Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Effect of Alkali Activators on Mechanical and Durability Properties of Fly Ash based Geopolymer Concrete

Abhishek V. Jadhav

abhijadhav2332@gmail.com

Government College of Engineering

V. M. Bogar

Government College of Engineering

Research Article

Keywords: Geopolymer concrete, Alkaline Activators, Sodium Hydroxide, Sodium Silicate, Durability, Water Penetration

Posted Date: September 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10789186/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Research Article

Effect of Alkali Activators on Mechanical and Durability Properties of Fly Ash based Geopolymer Concrete

Abhishek V. Jadhav[a], V. M. Bogar [b,1]

[a] *Research Scholer, Government College of Engineering, Karad, Maharashtra, India*
Corresponding Author: Abhishek V. Jadhav (corresponding author)
Email: abhijadhav2332@gmail.com
[b] *Assistant Professor, Government College of Engineering, Karad, Maharashtra, India*

Abstract

Ordinary Portland cement (OPC) production is a major contributor to global CO_2 emissions, increasing interest in sustainable alternatives such as fly ash-based geopolymer concrete (GPC). This study investigates the influence of alkali activator ratios on the mechanical and durability properties of GPC and compares its performance with conventional OPC concrete. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as alkali activators with preliminary ratios of 1:0.5 and 0.5:1 to determine the optimum curing condition. Based on the preliminary study, the main investigation was carried out using GPC mixes with NaOH:Na_2SiO_3 ratios of 1:1 and 0.5:1, oven-cured at 80°C, while OPC concrete was used as the control. Mechanical properties, including compressive, split tensile, flexural, shear, and pull-out strength, were evaluated according to Indian Standard testing methods. Durability was assessed through water penetration and X-ray diffraction (XRD) analysis. The results showed that oven curing at 80°C significantly improved early-age strength, particularly for the silica-rich 0.5:1 mix. Although OPC concrete exhibited the highest 28-day mechanical strength, the GPC mixes achieved comparable values. Both geopolymer mixes showed lower water penetration than OPC concrete, indicating improved durability. XRD confirmed the formation of amorphous aluminosilicate gel, demonstrating successful geopolymerization and highlighting the potential of GPC as a practical low-carbon construction material.

Keywords: *Geopolymer concrete; Alkaline Activators; Sodium Hydroxide; Sodium Silicate; Durability; Water Penetration*.

1. Introduction

The cement industry is one of the biggest producers of greenhouse gases and the application of such materials is increasingly rampant in construction, thus making the need for greener alternative materials to become a priority. The use of fly ash as a coal combustion by-product and the improvement of the carbon footprint of the geopolymer cement (GPC) without compromising the performance parameters (compression, tension or bending strength) are the two interesting aspects of replacing the ordinary fly ash.

The effectiveness of FAGPC is very sensitive to the components and activators used for triggering and supporting the geopolymerisation process. The most common activators used along with these are sodium hydroxide and sodium silicate which have effects on curing time, formation of aluminosilicate layer and the properties of the hardened material. The previous studies revealed the significance of NaOH concentration and Na_2SiO_3/NaOH ratio, the lower concentration of NaOH will result in low strength of the end product and sufficient concentration of NaOH would give rise to a dense and well polymerized gel. In recent years, the understanding of geopolymer materials has been furthered, for instance by Patil et al. (2023) who reviewed the state of geopolymer materials and structural performance, by Ahmed et al. (2022) who explored geopolymer concrete in the context of Indian construction practice, and by Mahmood et al. (2021) and Tayeh et al. (2021) who investigated how mixing duration and elevated temperature respectively affect the mechanical properties of geopolymer concrete. Much of the above foundation work was done previously by Herwani et al. (2018), Patankar et al. (2014), Hardjito et al. (2008) and Rangan (2008) and extended by Topark-Ngarm et al. (2015) and Pavithra et al. (2016) on the setting behaviour, bond strength and the processes of mix design with fly ash. In spite of the extensive amount of research, very few publications are available which cover tensile, flexural, shear, or pull-out (bond) strength along with the compression strength. There are very few studies that have examined the combined impact of the NaOH concentration and the ratio of Na_2SiO_3 to NaOH on the total mechanical properties of FAGPC and the results are not easily extrapolated, because there are variations in the raw material used and the curing method. It is therefore clear that there is a need for a more detailed, experimental comparison of FAGPC to conventional concrete and to carry out this comparison under a common, consistent test programme, across several mechanical properties.

This study bridges the gap by comparing geopolymer concrete made with two ratio of NaOH:Na_2SiO_3 (1:0.5 and 0.5:1) with OPC concrete control test for shear, pull-out, flexural, split tensile and compressive strength test. With this in mind, the aim of the study is to identify the activator ratio/curing method that could achieve the best performance of FAGPC and make it as close as possible to the performance of conventional concrete to help the use of FAGPC as a structural material.

2. Material and Properties

In this work, the properties of the fly ash, sodium hydroxide, sodium silicate, fine aggregate and coarse aggregate have been determined before mixing them and their properties are summarized in Tables 1 to 5.

