the percentage of binder and CS

3.3. Analysis of CT and Curing Time

Figure 5 presents the variation in the CS of the GPC reported by different researchers as a function of CT and curing duration. Examination of the graph reveals a clear trend of increasing CS with rising CT. Under ambient temperature conditions (23–28 °C), CS values range from approximately 18 MPa to 42 MPa, depending on the mix composition and curing duration. Increasing the CT to a range of 40–75 °C significantly enhances CS by accelerating polymerization reactions. In particular, curing at 75–80 °C for 24–48 hours yielded CS values above 50 MPa in most studies, with some cases reaching around 60 MPa.

The maximum CS values were reported at approximately 90 °C (CT). Nagral et al. (2014) achieved 76.53 MPa after 12 hours of curing, while Noushini and Castel (2016) reported 60.91 MPa after 8 hours of curing. This indicates that heat curing at approximately 90 °C accelerates the dissolution of reactive aluminosilicate phases and promotes the formation of a dense N–A–S–H gel, thereby densifying the microstructure. However, increasing the CT to 100 °C or above, particularly at 120 °C, led to a significant reduction in CS (approximately 22–24 MPa). This decrease can be attributed to rapid moisture loss, internal drying, shrinkage-induced stresses, and microcracking. In addition, premature precipitation of the gel at high temperatures may result in a porous and loosely packed matrix.

The literature reports a wide range of curing durations, from 8 to 120 hours. The general trend shows that extending the curing duration from 8–12 hours to 24–48 hours improves CS; however, further extensions beyond 48 hours (e.g., up to 120 hours) have only a limited effect. This suggests that the majority of polycondensation is completed within the first 24–48 hours and that additional gains at longer durations are marginal.

