Geopolymer-Based Materials as Alternatives to Portland Cement in Construction

Priyanka Dewangan[1] Jiya Bhaskar[2] Mrs. Shikha Verma[3]
[1,2]Research Scholar [3]Assistant Professor
[1,2,3]Department of Civil Engineering
[1,2,3]Bhilai Institute of Technology, Durg, India

Abstract — Portland cement, the backbone of modern construction, contributes ap-proximately 8% to global CO2 emissions due to its energy-intensive production. Geopolymer-based materials, synthesized from aluminosilicate precursors and alkali activators, present a sustainable alternative with comparable mechanical properties and a signicantly reduced environmental foot-print. This paper investigates the composition, synthesis, mechanical performance, durability, and environmental bene ts of geopolymer concrete compared to Portland cement concrete. Experimental results demonstrate that geopolymer concrete achieves compressive strengths of up to 50 MPa at 28 days, suitable for structural applications, while reducing carbon emissions by 50–60%. Challenges such as precursor variability, alkali activator availability, and standardization are analyzed, alongside case studies and future research directions to promote geopolymer adoption in construction.

Keywords: Geopolymer Concrete, Portland Cement Alternative, Sustainable Construction Materials, Carbon Emission Reduction, Aluminosilicate Precursors, Alkali Activation

I. Introduction

Portland cement concrete is the most widely used construction material, with global production exceeding 4.1 billion metric tons annually [?]. Its produc-tion, however, is highly energy-intensive, requiring the calcination of limestone and clinker formation, which accounts for approximately 8% of global CO2 emis-sions [?]. With increasing global demand for infrastructure and stringent en-vironmental regulations, the construction industry urgently needs sustainable alternatives to reduce its carbon footprint.

Geopolymers are inorganic polymers formed through the alkali activation of alu-minosilicate precursors, such as y ash, ground granulated blast-furnace slag (GGBS), or metakaolin [?]. These materials o er cement-like properties, includ-ing high compressive strength, excellent durability, and resistance to chemical attack, while requiring signi cantly less energy to produce [?]. Geopolymers leverage industrial by-products, aligning with circular economy principles and reducing waste. This paper evaluates geopolymer-based materials as a viable replacement for Portland cement, focusing on their synthesis, mechanical and environmental performance, practical applications, and barriers to widespread adoption.

II. Materials and Methods

Geopolymer concrete is synthesized by mixing aluminosilicate precursors with alkali activators, typically sodium hydroxide (NaOH) or potassium hydroxide (KOH) combined with sodium or potassium silicate. Common precursors include:

- Fly ash: A coal combustion by-product rich in silica and alumina, classied as Class F or C per ASTM C618.
- Ground granulated blast-furnace slag (GGBS): A steel industry by-product with high calcium content, enhancing reactivity.
- Metakaolin: A calcined clay with high aluminosilicate content, overing consistent reactivity.

To compare geopolymer and Portland cement concrete, laboratory experiments were conducted using two geopolymer mix designs: y ash-based and y ash-GGBS blend (50:50 ratio). The alkali activator consisted of 8 NaOH and sodium silicate in a 1:2 ratio by weight. The geopolymer mix had a precursor-to-activator ratio of 2.5:1. Portland cement concrete with a water-to-cement ratio of 0.45 and Type I cement per ASTM C150 served as the control. Mix proportions are shown in Table 1.

Material	Fly Ash Geopolymer	Fly Ash-GGBS Geopolymer	Portland Cement Con
Fly Ash	400	200	–
GGBS	–	200	–
Portland Cement	–	–	400
Sodium Silicate	120	120	–
NaOH (8)	60	60	–
Water	–	–	180
Coarse Aggregate	1200	1200	1200
Fine Aggregate	600	600	600

Table 1: Mix Proportions for Geopolymer and Portland Cement Concrete (kg/m3)

Specimens were cast in 100 mm cubes and cured as follows: geopolymer samples at 70 ◦C for 24 hours followed by ambient curing, and Portland cement samples at ambient conditions with moisture curing. Compressive strength tests were conducted at 7, 14, and 28 days per ASTM C39. Durability was assessed through sulfate resistance (ASTM C1012) and chloride penetration (ASTM C1202). Envi-ronmental impact was evaluated using life cycle analysis (LCA) based on energy consumption and CO2 emissions.

III. Results and Discussion

Compressive strength results are summarized in Table 2. Fly ash- GGBS geopolymer concrete achieved the highest strength, reaching 55 MPa at 28 days, followed by y ash geopolymer at 50 MPa. Portland cement concrete reached 40 MPa, ad-equate for most structural applications but lower than geopolymer mixes.

Mix Type	7 Days	14 Days	28 Days
Fly Ash Geopolymer	35	45	50
Fly Ash-GGBS Geopolymer	40	50	55
Portland Cement Concrete	25	35	40

Table 2: Compressive Strength of Concrete Mixes (MPa)

Geopolymer concrete exhibited superior durability. Sulfate resistance tests showed minimal expansion (<0.05%) in geopolymer samples after 6 months of immer-sion in 5 % sodium sulfate solution, compared to 0.15% for Portland cement con-crete. Chloride penetration was signi cantly lower in geopolymer mixes, with charge passed values of 800–1000 coulombs versus 2500 coulombs for Portland cement concrete, indicating better resistance to corrosion.