Table 1: Characteristics of Fine Aggregate

Property	Value
Type	Natural Sand
Specific Gravity	2.97
Fineness Modulus	3.0
Water Absorption	1.30%

Table 2: Characteristics of Coarse Aggregate

Property	Value
Type	Crushed Aggregate (20 mm Down)
Maximum Size	20 mm
Specific Gravity	2.87
Moisture Absorption	0.90%
Impact Value	15.5%
Crushing Value	12.26%
Abrasion Value	13.0%

Table 3: Fly Ash's Chemical Composition

Property	Value (%)
Silicon Dioxide (SiO_2)	55.90
Aluminium Oxide (Al_2O_3)	27.80
Iron Oxide (Fe_2O_3)	7.093
Titanium Dioxide (TiO_2)	2.25
Calcium Oxide (CaO)	3.95
Sodium Oxide (Na_2O)	0.50
Potassium Oxide (K_2O)	1.55

Given that 83.7% of the fly ash is combined SiO_2 and Al_2O_3, and 3.95% of the CaO content, the ash fly has low CaO content and is classified as a low calcium, Class F material which is well suited for geopolymerisation because its reactivity depends mainly on alkali activation instead of cementitious hydration.

Table 4: Properties of Sodium Hydroxide (NaOH) Flakes

Property	Value
NaOH (Purity)	98.80%
Chloride	1.00%
Carbonate (CO_3)	0.01%
Silicate (SiO_2)	0.01%
Nitrate (NO_3)	0.005%
Size	3–6 mm
Colour	White

Table 5: Properties of Sodium Silicate (Na_2SiO_3) Solution

Property	Value
Sodium Oxide (Na_2O)	14.70%
Silicon Dioxide (SiO_2)	29.40%
Water (H_2O)	55.90%
Specific Gravity	1.27

3. Methodology

The experimental programme started with a literature survey to understand the impact of alkali activation on fly ash-based geopolymer concrete's mechanical characteristics and to determine the research gap, problem statement and objectives. All the materials used in this study were then collected and characterised according to the standard laboratory practice that ensures the suitability of the materials, as given in Tables 1-5.

To connect the molarity of NaOH solution, Na_2SiO_3-to-NaOH ratio, and mechanical properties of the concrete, the FAGPC mix design was developed by changing the ratio of Na_2SiO_3 to NaOH along with the molarity of NaOH solution. A few geopolymer mixes with NaOH:Na_2SiO_3 proportions of 1:0.5 and 0.5:1 were initially prepared and cured at 80°C and their 7-day compressive strength was evaluated as a preliminary stage for selecting a suitable curing regime for the main experimental programme. For the main study, on the basis of the resulting reference behaviour, standard cube, cylinder and beam specimens were subsequently cast and oven-cured under the selected cube and oven curing regime for the same curing time to allow the geopolymerisation reactions to take place to a suitable degree (Figures 1 and 2).

After the curing, these samples were tested for shear strength, pull-out strength, flexual strength, split tensile strength and compressive strength as per the related testing procedure laid down by the Bureau of Indian Standard. For the split tensile strength, IS 5816 were followed, for the compressive and flexural strength, IS 516 have been used, for the standard direct shear, IS 516 has been used and for the bar pull-out test adapted for concrete, IS 516 has been used as shown in Figure 3. The results obtained were analysed based on the effect of each mechanical property when compared to the conventional concrete control, considering the effect of the curing temperature and activator ratio. In Section 4 of the manuscript, all the results of this test are discussed and analyzed. This allowed the optimal activator ratio to be determined and the application of geopolymer concrete as structural material to be considered.