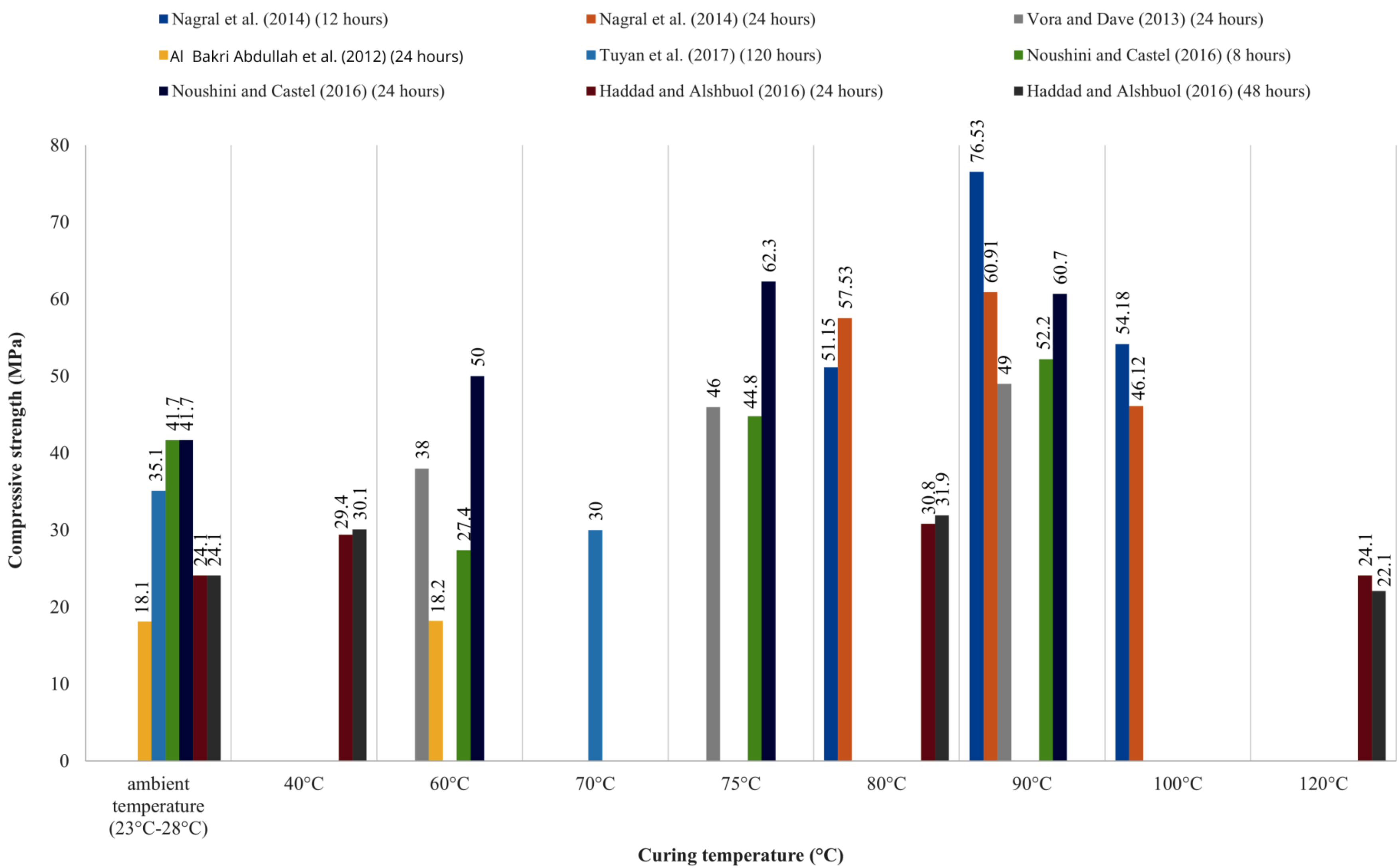

Figure 5. CS values of GPC with different CTs and curing times.

The differences in reported CS among studies are likely due to variations in raw material type (FA, GGBS, MK, etc.), activator solution composition (NaOH molarity, Na_2SiO_3/NaOH ratio, total Na_2O content), water-to-binder ratio, specimen size, heating–cooling rate, and curing environment (sealed container, steam curing, dry oven, etc.).

In conclusion, analysis of Figure 5 suggests that the optimum CS for most GPC systems is achieved at CT values of 75–90 °C and durations of 24–48 hours, while very high CT (>100 °C) can adversely affect CS due to microstructural degradation. This finding aligns with the commonly emphasized approach in the literature that employs "moderately high CT and controlled duration" curing conditions.

Figure 6 presents the relationship between CS and CT for GPC, based on data obtained from various researchers, together with the coefficients of determination (R^2). Several datasets in the graph exhibit R^2 values approaching 1, indicating a strong correlation between CT and CS and that the selected regression models explain the data almost entirely. For datasets with R^2 values in the range of 0.85–0.88, the correlation remains high; however, in addition to temperature, factors such as raw material composition, curing time, moisture content, and activator concentration influence CS (Skane et al., 2025; Yurt and Bayraktar, 2025).

The overall trend suggests that CS increases with CT. Nevertheless, in certain studies, a decrease in strength is observed at elevated temperatures (100–120 °C). This reduction can be attributed to microcrack formation, rapid moisture loss, or accelerated polymerization reactions at high temperatures, all of which may introduce defects into the binder structure.

In conclusion, high R^2 values demonstrate that the mathematical models employed are well-suited to the corresponding datasets, while lower R^2 values highlight the influence of additional parameters beyond CT. These findings support the notion that CT must be carefully optimized to achieve the best mechanical performance of GPC.