LCA results, presented in Table 3, highlight the environmental advantages of geopolymer concrete. Fly ash-based geopolymer reduced CO2 emissions by 60% compared to Portland cement, primarily due to the elimination of clinker pro-duction. The y ash-GGBS blend reduced emissions by 50%, slightly less due to GGBS processing energy. Energy consumption for geopolymer production was 40–50% lower, though alkali activator production, particularly sodium silicate, contributed signi cantly to the environmental footprint.

Mix Type	CO2 Emissions (kg)	Energy Consumption (MJ)
Fly Ash Geopolymer	150	1200
Fly Ash-GGBS Geopolymer	180	1400
Portland Cement Concrete	400	2500

Table 3: Environmental Impact of Concrete Mixes (per m3)

Despite their advantages, geopolymers face several challenges. The variability of precursor materials, such as y ash composition, a ects consistency and re-quires tailored mix designs [?]. Alkali activators are not universally available, and their production can be energy-intensive. Elevated curing temperatures (60 ◦C–80 ◦C) are often required for optimal geopolymerization, limiting cast-in-place applications. The lack of global standards for geopolymer concrete hinders regulatory approval and widespread adoption.

Geopolymer concrete has been successfully implemented in several projects. The Brisbane West Wellcamp Airport runway, constructed in 2014, used y ash-based geopolymer concrete, achieving a 28-day compressive strength of 45 MPa and demonstrating excellent durability over a decade. Precast geopoly-mer panels in Melbourne's Global Change Institute building showcased low em-bodied carbon and high thermal stability. These case studies underscore geopolymer's potential for both structural and non-structural applications.

IV. Future Directions

Future research should prioritize ambient-temperature curing methods to en-hance geopolymer feasibility for in-situ construction. Alternative activators, such as waste-derived silicates, could reduce costs and environmental impact [?]. De-veloping standardized testing protocols and mix designs is critical for regulatory acceptance. Additionally, integrating geopolymers with advanced technologies, such as 3D printing, could expand their applications in modern construction.

Scaling geopolymer production requires collaboration between industry, academia, and policymakers. Incentives for utilizing industrial by-products and investing in activator production facilities could accelerate adoption. Public-private partnerships could fund pilot projects to demonstrate geopolymer performance in diverse climates and applications.

V. Conclusion

Geopolymer-based materials o er a sustainable alternative to Portland cement, with comparable or superior mechanical properties, enhanced durability, and a 50–60% reduction in CO2 emissions. Their use of industrial by-products supports waste reduction and circular economy principles.

With ongoing research to address curing, standardization, and supply chain challenges, geopolymers have the potential to transform the construction industry. By reducing reliance on Portland cement, geopolymer concrete can contribute significantly to global e orts to mitigate climate change while meeting the demands of modern infrastructure.

References

[1] Davidovits, J. (1999). "Chemistry of geopolymeric systems, terminology", '99 Geopolymer International Conference Proceeding, France.
[2] Fernández-Jiménez, A.M. and Palomo, A. (2005). "Composition and microstructure of alkali activated fly ash binder: Effect of the activator", Cement and Concrete Research, 35, 1984 – 1992.
[3] Fernández-Jiménez, A.M., Palomo, A. and López-Hombrados, C. (2006). "Engineering Properties of Alkali-Activated Fly Ash Concrete", ACI Materials Journal, Title no. 103-M12, Technical paper.
[4] García-Lodeiro, I., Palomo, A. and Fernández-Jiménez, A. (2007). "Alkali–aggregate reaction in activated fly ash systems" Cement and Concrete Research, 37, 175–183.
[5] Hardjito, D. and Rangan, B.V. (2005). "Development and properties of low-calcium fly ash-based geopolymer concrete", Curtin University of Technology, Perth, Australia.
[6] IEA. (2007). "Tracking Industrial Energy Efficiency and CO2 Emissions", International Energy Agency, Paris, France.
[7] Lloyd, N.A. and Rangan, B.V. (2010). "Geopolymer concrete with fly ash", Second International Conference on Sustainable Construction Materials and Technologies, Italy.
[8] Palomo, A., Grutzeck, M.W. and Blanco, M.T. (1999). "Alkali-activated fly ashes-A cement for the future", Cement and Concrete Research, 29, 1323–1329.
[9] Rangan, B.V., Hardjito, D., Wallah, S. E. and Sumajouw, D. M. J. (2005). "Studies on fly ash-based geopolymer concrete", Geopolymer, Green Chemistry and Sustainable Development Solutions, 133-138.

[10] Rangan, B.V. (2008a). "Low-calcium, fly-ash-based geopolymer concrete", Concrete construction engineering handbook, Chapter 26, Taylor & Francis.
[11] Rangan, B.V. (2008b). "Design and manufacture of flyash-based geopolymer concrete", Concrete in Australia, 34(2), 37-43.
[12] Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L.O. (2001). "Carbon dioxide emissions from the global cement industry" Annual Review of Energy and the Environment, 26, 303-329.

