iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VIII **Month of publication:** August 2026

DOI: https://doi.org/10.22214/ijraset.2026.84664

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

Abhishek Vijay Jadhav[1], V. M. Bogar[2]
[1]*PG Scholar, Department of Applied Mechanics, Government College of Engineering, Karad*
[2]*Assistant Professor, Department of Applied Mechanics, Government College of Engineering, Karad*

Abstract: The production of ordinary Portland cement (OPC) is one of the major sources of carbon dioxide emissions in the construction industry, creating a need for more sustainable building materials. Fly ash-based geopolymer concrete (GPC) has emerged as a promising alternative because it can reduce environmental impact while providing good engineering performance. This study examines how different proportions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) affect the strength and durability of GPC compared with conventional OPC concrete. Initial trials using NaOH:Na_2SiO_3 ratios of 1:0.5 and 0.5:1 were conducted to identify a suitable curing condition. The main investigation was then carried out using geopolymer mixes with activator ratios of 1:1 and 0.5:1, all oven-cured at 80°C, with OPC concrete used as the control mix. Compressive, split tensile, flexural, shear, and pull-out strengths were evaluated using Indian Standard methods, while durability was assessed through water penetration and X-ray diffraction (XRD) tests. The results showed that heat curing significantly improved early-age strength, especially for the 0.5:1 mix. Although OPC concrete achieved slightly higher 28-day strength, the geopolymer mixes showed comparable mechanical performance, lower water penetration, and clear evidence of successful geopolymerization.
Keywords: Geopolymer concrete; Alkaline Activators; Sodium Hydroxide; Sodium Silicate; Durability; Water Penetration; XRD.

I. INTRODUCTION

The construction industry is one of the largest contributors to greenhouse gas emissions, with ordinary Portland cement (OPC) production accounting for a significant share of global carbon dioxide emissions. As the demand for infrastructure continues to grow, the development of environmentally friendly construction materials has become increasingly important. Fly ash, a by-product of coal-fired power plants, offers an effective solution by serving as a key precursor material in geopolymer concrete (GPC). Replacing OPC with fly ash-based geopolymer binders can significantly reduce the carbon footprint of concrete while maintaining the strength and durability required for structural applications. The performance of fly ash-based geopolymer concrete (FAGPC) is highly dependent on the type and proportion of alkali activators used during the geopolymerization process. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are the most widely used activators, and their concentration and ratio play a crucial role in controlling dissolution of silica and alumina, gel formation, curing behavior, and the final properties of hardened concrete. Previous studies have shown that insufficient NaOH concentration often results in poor strength development, whereas an optimized activator system promotes the formation of a dense and well-polymerized aluminosilicate gel. Several researchers have contributed to the advancement of geopolymer technology. Patil et al. (2023) reviewed recent developments in geopolymer materials and structural performance, while Ahmed et al. (2022) examined the use of geopolymer concrete in Indian construction practice. Mahmood et al. (2021) and Tayeh et al. (2021) reported the influence of mixing duration and elevated curing temperature on the mechanical behavior of geopolymer concrete. Earlier investigations by Hardjito et al. (2008), Rangan (2008), Patankar et al. (2014), and Herwani et al. (2018) established the fundamental relationships between alkali activation and strength development, whereas Topark-Ngarm et al. (2015) and Pavithra et al. (2016) explored setting behavior, bond characteristics, and mix design procedures for fly ash-based systems. Although a large body of research exists, most studies have primarily focused on compressive strength. Comparatively fewer investigations have evaluated split tensile, flexural, shear, and pull-out strengths together with durability characteristics under a single experimental program. Moreover, the combined influence of NaOH concentration and the Na_2SiO_3/NaOH ratio on the overall mechanical performance of FAGPC remains insufficiently understood because published results often vary due to differences in source materials, curing conditions, and testing procedures. A systematic comparison with conventional OPC concrete under identical conditions is therefore necessary.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

To address this research gap, the present study compares fly ash-based geopolymer concrete prepared with $NaOH_2SiO_3$ ratios of 1:0.5 and 0.5:1 with conventional OPC concrete. The investigation includes compressive, split tensile, flexural, shear, and pull-out strength tests, along with durability assessments, to identify an activator ratio and curing regime capable of producing geopolymer concrete with performance comparable to conventional concrete for structural applications.