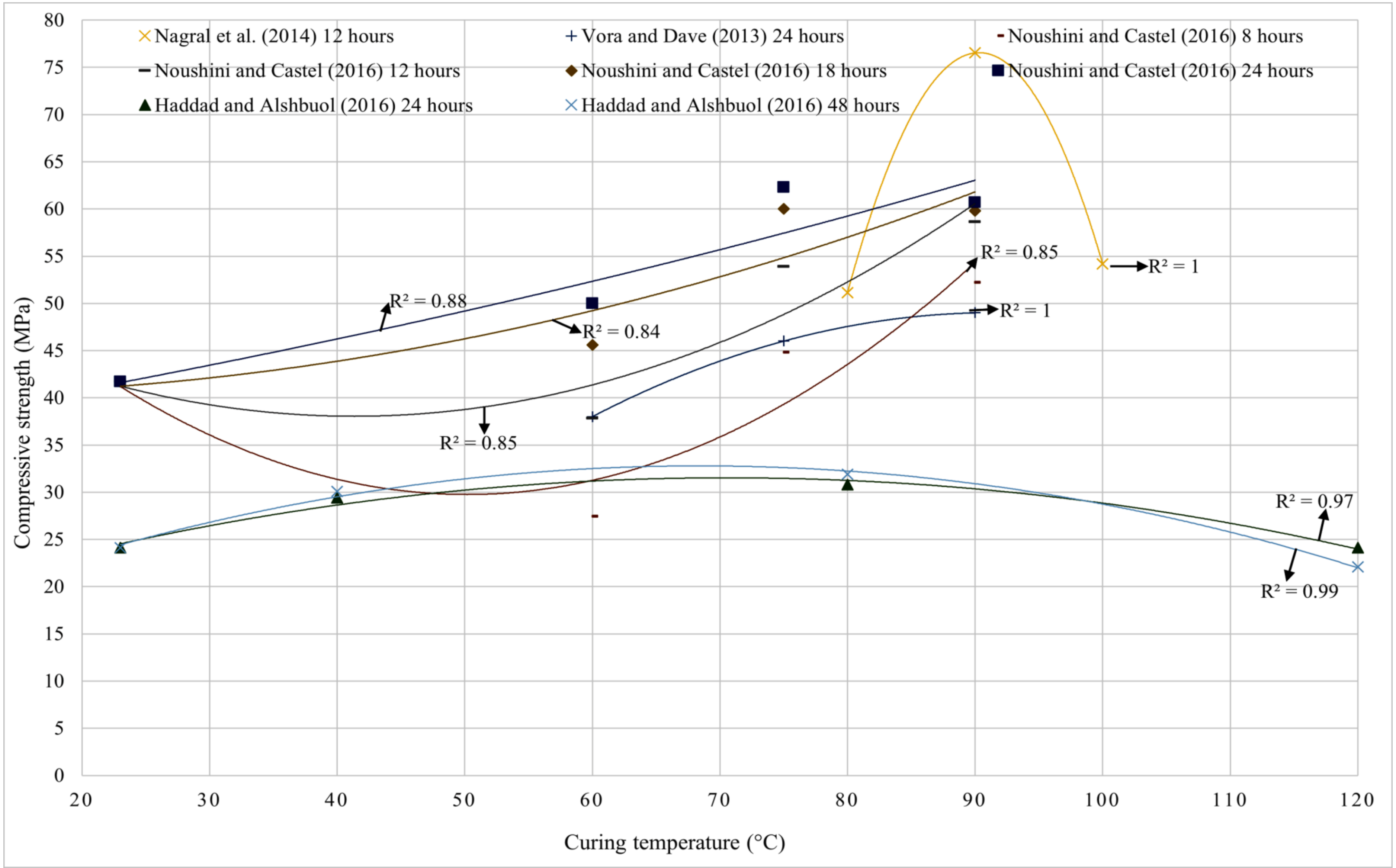

Figure 6. Correlation coefficient values between CT and CS.

For Class F FA–based systems, ambient curing typically results in incomplete reaction and low CS, whereas curing at temperatures between 75–90 °C produces much higher strengths. Consequently, the same binder may appear inferior under ambient curing, yet competitive under heat curing. At very high CTs (>100 °C), rapid water loss and microcracking often reverse the strength gains, further contributing to inconsistencies.

It should be noted that the data and correlations presented in the graphs in Figures 1 through 6 are based on aggregate results from different studies conducted under heterogeneous experimental conditions (e.g., raw material chemistry, binder type, ABR, water/geopolymer solids ratio, Na_2SiO_3/NaOH ratio, activator molarity, curing regimes, and sample size). Therefore, the relationships presented should be interpreted as indicative of general trends rather than definitive predictive models. Numerous parameters influence the CS of GPC.

4. Conclusions

By compiling and analysing the studies in the literature, the following conclusions about the effect of ABR, binder type, CT and curing time on the mechanical and durability properties of GPC were obtained.

1. Reducing ABR in GPC generally increases its CS by up to 50%. ABR is one of the most important parameters affecting the strength.

2. Since an ABR level of 0.25 in GPC reduces workability, it may cause settlement problems that could negatively affect its CS. Reducing the ABR from 0.30 to 0.25 may decrease CS by up to 11%. Therefore, it is recommended that the ABR not be lower than 0.25 in GPC.

3. An ABR level above 0.6 significantly reduces the CS of GPC. Depending on the chemical composition of FA, the reduction in strength can be as high as 97% when the ABR increases from 0.40 to 0.85.

4. The strength loss caused by an increase in ABR in GPC can be compensated by

extending the curing time, and even higher CS values can be achieved. The CS of the mixture cured for 168 hours with an ABR of 0.58 was 12% higher than that of the mixture cured for 18 hours with an ABR of 0.45.

5. GPC using GGBS as a binder achieved the highest CS when FA, SF, MK, or FS were used as source materials. GGBS increased the CS of GPC by up to 397%.

6. In GGBS-based GPC, replacing 60% of GGBS with FA, SF, and MK resulted in decreases in CS of 41%, 52%, and 58%, respectively. However, the addition of FA, SF, and MK increased the initial setting times by up to 200%, 180%, and 120%, respectively, and the final setting times by up to 90%, 82%, and 64%, respectively.

7. Replacing GGBS with FS resulted in a 72% decrease in the CS of GPC. When GGBS was replaced with FS (100%), the CS of GPC decreased from 61.53 MPa to 17.35 MPa.

8. The addition of SF to FA-based GPC increased its CS by 7% and significantly improving durability properties, such as resistance to acid, sulfate, and chloride.