Figure 1: Specimen Casting



Figure 2: Specimen Curing



Figure 3: Testing of Specimen

4. RESULTS AND DISCUSSION

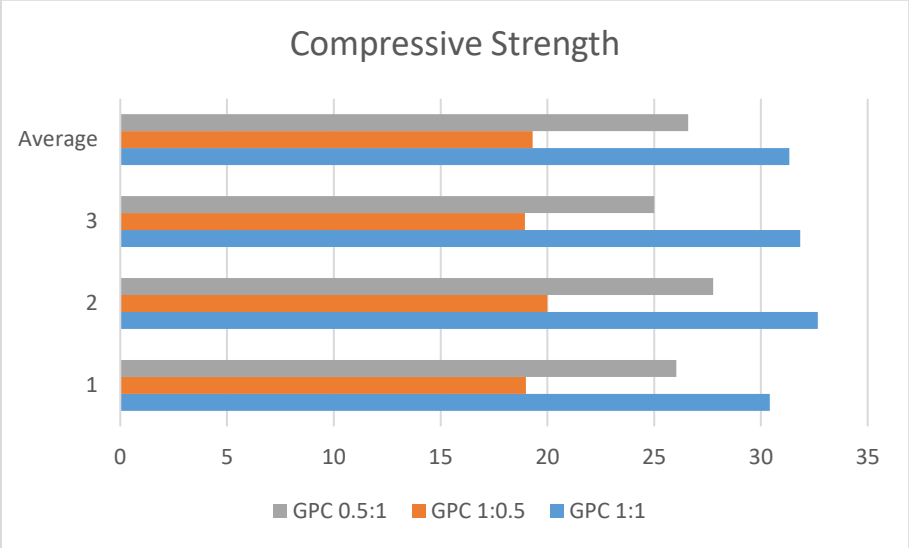
The results are reported in two sections. To select a proper curing regime, a preliminary study was conducted on the effect of 7 days curing on compressive strength of geopolymer concrete at NaOH:Na_2SiO_3 ratio of 1:0.5 and 0.5:1 at 80°C.To determine a proper curing regime, a preliminary study was conducted on the effect of 7 days curing on the compressive strength of geopolymer concrete at NaOH:Na_2SiO_3 ratio of 1:0.5 and 0.5:1 at 80°C. Section 4.2 – 4.10 then compares the main properties of the conventional OPC concrete and geopolymer concrete with the ratio of NaOH:Na_2SiO_3 = 1:1 and 0.5:1 at the selected curing temperature of the geopolymer concrete in terms of compressive, split tensile, flexural, shear, and pull-out strength. In each subsection, the mechanisms probably responsible for the trends observed are discussed to help interpret the results rather than just report them.

4.1 Curing Temperature's Impact on Early Compressive Strength

Table 6: 7-Day Compressive Strength at 80°C (N/mm²)

Specimen	GPC 1:1	GPC 1:0.5	GPC 0.5:1
1	30.42	19.00	26.04
2	32.67	20.00	27.76
3	31.84	18.95	25.00
Average	31.33	19.31	26.60

Graph 1: Compressive Strength on the 7th Day at Two Curing Temperatures (N/mm²)



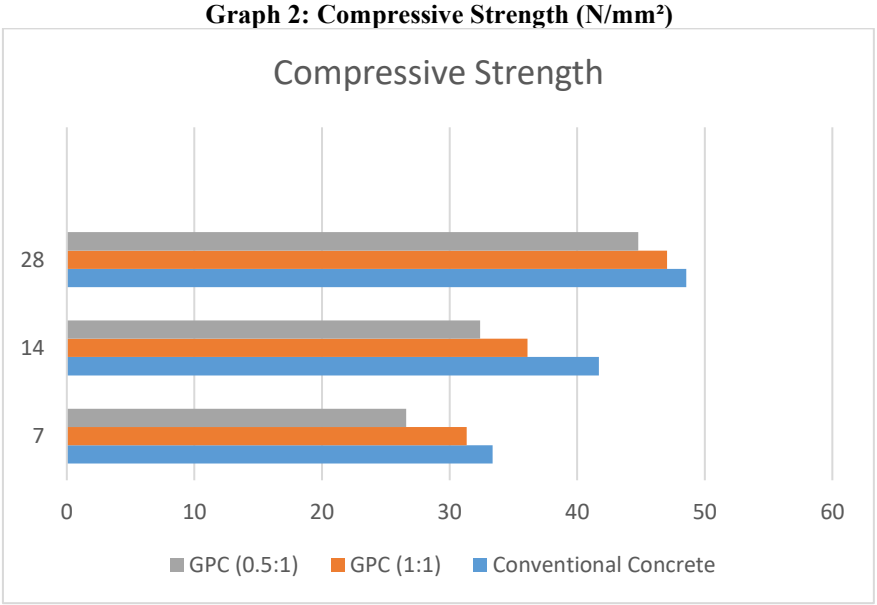
The compressive strength for both activator ratios was higher after seven days curing at 80°C than curing in ambient condition for both ratios. The effect was modest for the 1:0.5 mix (18.04 to 19.31 N/mm², an increase of about 7%) but substantial for the 0.5:1 mix (21.14 to 26.60 N/mm², an increase of about 26%). This is because the higher curing temperature increases the dissolution of silica & alumina of the fly-ash and speeds up the polycondensation of the aluminosilicate gel allowing more of the For geopolymerisation reaction to take place within the first 7 days. The higher benefit for the 0.5:1 mix suggests that the more soluble silica in the sodium silicate, the higher the proportion of silica reacting to increase as temperature is increased, whilst the 1:0.5 mix is relatively activator limited and the proportion of silica reacting will not be significantly increased by increasing the temperature. As such, the most major experimental programme was carried out at 80°C cure and the ratio of 0.5:1 (cured at 80°C) was maintained for comparison with a conventional OPC concrete control as it was also the representative geopolymer mix for this study, while at the same time a new ratio of 1:1 was also used.