II. 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

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

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

III.METHODOLOGY

The experimental investigation began with a comprehensive review of existing literature to understand the influence of alkali activation on the mechanical performance of fly ash-based geopolymer concrete and to identify the research gap, objectives, and problem statement. All constituent materials, including fly ash, sodium hydroxide, sodium silicate, fine aggregate, and coarse aggregate, were collected and characterized using standard laboratory procedures to ensure their suitability for concrete production. The geopolymer mix design was developed by varying the Na_2SiO_3-to-NaOH ratio and the molarity of the NaOH solution. Initially, geopolymer mixes with $NaOH_2SiO_3$ ratios of 1:0.5 and 0.5:1 were prepared and oven-cured at 80°C, and their 7-day compressive strength was evaluated to determine the most suitable curing condition for the main experimental program. Based on these preliminary results, standard cube, cylinder, and beam specimens were cast and cured under the selected oven-curing regime to allow sufficient geopolymerization. After curing, the specimens were tested for compressive, split tensile, flexural, shear, and pull-out strength in accordance with the relevant Bureau of Indian Standards, including IS 5816 for split tensile strength and IS 516 for compressive, flexural, shear, and pull-out tests. The results were then compared with those of conventional OPC concrete to evaluate the influence of curing temperature and activator ratio, enabling the identification of the most effective geopolymer mix for structural applications.

Figure 1: Specimen Casting

Figure 2: Specimen Curing

Figure 3: Testing of Specimen

IV. RESULTS AND DISCUSSION

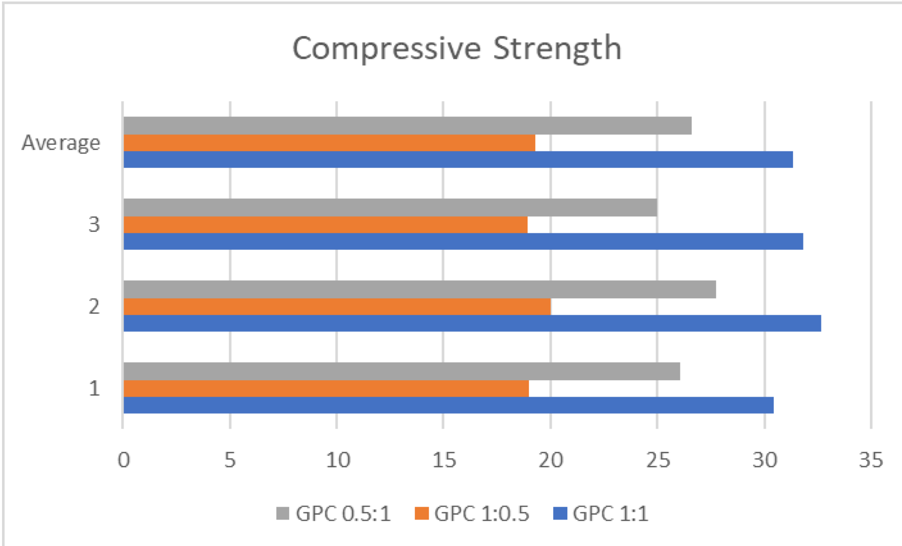
The results of this study are presented in two stages. The first stage involved a preliminary investigation to identify the most suitable curing condition by evaluating the 7-day compressive strength of geopolymer concrete prepared with $NaOH:Na_2SiO_3$ ratios of 1:0.5 and 0.5:1 and cured at 80°C. Based on the outcome of this initial assessment, an appropriate curing regime was selected for the main experimental program. The second stage compares the performance of conventional OPC concrete with geopolymer concrete mixes having $NaOH:Na_2SiO_3$ ratios of 1:1 and 0.5:1 under the selected curing condition. The comparison includes compressive, split tensile, flexural, shear, and pull-out strengths. In addition to presenting the experimental results, each section discusses the possible mechanisms responsible for the observed behavior, providing a clearer understanding of how the activator ratio and curing temperature influence the overall performance of geopolymer concrete.