9. GGBS-based GPC, with a CS of up to 100 MPa, exhibited greater stability and durability than FA-based GPC and OPC. It can be up to twice as strong as FA-based GPC.

10. Because BA has a large particle size, low fineness, and weak binding properties, the strength of BA-based GPC is negligible.

11. When used as a binder, The chemical structure and particle size distribution of a material affect the strength of GPC. While soluble silicates contribute to the geopolymerization process and increase the CS of the concrete, low CaO content in the source material can delay geopolymerization, resulting in decreased CS.

12. For most GPC systems, optimal CS is achieved at CT values of 75–90°C and at durations of 24–48 h. However, CTs above 90°C generally disrupt the microstructure of GPC, resulting in significant reductions in CS. Increasing the CT from 90°C to 100°C causes an

average 26.7% decrease in CS, while increasing it from 80°C to 120°C results in an average 26.2% reduction in CS.

13. The strength development rate of GPC cured at ambient temperature is relatively low; therefore, its CS is also low. This indicates that ambient-temperature curing is impractical, especially for F-class FA-based GPC.

14. As the dry curing time decreases, the difference in CS between ambient-cured and dry-cured specimens also decreases. The CS difference between specimens cured at 90°C for 24 hours and those cured at ambient temperature is 45.5%, but it decreases to 25.1% when the curing time is 8 hours.

15. Curing time significantly increases the CS of GPC. The optimum curing time is 48 hours for low CTs and 24 hours for high CTs.

16. When dry curing is applied to GPC, longer curing times at low temperatures and shorter curing times at high temperatures are more appropriate. Therefore, 75°C for longer and 90°C for shorter curing times can be considered the optimal CTs.

Finally, the information presented in this study will be helpful in designing GPC for application at ambient temperature or during dry curing. In addition to the type of binder, ABR, CT, and curing time are important for improving the mechanical and durability properties of GPC. GPC is an important consideration when evaluating industrial wastes rich in silicon (Si) and aluminium (Al). Dry-cured GPC can be a suitable, fast, and economical option for precast structures since GPC reaches 85–90% of its strength within a few days. Dry-cured GPC may be offered, particularly to address urgent post-earthquake housing needs. GGBS-based GPC can achieve 100 MPa and be used in structures that require high strength. Materials such as FA, FS, BA, perlite, and clay can be used as binders in structures requiring low strength and in the production of wall materials.

5. Funding

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6. Conflicts of Interest

The authors declare no conflicts of interest.

7. References

Adeleke, B. O., Kinuthia, J., Oti, J., & Ebailila, M. (2023). "Physico-mechanical evaluation of geopolymer concrete activated by sodium hydroxide and silica fume-synthesised sodium silicate solution", *Materials*, 16(6), 2400. https://doi.org/10.3390/ma16062400

Al Bakri Abdullah, M. M., Hussin, K., Bnhussain, M., Ismail, K. N., Yahya, Z. and Razak, R. A. (2012). "Fly ash-based geopolymer lightweight concrete using foaming agent", *International journal of molecular sciences*, 13, 7186–7198, https://doi.org/10.3390/ijms13067186.

Aliabdo, A. A., Abd Elmoaty, A. E. M. and Salem, H. A. (2016). "Effect of cement addition, solution resting time and curing characteristics on fly ash based geopolymer concrete performance", *Construction and Building Materials*, 123, 581–593, https://doi.org/10.1016/J.CONBUILDMAT.2016.07.043.

Aneja, S., Sharma, A., Gupta, R. and Yoo, D.-Y. (2021). "Bayesian regularized artificial neural network model to predict strength characteristics of fly-ash and bottom-ash based geopolymer concrete", *Materials*, 14(7), 1729, https://doi.org/10.3390/ma14071729.

Atiş, C. D., Görür, E. B., Karahan, O., Bilim, C., Ilkentapar, S. and Luga, E. (2015). "Very high strength (120 MPa) class F fly ash geopolymer mortar activated at different NaOH amount, heat curing temperature and heat curing duration", *Construction and Building Materials*, 96, 673–678, https://doi.org/10.1016/J.CONBUILDMAT.2015.08.089.

Bertoldo, N., Qureshi, T., Simpkins, D., Arrigoni, A. and Dotelli, G. (2023). "Concrete with organic waste materials as aggregate replacement", *Applied Sciences*, 14(1), 108, https://doi.org/10.3390/app14010108.

Bourzik, O., Baba, K. and Akkouri, N. (2024). "Eco-friendly geopolymer mortar prepared from geopolymer waste: Mechanical and thermal properties", *Environmental Quality Management*, 33(3), 411–419, https://doi.org/10.1002/tqem.22132.