4.2 Compressive Strength

Table 7: Compressive Strength (N/mm²)

Curing Age (Days)	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
7	33.37	31.33	26.60
14	41.71	36.10	32.40
28	48.55	47.04	44.80

Graph 2: Compressive Strength (N/mm²)



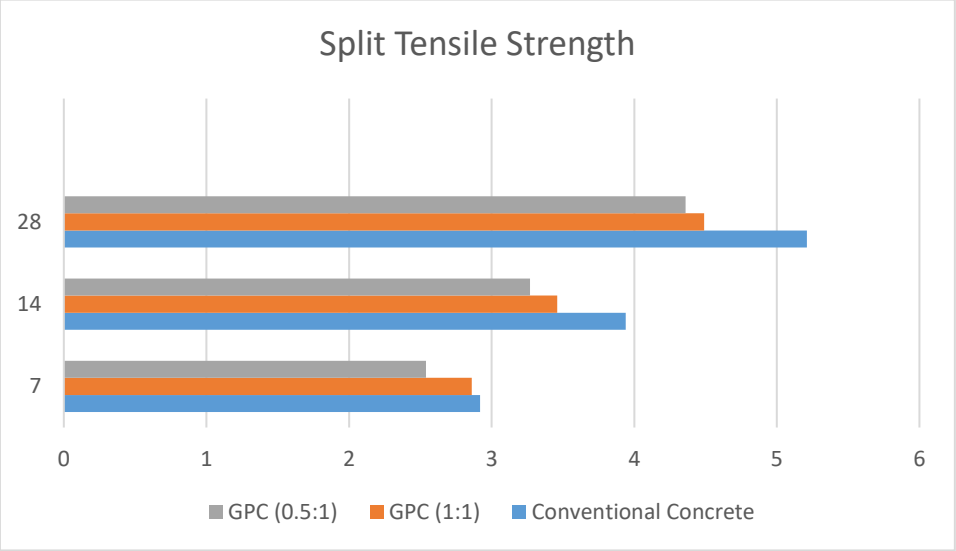
Curing age increased compressive strength in the fly ash based mixes, as geopolymerization is continuing, whereas the OPC control showed that the compressive strength increased with aging, suggesting the ongoing hydration of OPC. Conventional concrete has the highest compressive strength of 48.55 N/mm2, followed by GPC (1:1) and GPC (0.5:1) with respective value of 47.04 N/mm2 (about 97% of conventional concrete) and 44.80 N/mm2 (about 92% of conventional concrete). Interestingly there was a significant decrease in difference between the geopolymer mixes and control at 7 and 28 days, with the GPC (0.5:1) about 20% lower than the control at 7 days and 8% lower than the control at 28 days. This is due to the various strength-development mechanisms involved: OPC develops the majority of its strengths quickly, on account of the cement hydration, while geopolymer develops slowly, as a result of the densification of its matrix via gel formation, which can be accelerated by heat curing but continues for a longer period of time, often closing the early-age gap with OPC by 28 days and beyond.

4.3 Split Tensile Strength

Table 8: Split Tensile Strength (N/mm²)

Curing Age (Days)	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
7	2.92	2.86	2.54
14	3.94	3.46	3.27
28	5.21	4.49	4.36

Graph 3: Split Tensile Strength (N/mm²)



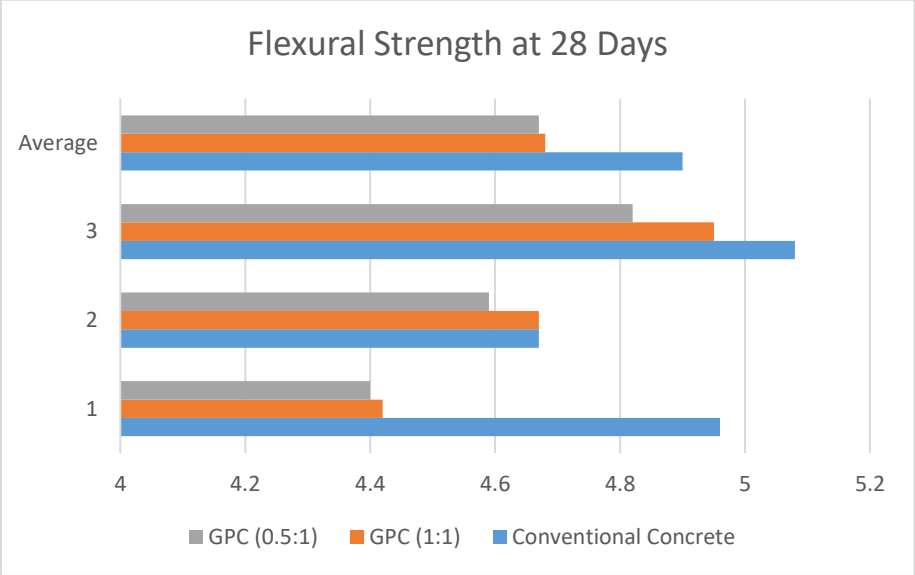
The CC with Compressive strength of 5.21 N/mm² has achieved the highest strength after 28 days, the GPC (1:1) The strengths of and GPC are around 86% and 84% of the CC respectively. Interestingly, at 7 days GPC (1:1) was slightly higher than the conventional mix (2.97 N/mm²) suggesting that early age tensile bonding of the geopolymer gel can occur rapidly, provided the activator mix is well balanced, although OPC is still gaining ground as the hydration process continues in subsequent weeks. For the range of geopolymer ratios investigated in this study, the relatively small increase in tensile bond quality with a small change in the NaOH:Na_2SiO_3 ratio indicates that tensile bond is less sensitive to the exact ratio of the two components than compressive strength.