A. *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 7-day compressive strength results showed that oven curing at 80°C improved the strength of geopolymer concrete for both alkali activator ratios when compared with ambient curing. The improvement was relatively small for the 1:0.5 mix, increasing from 18.04 to 19.31 N/mm² (approximately 7%), whereas the 0.5:1 mix showed a much larger increase, rising from 21.14 to 26.60 N/mm² (about 26%). The enhanced strength can be attributed to the elevated curing temperature, which accelerates the dissolution of silica and alumina from the fly ash and promotes faster formation of the aluminosilicate gel responsible for geopolymerization. The greater improvement observed in the 0.5:1 mix indicates that a higher sodium silicate content provides additional soluble silica, allowing the geopolymerization reaction to proceed more effectively under heat curing. In contrast, the 1:0.5 mix appears to be limited by the available activator, resulting in a comparatively smaller strength gain. Based on these findings, 80°C oven curing was selected as the curing condition for the main experimental program. The 0.5:1 mix was retained as a representative geopolymer mixture for comparison with conventional OPC concrete, while an additional 1:1 activator ratio was included to evaluate the effect of a balanced activator composition on concrete performance.

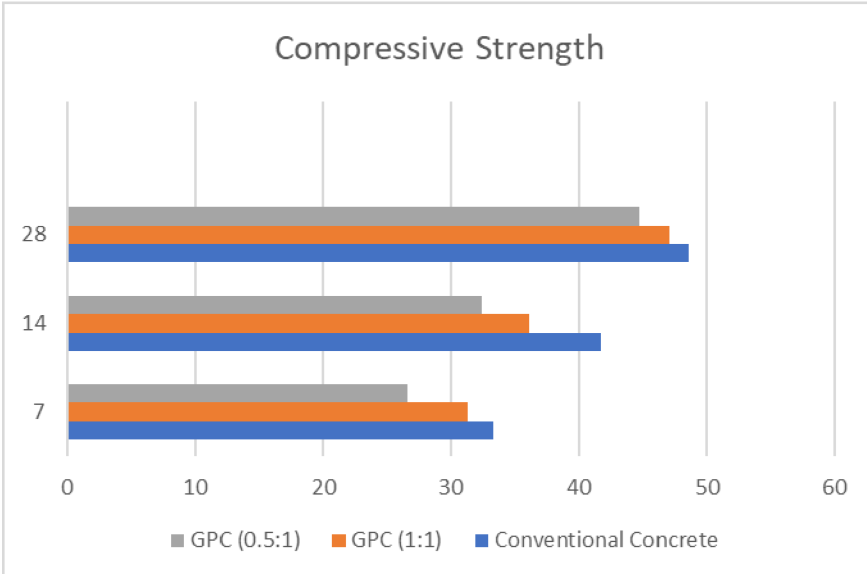
B. Compressive Strength

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

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

Graph 2: Compressive Strength (N/mm²)