Bujang, H., Aman, M. Y., Arumugam, T. N. and Taher, M. N. M. (2023). "Physical characterization of modified asphalt binder with differing fly ash geopolymer contents", *International Journal of Integrated Engineering*, 15(1), 331–338, https://doi.org/10.30880/ijie.2023.15.01.030.

Cai, J., Li, X., Tan, J. and Vandevyvere, B. (2020). "Thermal and compressive behaviors of fly ash and metakaolin-based geopolymer", *Journal of Building Engineering*, 30, 101307, https://doi.org/10.1016/J.JOBE.2020.101307.

Cao, Z., Shen, L., Løvik, A. N., Müller, D. B. and Liu, G. (2017). "Elaborating the history of our cementing societies: an in-use stock perspective", *Environmental Science & Technology*, 51(19), 11468–11475, https://doi.org/10.1021/acs.est.7b03077.

Chi, M. and Huang, R. (2013). "Binding mechanism and properties of alkali-activated fly ash/slag mortars", *Construction and Building Materials*, 40, 291–298, https://doi.org/10.1016/J.CONBUILDMAT.2012.11.003.

Choeycharoen, P., Sornlar, W. and Wannagon, A. (2022). “A sustainable bottom ash-based alkali-activated materials and geopolymers synthesized by using activator solutions from industrial wastes”, *Journal of Building Engineering*, 54, 104659, https://doi.org/10.1016/J.JOBE.2022.104659.

Deb, P. S., Nath, P. and Sarker, P. K. (2014). “The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature”, *Materials & Design (1980-2015), 62*, 32–39, https://doi.org/10.1016/J.MATDES.2014.05.001.

Diaz-Loya, E. I., Allouche, E. N. and Vaidya, S. (2011). “Mechanical properties of fly-ash-based geopolymer concrete”, *ACI Materials Journal*, 108(3), 300–306.

Frangieh, C., Saba, M., Karmaoui, D. and Lafhaj, Z. (2022). “Geopolymer: a new sustainable repairing material for concrete cracks”, *IOP Conference Series: Earth and Environmental Science*, 1123(1), 012061, https://doi.org/10.1088/1755-1315/1123/1/012061.

Frangieh, C., Saba, M., Karmaoui, D. and Lafhaj, Z. (2023). “Sustainability and durability of cracked concrete with geopolymer binder”, *E3S Web of Conferences*, *436*, 08003, https://doi.org/10.1051/e3sconf/202343608003.

Gök, S. G. and Kılınç, K. (2017). “Mechanical properties of fly ash and blast furnace slag based alkali activated concrete”, *Kirklareli University Journal of Engineering and Science*, 3(2), 123–131.

Güzelküçük, S. and Demir, İ. (2019). “Effect of curing time and temperature on perlite-based geopolimer composites”, *International Journal of Engineering Research and Development*, *11*(2), 730–737, https://doi.org/10.29137/umagd.558983.

Haddad, R. H. and Alshbuol, O. (2016). “Production of geopolymer concrete using natural pozzolan: A parametric study”, *Construction and Building Materials*, 114, 699–707, https://doi.org/10.1016/J.CONBUILDMAT.2016.04.011.

Hadi, M. N. S., Farhan, N. A. and Sheikh, M. N. (2017). “Design of geopolymer concrete with GGBFS at ambient curing condition using Taguchi method”, *Construction and Building Materials*, 140, 424–431, https://doi.org/10.1016/j.conbuildmat.2017.02.131.

Hardjito, D., Wee, V. J. S. and Fu, Ee, T. (2011). “The use of fly ash and bottom ash in geopolymer mortar”, *In: Seminar Nasional Zeolit VII, 17-18 October 2011, Hotel Majapahit, Surabaya, Indonesia.*

Hosseini, S., Brake, N. A., Nikookar, M., Günaydın-Şen, Ö. and Snyder, H. A. (2021). “Mechanochemically activated bottom ash-fly ash geopolymer”, *Cement and Concrete Composites*, 118, 103976, https://doi.org/10.1016/J.CEMCONCOMP.2021.103976.

Huynh, A. T., Magee, B. and Woodward, D. (2020). “A preliminary characterisation of innovative semi-flexible composite pavement comprising geopolymer grout and reclaimed asphalt planings”, *Materials*, 13(16), 3644, https://doi.org/10.3390/ma13163644.

Jin, L., Huang, G., Li, Y., Zhang, X., Ji, Y. and Xu, Z. (2021). “Positive influence of liquid sodium silicate on the setting time, polymerization, and strength development mechanism of MSWI bottom ash alkali-activated mortars”, *Materials*, 14(8), 1927, https://doi.org/10.3390/ma14081927.