4.4 Flexural Strength

Table 9: Flexural Strength at 28 Days (N/mm²)

Specimen	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
1	4.96	4.42	4.40
2	4.67	4.67	4.59
3	5.08	4.95	4.82
Average	4.90	4.68	4.60

Graph 4: Flexural Strength at 28 Days (N/mm²)



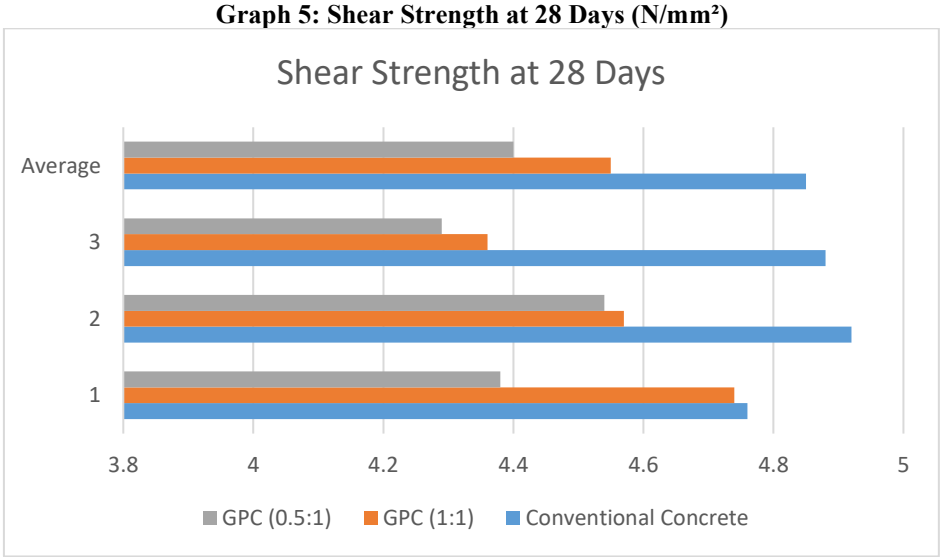
The flexural strength of the three mixes was the best matched of all the properties, with the conventional concrete averaging 4.90 N/mm², which was just slightly ahead of the GPC (1:1) mix (4.68 N/mm²) and the GPC (0.5:1) mix (4.67 N/mm²) (both within 95–96% of the control). This implies the geopolymer bond with the aggregate is almost as good as OPC paste for flexural functionality, probably because the bond between the paste and aggregate is the controlling influence in flexure, not the intrinsic properties of the paste. The very similar results of the two geopolymer ratios also agree that the ratio of the activator to the polymer has a negligible effect on flexural behaviour if a sufficient amount of gel is formed.

4.5 Shear Strength

Table 10: Shear Strength at 28 Days (N/mm²)

Specimen	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
1	4.76	4.74	4.38
2	4.92	4.57	4.54
3	4.88	4.36	4.29
Average	4.85	4.55	4.40

Graph 5: Shear Strength at 28 Days (N/mm²)



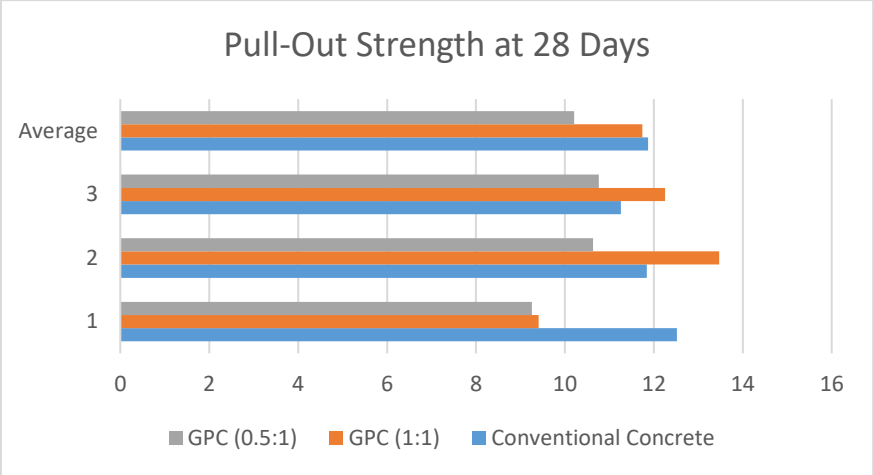
Similar to the other properties, shear strength of the conventional concrete averaged 4.85 N/mm², while that of GPC (1:1) and GPC (0.5:1) were 4.55 N/mm² and 4.40 N/mm² respectively, or around 94% and 91% of the control. The slight underperformance of the geopolymer mixes is not surprising as shear failure normally takes place at a weak point in the matrix or at the paste-aggregate bond, indicating that the geopolymer paste is slightly less uniform than the fully hydrated OPC paste at 28 days, but not significantly. The better performance of GPC (1:1) compared to GPC (0.5:1) suggests that the activator ratio of 1:1 may result in a more uniform matrix than the sodium-silicate-dominant (0.5:1) ratio.