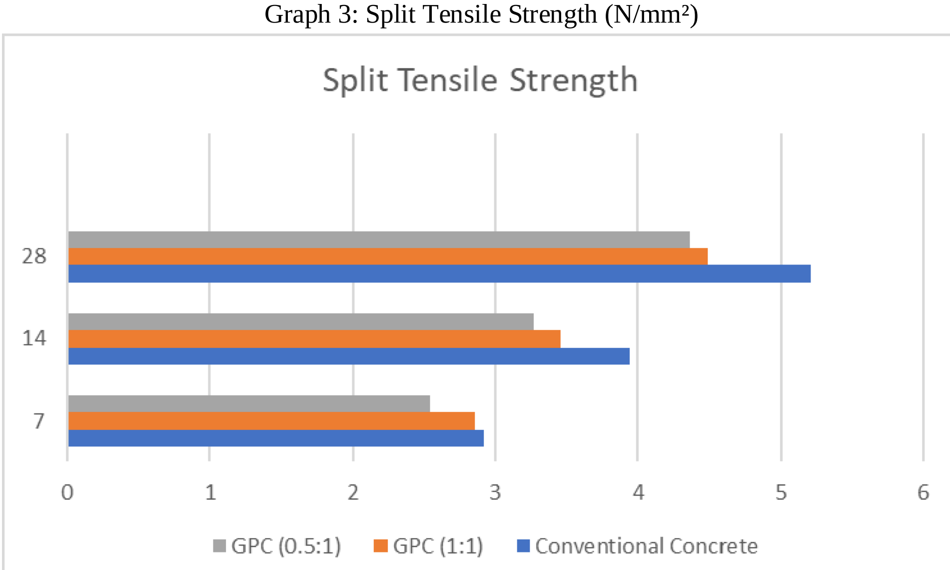


C. Split Tensile Strength

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)



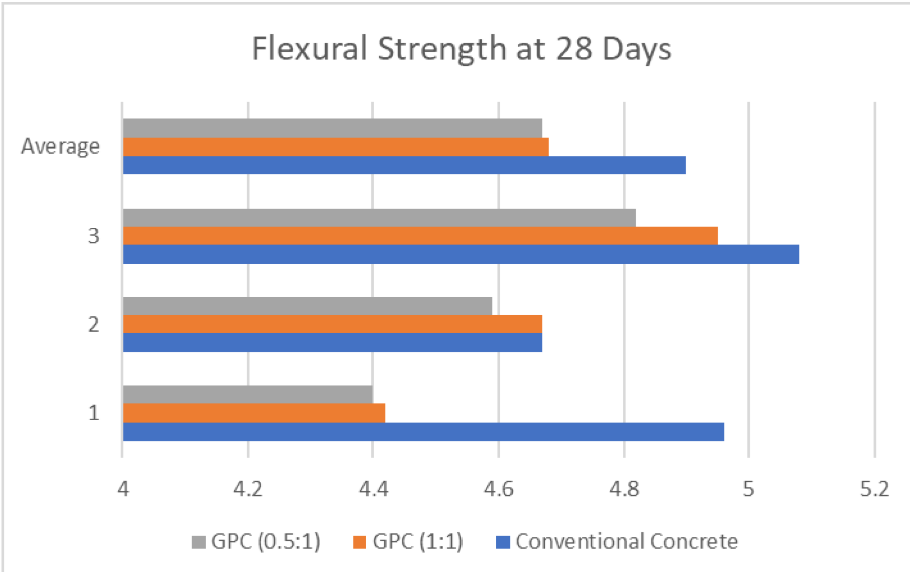
International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

D. 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)

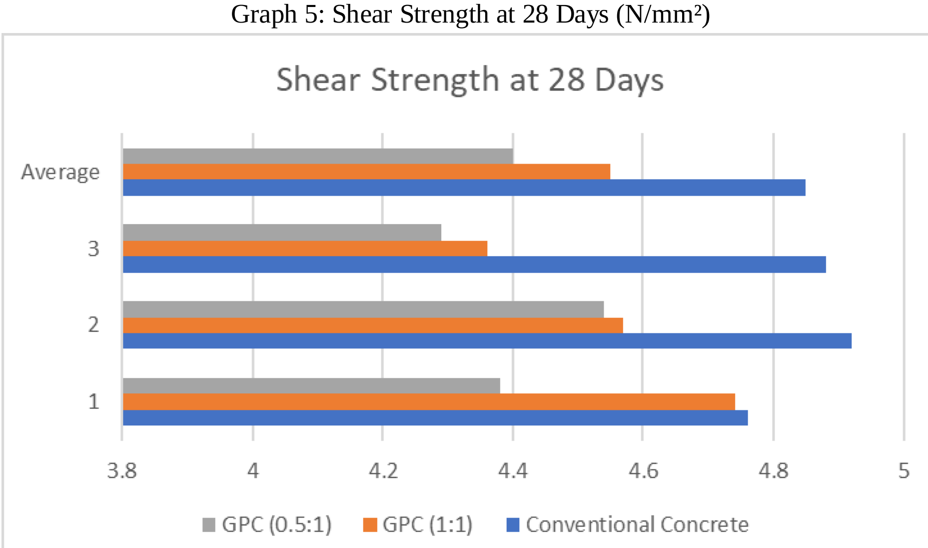


E. Shear Strength

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)