Kim, J. S. and Park, J. (2014). “An experimental evaluation of development length of reinforcements embedded in geopolymer concrete”, *Applied Mechanics and Materials*, 578–579, 441–444, https://doi.org/10.4028/www.scientific.net/AMM.578-579.441.

Kumar, P., Pankar, C., Manish, D. and Santhi, A. S. (2018). “Study of mechanical and microstructural properties of geopolymer concrete with ggbs and metakaolin”, *Materials Today: Proceedings*, 5(14), 28127–28135, https://doi.org/10.1016/J.MATPR.2018.10.054.

Kurtoğlu, A. E., Alzeebaree, R., Aljumaili, O., Niş, A., Gülşan, M. E., Humur, G. and Çevik, A. (2018). “Mechanical and durability properties of fly ash and slag based geopolymer

concrete", *Advances in Concrete Construction*, 6(4), 345–362, https://doi.org/10.12989/acc.2018.6.4.345.
Ma, L., Azari, R. and Elnimeiri, M. (2024). "A building information modeling-based life cycle assessment of the embodied carbon and environmental impacts of high-rise building structures: A case study", *Sustainability*, 16(2), 569, https://doi.org/10.3390/su16020569.
Malacatus, P. N., Manobanda, P. E. and Romero, I. (2024). "Hazard study of sludge from mining wastewater treatment systems (tailings), accumulation of contaminants and potential utilization proposals", *Sustainability*, 16(23), 10569, https://doi.org/10.3390/su162310569.
Malathy, R., Mohan, P., Kathirvel, P., & Murali, G. (2022). "Flexural performance and microstructural studies of trough-shaped geopolymer ferrocement panels", *Materials*, 15(16), 5477. https://doi.org/10.3390/ma15165477
Maras, M. M. (2021). "Characterization of performable geopolymer mortars for use as repair material", *Structural Concrete*, 22(5), 3173–3188, https://doi.org/10.1002/suco.202100355.
Marathe, S., Szemiot-Jankowska, N., Kumar, S. and Muthu, M. (2025). "Degradation potential of metakaolin-based geopolymer composites immersed in real and simulated acidic environments", *Sustainability*, 17(2), 468, https://doi.org/10.3390/su17020468.
Memon, F. A., Nuruddin, F. and Shafiq, N. (2013). "Effect of silica fume on the fresh and hardened properties of fly ash-based self-compacting geopolymer concrete", *International Journal of Minerals, Metallurgy and Materials V*, 20(2), 205–213, https://doi.org/10.1007/s12613-013-0714-7.
Midhin, M. A. K., Wong, L. S. and Jasim, A. M. D. A. (2024). "Assessing the influence of calcium-based alkaline activators and metakaolin on the compressive strength development of geopolymer concrete for different mix design parameters", *Annales de Chimie - Science Des Matériaux*, 48(5), 667–677, https://doi.org/10.18280/acsm.480507.
Muhammad Faheem, M. T., Al Bakri Abdullah, M. M., Hussin, K., Binhussain, M., Ghazali, C. M. R. and Izzat, A. M. (2012). "Application of clay-based geopolymer in brick production: A review", *Advanced Materials Research*, 626, 878–882, https://doi.org/10.4028/www.scientific.net/AMR.626.878.
Nadelman, E. I. and Kurtis, K. E. (2014). "A resistivity-based approach to optimizing concrete performance", *Concrete International*, 36(5), 50–54.
Nagral, M. R., Ostwal, T. and Chitawadagi, M. V. (2014). "Effect of curing temperature and curing hours on the properties of geo-polymer concrete", *International Journal of Computational Engineering Research*, 4(9), 1–11.
Naqi, A. and Jang, J. G. (2019). "Recent progress in green cement technology utilizing low-carbon emission fuels and raw materials: A review", *Sustainability*, 11(2), 537, https://doi.org/10.3390/su11020537.
Nath, P. and Sarker, P. K. (2014). "Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition", *Construction and Building Materials*, 66, 163–171, https://doi.org/10.1016/J.CONBUILDMAT.2014.05.080.
Nath, S. K. (2018). "Geopolymerization behavior of ferrochrome slag and fly ash blends", *Construction and Building Materials*, 181, 487–494, https://doi.org/10.1016/J.CONBUILDMAT.2018.06.070.
Nawaz, M., Heitor, A. and Sivakumar, M. (2020). "Geopolymers in construction - recent developments", *Construction and Building Materials*, 260, 120472, https://doi.org/10.1016/J.CONBUILDMAT.2020.120472.
Noushini, A. and Castel, A. (2016). "The effect of heat-curing on transport properties of low-

calcium fly ash-based geopolymer concrete", *Construction and Building Materials*, 112, 464–477, https://doi.org/10.1016/J.CONBUILDMAT.2016.02.210.