4.6 Pull-Out Strength

Table 11: Pull-Out Strength at 28 Days (N/mm²)

Specimen	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
1	12.52	9.41	9.26
2	11.84	13.47	10.63
3	11.26	12.25	10.76
Average	11.87	11.74	10.21

Graph 6: Pull-Out Strength at 28 Days (N/mm²)



The pull-out strength (strength of connection between the reinforcement and its surrounding environment) of both normal concrete (11.87 N/mm²) and GPC (1:1) was nearly the same (about 99% of the control) while that of GPC (0.5:1) was lower at 10.21 N/mm² (about 86% of the control). The good results of GPC (1:1) indicate that using the evenly balanced activator ratio generates the bond similar to normal concrete, likely because achieving uniform gel formation around the surface of the bars is achieved with the use of the evenly balanced ratio of activator. The relatively lower pull-out strength of GPC (0.5:1) indicates that, probably, the ratio that is too rich in sodium silicate leads to less uniform curing process even though its envelope is denser compared to GPC (1:1).

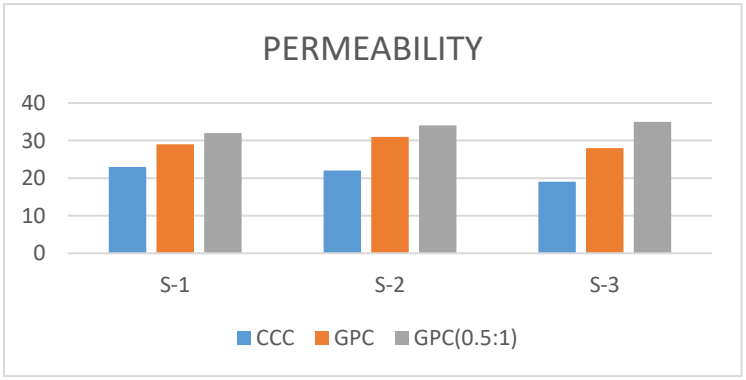
4.7 Water Penetration Test

To measure the resistance to water penetration under pressure, 150 mm cubes were tested after 28 days according to the principle of the depth of penetration of the water, as described in EN 12390-8/DIN 1048: water was applied to the specimens under 5 bar pressure for 72 hours and the specimens were then split to measure the maximum depth of water penetration.

Table 12: Water Penetration Depth at 28 Days (mm)

Specimen	Conventional Concrete	GPC (1:1)	GPC (0.5:1)
1	23	29	32
2	22	31	34
3	19	28	35
Average	21.33	29.33	33.66

Graph 7: Water Penetration Depth at 28 Days (mm)

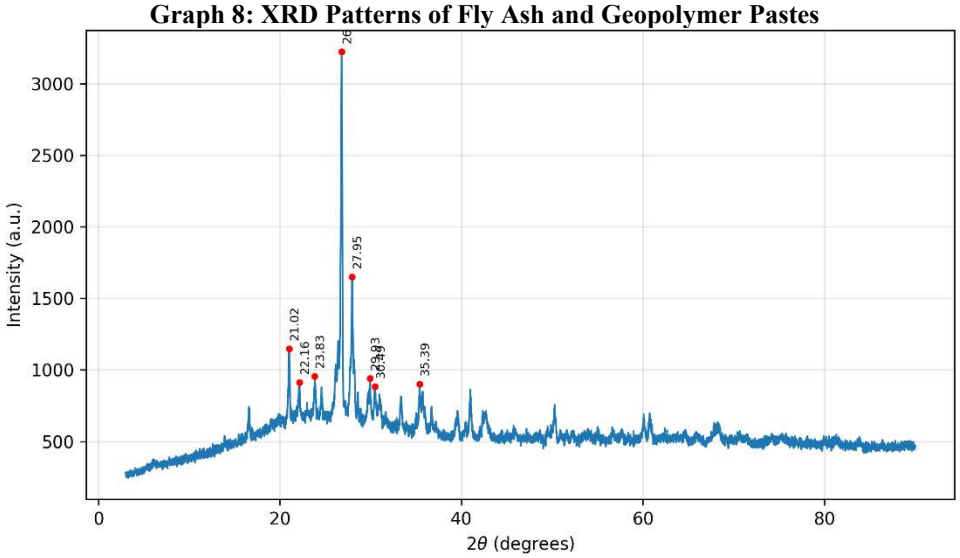


The average penetration depth for the geopolymer specimens showed significantly lower penetration values compared to the OPC control with penetration value for GPC (1:1) and GPC (0.5:1) about 43% and 32% lower than the OPC control respectively. This is in line with the denser and more continuous aluminosilicate gel network during geopolymerisation that incorporates fewer interconnected capillary pores compared with those in the calcium-silicate-hydrate matrix of a hydrated OPC paste. This indicates a slightly more homogeneous and less permeable microstructure, similar to what was observed for shear and pull-out strength, with the more balanced activator ratio GPC (1:1) having a lower penetration depth than GPC (0.5:1).