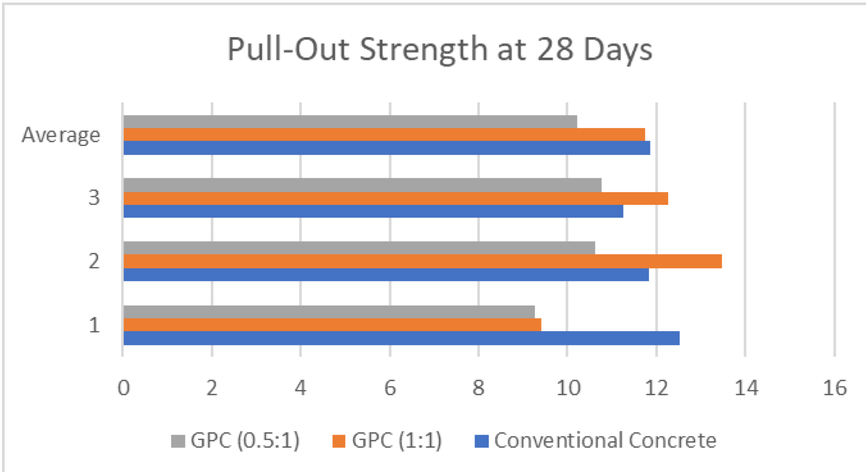


F. Pull-Out Strength

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)



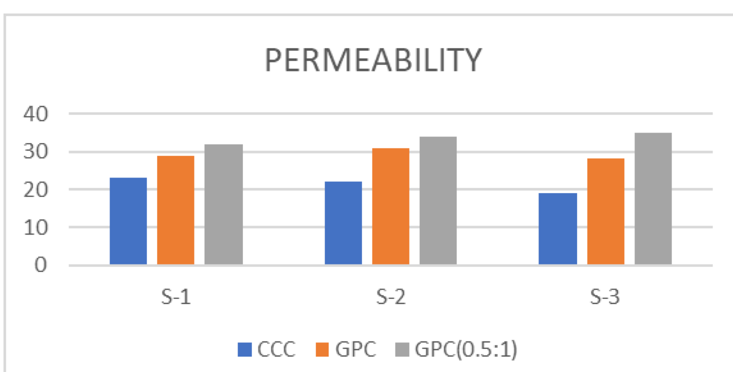
G. Water Penetration Test

The water penetration test was conducted on 150 mm concrete cube specimens after 28 days of curing to evaluate the resistance of the concrete to water penetration under pressure. The test was performed in accordance with the procedure described in EN 12390-8/DIN 1048, where water pressure of 5 bar was applied to the specimens continuously for 72 hours. After the testing period, the cubes were split into two halves, and the maximum depth of water penetration was measured. This test provides an indication of the permeability and durability of the concrete by assessing its ability to resist the ingress of water under sustained pressure.