Okeyinka, O. M., Oloke, D. A., Adebisi, W. A. and Ayininuola, G. M. (2019). "Investigation into the applicability of brewery sludge residue-ash as a base material for geopolymer concrete", *Construction and Building Materials*, 223, 28–32, https://doi.org/10.1016/J.CONBUILDMAT.2019.06.214.

Okoye, F. N., Durgaprasad, J. and Singh, N. B. (2015). "Mechanical properties of alkali activated flyash/Kaolin based geopolymer concrete", *Construction and Building Materials*, 98, 685–691, https://doi.org/10.1016/J.CONBUILDMAT.2015.08.009.

Okoye, F. N., Prakash, S. and Singh, N. B. (2017). "Durability of fly ash based geopolymer concrete in the presence of silica fume", *Journal of Cleaner Production*, 149, 1062–1067, https://doi.org/10.1016/J.JCLEPRO.2017.02.176.

Olivia, M. and Nikraz, H. (2012). "Properties of fly ash geopolymer concrete designed by Taguchi method", *Materials & Design (1980-2015)*, 36, 191–198, https://doi.org/10.1016/J.MATDES.2011.10.036.

Osholana, T. S., Dludlu, M. K., Oboirien, B. and Sadiku, R. (2020). "Enhanced reactivity of geopolymers produced from fluidized bed combustion bottom ash", *South African Journal of Chemical Engineering*, 34, 72–77, https://doi.org/10.1016/J.SAJCE.2020.06.006.

Özcan, A. (2018). "Investıgatıon of the durabılıty of geopolymer concretes produced by usıng ferrochrome slag and blast furnace slag agaınst to acıd, salt and sulfate effects", Master of Science Thesis, Graduate School of Natural and Applied Sciences, Inönü University, pp.133.

Pan, Z., Sanjayan, J. G. and Rangan, B. V. (2011). "Fracture properties of geopolymer paste and concrete", *Magazine of Concrete Research*, 63(10), 763–771, https://doi.org/10.1680/macr.2011.63.10.763.

Park, Y., Abolmaali, A., Kim, Y. H. and Ghahremannejad, M. (2016). "Compressive strength of fly ash-based geopolymer concrete with crumb rubber partially replacing sand", *Construction and Building Materials*, 118, 43–51, https://doi.org/10.1016/J.CONBUILDMAT.2016.05.001.

Pham, T.-T., Nguyen, N.-L., Nguyen, T.-T., Nguyen, T.-T. and Pham, T.-H. (2023). "Effects of superplasticizer and water–binder ratio on mechanical properties of one-part alkali-activated geopolymer concrete", *Buildings*, 13(7), 1835, https://doi.org/10.3390/buildings13071835.

Rajini, B. and Rao, A. V. N. (2014). "Mechanical properties of geopolymer concrete with fly ash and GGBS as source materials", *International Journal of Innovative Research in Science, Engineering and Technology*, 03(09), 15944–15953, https://doi.org/10.15680/ijirset.2014.0309023.

Ramesh, V. and Srikanth, Dr. K. (2020). "Mechanical properties and mix design of geopolymer concrete – A review", *E3S Web of Conferences*, 184, 01091, https://doi.org/10.1051/e3sconf/202018401091.

Rawat, R., Bachheti, I. and Pratap, B. (2024). "Advancements in Geopolymer Concrete Technology: A Comprehensive Review of Fresh, Hardened and Microstructural Properties", *Civil Engineering Infrastructures Journal*. https://doi.org/10.22059/ceij.2024.376588.2062

Razak, S. N. A., Shafiq, N., Guillaumat, L., Farhan, S. A. and Lohana, V. K. (2022). "Fire-exposed fly-ash-based geopolymer concrete: Effects of burning temperature on mechanical and microstructural properties", *Materials*, 15(5), 1884, https://doi.org/10.3390/ma15051884.

Reddy, M. S., Dinakar, P. and Rao, B. H. (2018). "Mix design development of fly ash and ground granulated blast furnace slag based geopolymer concrete”, *Journal of Building Engineering*, 20, 712–722, https://doi.org/10.1016/J.JOBE.2018.09.010.

Sadat, M. R., Bringuier, S., Asaduzzaman, A., Muralidharan, K. and Zhang, L. (2016). “A molecular dynamics study of the role of molecular water on the structure and mechanics of amorphous geopolymer binders”, *The Journal of Chemical Physics*, 145(13), https://doi.org/10.1063/1.4964301.

Safari, Z., Younis, K. H. and Kamal, I. (2024). “Sustainable utilization of waste pumice powder in slag-based geopolymer concretes: fresh and mechanical properties”, *Sustainability*, 16(21), 9296, https://doi.org/10.3390/su16219296.