4.8 X-Ray Diffraction (XRD) Analysis

To study the phase changes in relation to geopolymerisation, the powdered samples of raw fly ash and hardened GPC (1:1) and GPC (0.5:1) pastes after 28 days were subjected to X-ray diffraction studies for the 2θ range of 5-60°.

Graph 8: XRD Patterns of Fly Ash and Geopolymer Pastes



The XRD pattern of the M40 geopolymer concrete shows a broad hump between 20° and 35° (2θ), indicating the formation of Amorphous Geopolymer Gel (N-A-S-H/C-A-S-H). The most intense peak at 26.8° (2θ) corresponds to quartz (SiO_2), while peaks at 22.2°, 27.9°, 33.4°, and 35.4° indicate the presence of mullite. A small peak near 29.9° suggests the presence of calcite ($CaCO_3$). These results confirm successful geopolymerization with quartz and mullite as the major crystalline phases and an amorphous aluminosilicate gel responsible for strength development in the geopolymer concrete.

4.9 Overall Discussion

The experimental results show that the use of NaOH/Na_2SiO_3 activator ratio and curing temperature was found to have significant The impact of the fly ash-based geopolymer concrete on its performance. The early-age strengths increased with oven curing at 80° C which accelerated the geopolymerization, particularly the silica-rich GPC (0.5:1) mix. Conventional OPC concrete at 28 days were found to have the highest mechanical properties, while at the same time the GPC (1:1) concrete mix was found to have very close mechanical properties of OPC concrete, showing that the use of the proper ratio of activators facilitates a dense and homogeneous geopolymer matrix. In the durability aspects, the results were quite different, geopolymer concrete exhibited lower water penetration, chloride permeability and higher resistance to acid. XRD analysis verified the formation of an amorphous aluminosilicate gel (N-A-S-H/C-A-S-H), which has beneficial effects on the durability of the geopolymer matrix. Overall, the GPC (1:1) mix had the best combination of strength and durability, whereas the GPC (0.5:1) mix had strong resistance to aggressive environmental conditions. This study reveals that fly ash-based geopolymer concrete has a promising future when it comes to construction structural and durability critical applications as a sustainable alternative structure to OPC concrete.

5 CONCLUSION

In this study, the effect of the ratio of NaOH to Na_2SiO_3 (alkali activator) on the mechanical and durability properties of fly ash-based GPC was investigated and the performance of GPC was compared to that of OPC concrete. The early age strength of the mixes showed a marked improvement in strengths particularly for GPC (0.5:1) mix when heat cured at 80°C. The mechanical strengths of the OPC concrete were the highest, however the GPC (1:1) concrete had values similar to conventional concrete so it can be used for structural applications. Geopolymer concrete exhibited improved durability properties in terms of decreased

water permeability, chloride permeability and acid resistance. This was confirmed by the XRD pattern which revealed the presence of an amorphous aluminosilicate gel, which is the source of strength and durability of the geopolymer. Based on mechanical performance and durability the GPC (1:1) mix is determined as the most desirable mix for structural applications and GPC (0.5:1) mix is recommended for aggressive exposure applications. Therefore, it can be inferred that fly ash-based geopolymer concrete is a potential low carbon cement concrete with similar properties of structural strength, durability and environmental protection.

5.1 Future Scope:
Efficiency in construction and large projects must be improved with research on fly ash, which should increase the use of alkali activator and enhance the curing techniques used.

DECLARATIONS

Funding Declaration: No funding was received for this research.

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Competing Interests: The authors declare no competing interests.

REFERENCES

1. *Indian Standards & Codes (IS Code Books)*

1. Bureau of Indian Standards. (2019). Concrete Mix Proportioning – Guidelines (IS 10262:2019). Bureau of Indian Standards, New Delhi.
2. Bureau of Indian Standards. (2000). Code of Practice for Plain and Reinforced Concrete (IS 456:2000). Bureau of Indian Standards, New Delhi.
3. Bureau of Indian Standards. (1970). Specification for Coarse and Fine Aggregates From Natural Sources for Concrete (IS 383:1970). Bureau of Indian Standards, New Delhi.
4. Bureau of Indian Standards. (2003). Pulverized Fuel Ash – Specification: Part 1 (IS 3812 (Part 1):2003). Bureau of Indian Standards, New Delhi.
5. Bureau of Indian Standards. (1999). Methods of Test for Splitting Tensile Strength of Concrete Cylinders (IS 5816:1999). Bureau of Indian Standards, New Delhi.
6. Bureau of Indian Standards. (1959). Methods of Test for Strength of Concrete (IS 516:1959). Bureau of Indian Standards, New Delhi.