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

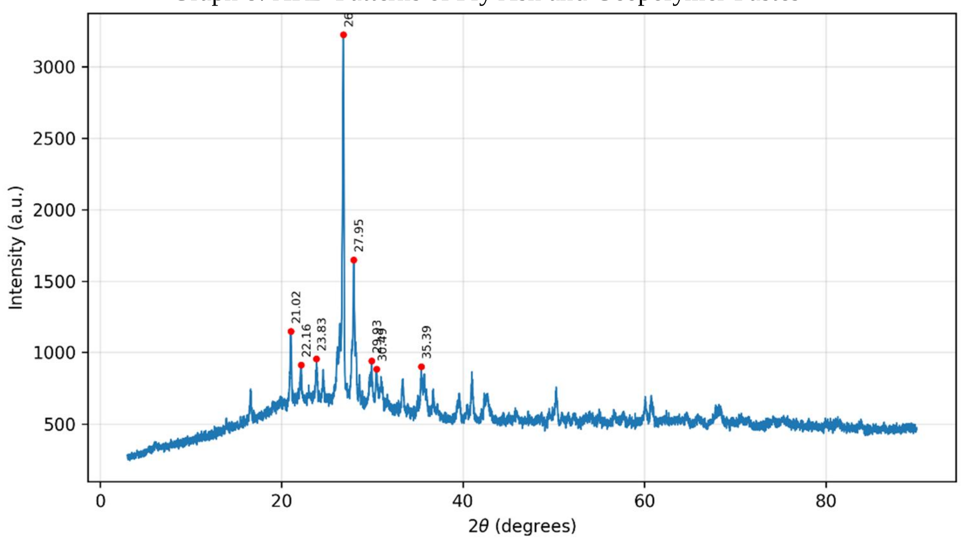
Graph 7: Water Penetration Depth at 28 Days (mm)



H. X-Ray Diffraction (XRD) Analysis

To examine the phase changes associated with the geopolymerization process, powdered samples of raw fly ash and 28-day hardened geopolymer paste specimens with $NaOH_2SiO_3$ ratios of 1:1 and 0.5:1 were analyzed using X-ray diffraction (XRD). The diffraction patterns were recorded over a 2θ range of 5°–60°, allowing the identification of crystalline phases and the formation of geopolymer reaction products within the hardened matrix.

Graph 8: XRD Patterns of Fly Ash and Geopolymer Pastes



The X-ray diffraction (XRD) pattern of the M40 fly ash-based geopolymer concrete exhibits a broad hump in the 20°–35° (2θ) region, which is characteristic of the formation of an amorphous geopolymer gel (N-A-S-H/C-A-S-H). The strongest diffraction peak observed at 26.8° (2θ) corresponds to quartz (SiO_2), while additional peaks at 22.2°, 27.9°, 33.4°, and 35.4° (2θ) indicate the presence of mullite. A weak diffraction peak near 29.9° (2θ) suggests a small amount of calcite ($CaCO_3$) in the geopolymer matrix. The appearance of the broad amorphous hump together with the crystalline quartz and mullite phases confirms that geopolymerization occurred successfully. The formation of the amorphous aluminosilicate gel is particularly significant, as it contributes to the dense microstructure and is primarily responsible for the development of strength and durability in the geopolymer concrete.

V. CONCLUSIONS

This study investigated the influence of $NaOH_2SiO_3$ alkali activator ratios on the mechanical and durability performance of fly ash-based geopolymer concrete (GPC) and compared its behavior with that of conventional ordinary Portland cement (OPC) concrete. The results showed that heat curing at 80°C significantly enhanced the early-age strength of the geopolymer mixes, with the 0.5:1 activator ratio exhibiting the greatest improvement. Although OPC concrete achieved the highest overall mechanical strength, the GPC (1:1) mix developed compressive, split tensile, flexural, shear, and pull-out strengths that were very close to those of conventional concrete, indicating its suitability for structural applications. In terms of durability, geopolymer concrete demonstrated superior resistance to water penetration and improved performance under aggressive environmental conditions. XRD analysis confirmed the formation of an amorphous aluminosilicate gel, which plays a key role in the development of both strength and durability in the geopolymer matrix. Considering the overall balance between mechanical performance and durability, the 1:1 activator ratio was found to be the most suitable for structural applications, while the 0.5:1 mix is recommended for environments requiring enhanced durability. Overall, fly ash-based geopolymer concrete can be considered a promising low-carbon alternative to conventional concrete, offering comparable structural performance along with improved environmental sustainability.