Saleh, P. (2018). “Development of a new type of fly ash based geopolymer concrete”, PhD Thesis, Graduate School of Natural & Applied Sciences, Hasan Kalyoncu University, pp.190.

Sangi, R., Sreenivas, B. S. and Shanker, K. (2023). “Mix design of fly ash and GGBS based geopolymer concrete activated with water glass”, *Engineering, Technology & Applied Science Research*, 13(5), 11884–11889, https://doi.org/10.48084/etasr.6216.

Shilar, F. A., Ganachari, S. V., Patil, V. B., Khan, T. M. Y., Javed, S. and Baig, R. U. (2022). “Optimization of alkaline activator on the strength properties of geopolymer concrete”, *Polymers*, 14(12), 2434, https://doi.org/10.3390/polym14122434.

Skane, R., Schneider, P. A., Jones, F., Riessen, A. van, Jamieson, E., Sun, X. and Rickard, W. D. A. (2025). “Predicting the stability of geopolymer activator solutions for optimised synthesis through thermodynamic modelling”, *Chemical Engineering Journal*, 515, 163543, https://doi.org/10.1016/J.CEJ.2025.163543.

Srinivasa, A. S., Swaminathan, K., & Yaragal, S. C. (2024). “Effect of Water to Geopolymer Solids Ratio on Properties of Fly Ash and Slag-Based One-Part Geopolymer Binders”, *Research Transcripts in Materials*, *2*, 81-92. https://doi.org/10.55084/grinrey/RTM/978-81-964105-5-1_6

Tekle, B. H., Holschemacher, K., Löber, P. and Heiden, B. (2020). “Mechanical behaviors and frost-resistance of alkali activated cement concrete with different binder systems”, Preprints, 1-14, Retrieved August 15, 2025, from, https://doi.org/10.20944/preprints202012.0747.v1.

The European Cement Association. (2025). “2024 Activity Report”, CEMBUREAU, 3-55, Retrieved August 15, 2025, from https://www.cembureau.eu/media/sblceede/cembureau-activity-report-2024.pdf.

Thumrongvut, J., Seangatith, S., Phetchuay, C. and Suksiripattanapong, C. (2022). “Comparative experimental study of sustainable reinforced portland cement concrete and geopolymer concrete beams using rice husk ash”, *Sustainability*, 14(16), 9856, https://doi.org/10.3390/su14169856.

Tuyan, M., Boyacı, O. C., Çakır, Ö. A. and Ramyar, K. (2017). “Investigation of mechanical properties and high temperature resistance of fly ash-based geopolymer concrete”, *Concrete 2017 Ready Mixed Concrete Congress and Cement, Aggregate, Construction Technologies and Equipment Exhibition*, İstanbul, Turkey.

Vora, P. R. and Dave, U. V. (2013). “Parametric studies on compressive strength of geopolymer concrete”, *Procedia Engineering*, 51, 210–219, https://doi.org/10.1016/J.PROENG.2013.01.030.

Tang, W., Pignatta, G., & Sepasgozar, S. M. E. (2021). “Life-cycle assessment of fly ash and cenosphere-based geopolymer material”, *Sustainability*, 13(20), 11167. https://doi.org/10.3390/su132011167

Xie, T. and Ozbakkaloglu, T. (2015). “Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature”, *Ceramics International*, 41(4), 5945–

5958, https://doi.org/10.1016/J.CERAMINT.2015.01.031.
Yang, W., Zhu, P., Liu, H., Wang, X., Ge, W. and Hua, M. (2021). "Resistance to sulfuric acid corrosion of geopolymer concrete based on different binding materials and alkali concentrations", *Materials*, 14(23), 7109, https://doi.org/10.3390/ma14237109.
Yu, Y., Xu, F., Wang, S., Fan, L., Zhang, J., Li, P. and Yu, L. (2025). "Influence mechanism of curing temperature on geopolymerization reaction: A comprehensive review", *Journal of Building Engineering*, 103, 112195, https://doi.org/10.1016/J.JOBE.2025.112195.
Yurt, Ü. and Bayraktar, H. (2025). "Towards innovative and sustainable building materials: Effect of alkali activator concentration on the performance of waste brick powder-based geopolymer composites", *Environmental Research*, 283, 122109. https://doi.org/10.1016/J.ENVRES.2025.122109.
Zhang, B., Ma, Y., Liang, Y., Wang, Y. and Ji, T. (2024). "Effect of alkali content on the high-temperature behavior of alkali-activated slag paste containing MSWI bottom ash", *Journal of Materials in Civil Engineering*, 36(6), 04024120, https://doi.org/10.1061/JMCEE7.MTENG-16522.