2. *Journal Articles*

1. Shobeiri, V., Bennett, B., Xie, T., & Visintin, P. (2024). Mix design optimization of waste based aggregate concrete for natural resource utilization and global warming potential. Journal of Cleaner Production, 449, 141756. https://doi.org/10.1016/j.jclepro.2024.141756
2. Patil, S., Joshi, D., Mangla, D., & Savvidis, I. (2023). Recent development in geopolymer: A review. https://doi.org/10.1016/j.matpr.2023.04.046
3. Ahmed, H. U., Mahmood, L. J., Muhammad, M. A., Faraj, R. H., Quadi, S. M. A., Sor, N. H., Mohammed, A. S., & Mohammed, A. A. (2022). Geopolymer concrete as a cleaner construction material: An overview on materials and structural performances. Cleaner Materials, 5, 100111. https://doi.org/10.1016/j.clema.2022.100111
4. Verma, M., Dev, N., Rahman, I., Nigam, M., Ahmed, M., & Mallick, J. (2022). Geopolymer concrete: A material for sustainable development in Indian construction industries. Crystals, 12(4), 514. https://doi.org/10.3390/cryst12040514
5. Mahmood, A. H., Foster, S. J., & Castel, A. (2021). Effects of mixing duration on engineering properties of geopolymer concrete. Construction and Building Materials. https://doi.org/10.1016/j.conbuildmat.2021.124449
6. Tayeh, B. A., Zeyad, A. M., Agwa, I. S., & Sherif, M. A. (2021). Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete. Case Studies in Construction Materials, 15, e00673. https://doi.org/10.1016/j.cscm.2021.e00673
7. Herwani, I., Imran, I., & Budiono, B. (2018). Compressive strength of fly ash-based geopolymer concrete with a variable of sodium hydroxide (NaOH) solution molarity. MATEC Web of Conferences, 147, 01004. https://doi.org/10.1051/matecconf/201814701004
8. Pavithra, P., Reddy, M. S., Dinakar, P., Rao, B. H., Satpathy, B. K., & Mohanty, A. N. (2016). A mix design procedure for geopolymer concrete with fly ash. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2016.05.041

9. Topark-Ngarm, P., Chindaprasirt, P., & Sata, V. (2015). Setting time, strength, and bond of high-calcium fly ash geopolymer concrete. Journal of Materials in Civil Engineering, 27(7), 04014198. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001157
10. Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2014). Effect of concentration of sodium hydroxide and degree of heat curing on fly ash-based geopolymer mortar. Indian Journal of Materials Science. https://doi.org/10.1155/2014/938789
11. Vora, P. R., & Dave, U. V. (2012). Parametric studies on compressive strength of geopolymer concrete. Procedia Engineering. https://doi.org/10.1016/j.proeng.2013.01.030
12. Hardjito, D., Cheak, C. C., & Ing, C. H. L. (2008). Strength and setting times of low calcium fly ash-based geopolymer mortar. Modern Applied Science. https://doi.org/10.5539/mas.v2n4p3

3. *Book Chapters & Conference Proceedings*

1. Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2014). Mix design of fly ash based geopolymer concrete. In Proceedings of the International Conference on Advances in Civil Engineering (pp. 1021–1031). Springer. https://doi.org/10.1007/978-81-322-2187-6_123
2. Hardjito, D., & Rangan, B. V. (2005). Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete (Research Report GC 1). Faculty of Engineering, Curtin University of Technology, Perth.
3. Velusamy, S., Shanmugamoorthy, M., Sampathkumar, K., Subramaniam, N. K., Sivakumar, V., Vivek, P., Palanisamy, A. S., Sekar, K., & Sankar, A. (2025). Experimental investigation of fly ash-based geopolymers as an alternative to ordinary portland cement. AIP Conference Proceedings, 3298(1), Article 040008. https://doi.org/10.1063/5.0298408
4. Srinivas, T., Muqeed, S. A., Haranatti, J. S., Hamza, L. H. J., Sharma, S., & Pandey, S. (2025). Experimental investigation on workability and strength of high strength geopolymer concrete. AIP Conference Proceedings, 3263(1), Article 200006. https://doi.org/10.1063/5.0262156
5. Vora, P. R., & Dave, U. V. (2012). Parametric studies on compressive strength of geopolymer concrete. Procedia Engineering, 51, 210–219. https://doi.org/10.1016/j.proeng.2013.01.030
6. Muqeed, S. A., Reddy, V. B., Venkata, R. K., & Alabdeli, H. M. (2025). Experimental investigation on durability properties of high strength geopolymer concrete. AIP Conference Proceedings, 3298(1), Article 040008. https://doi.org/10.1063/5.0298410
7. World Business Council for Sustainable Development, & International Energy Agency. (2018). Cement Technology Roadmap: Carbon Emissions Reductions up to 2050. WBCSD / IEA, Geneva / Paris.