REFERENCES

[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

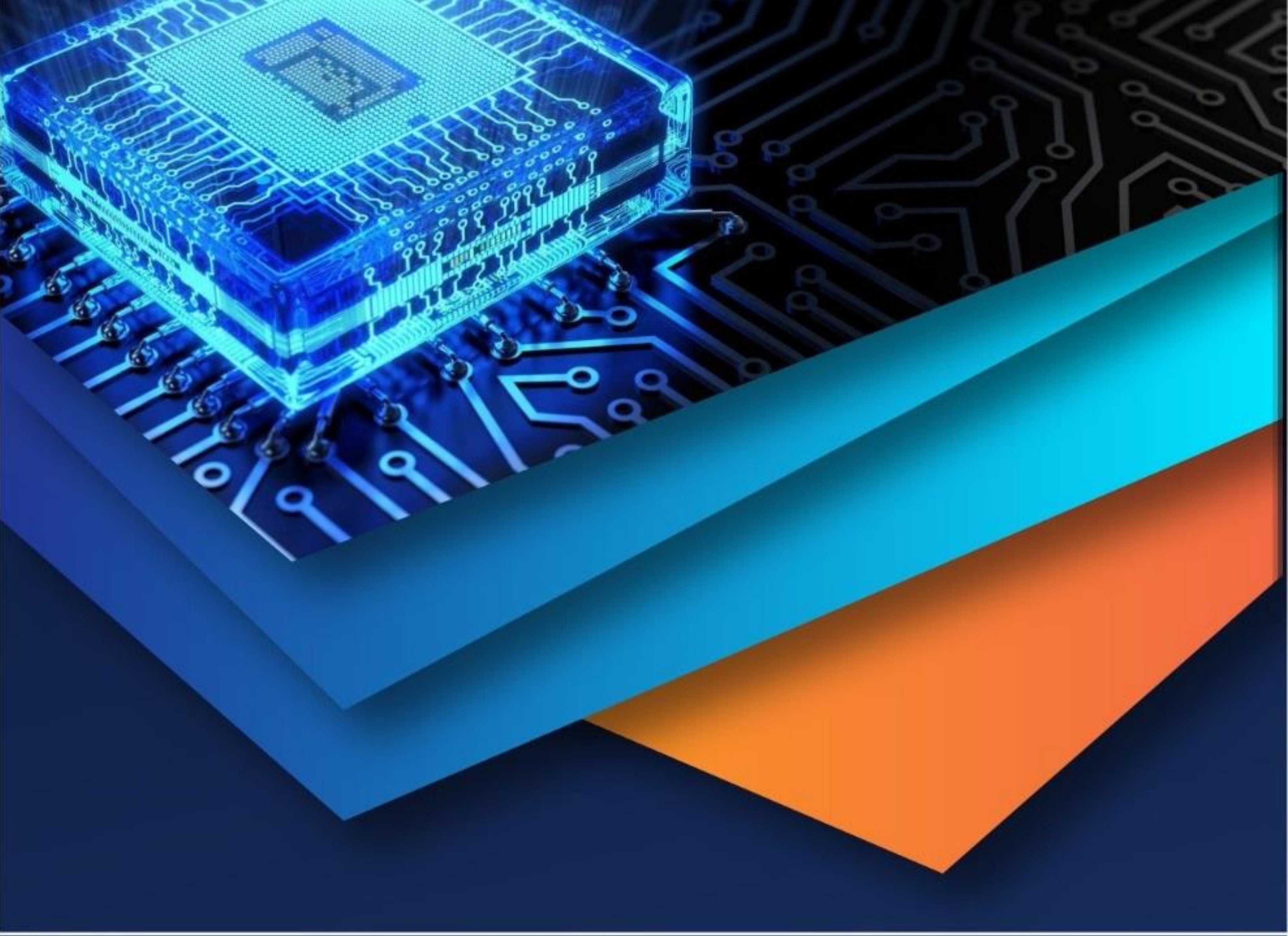
[8] Pavithra, P., Reddy, M. S., Dinakar, P., Rao, B. H., Satpathy, B. K., & Mohanty, A. N. (2016). A mix design procedure for geopolymer concrete with fly ash. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2016.05.041

[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



10.22214/IJRASET

45.98

IMPACT FACTOR: 7.129

IMPACT FACTOR: 7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY