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Strength and Durability Assessment of Geopolymer Concrete Incorporating Industrial Waste

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ABSTRACT

The construction industry is one of the major contributors to global carbon dioxide emissions due to the extensive production and consumption of conventional Portland cement. In response to growing environmental concerns, geopolymer concrete has emerged as a sustainable alternative that utilizes industrial waste materials as supplementary or primary binders. This study focuses on the strength and durability assessment of geopolymer concrete incorporating industrial waste materials, such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and other aluminosilicate-rich industrial by-products. The primary objective is to evaluate the mechanical performance, durability characteristics, and environmental benefits of geopolymer concrete under different mix proportions and curing conditions. The investigation considers important parameters, including compressive strength, split tensile strength, flexural strength, water absorption, sorptivity, permeability, resistance to sulphate and acid attacks, and resistance to chloride penetration. The influence of alkaline activators, including sodium hydroxide and sodium silicate, along with curing temperature, curing duration, and industrial waste replacement ratios, is also examined. The study highlights the role of geopolymerization in forming a dense three-dimensional aluminosilicate network that enhances the microstructural properties and long-term performance of concrete. Comparative assessment with conventional cement concrete indicates the potential of geopolymer concrete to achieve competitive or improved mechanical strength and durability while reducing cement consumption and industrial waste disposal problems. Furthermore, the utilization of industrial by-products supports resource conservation, waste valorization, and sustainable construction practices. The findings emphasize that geopolymer concrete can serve as an effective, durable, and environmentally responsible construction material, provided that its mix design, activator concentration, and curing conditions are appropriately optimized. This research contributes to the development of sustainable infrastructure materials and promotes the practical application of industrial waste-based geopolymer concrete in modern construction.

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INTRODUCTION

The construction industry plays a significant role in economic development and infrastructure expansion worldwide. Concrete is one of the most widely used construction materials because of its strength, durability, versatility, and cost-effectiveness. However, the production of ordinary Portland cement (OPC), which acts as the primary binding material in conventional concrete, is associated with substantial energy consumption and carbon dioxide emissions. Cement manufacturing contributes considerably to global greenhouse gas emissions, creating serious environmental concerns. Consequently, researchers and construction professionals are increasingly exploring alternative cementitious materials

that can reduce environmental impacts while maintaining the required mechanical properties and long-term performance of concrete. One promising alternative is geopolymer concrete, which has attracted considerable attention as a sustainable and environmentally friendly construction material.

Geopolymer concrete is produced by activating aluminosilicate-rich materials using alkaline solutions, commonly sodium hydroxide and sodium silicate. These materials undergo a chemical reaction known as geopolymerization, resulting in the formation of a three-dimensional aluminosilicate binding structure. Unlike conventional concrete, geopolymer concrete can be manufactured with little or no ordinary Portland cement, depending on the mix design. Industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), rice husk ash, metakaolin, and silica fume can be utilized as source materials. Their incorporation not only reduces dependence on conventional cement but also provides an effective approach to managing industrial waste generated by thermal power plants, steel industries, and agricultural processing activities.

The utilization of industrial waste in geopolymer concrete offers several environmental and economic advantages. Large quantities of fly ash and blast furnace slag are generated annually, and their improper disposal may create environmental problems related to land occupation, air pollution, and groundwater contamination. Converting these waste materials into useful construction resources supports the principles of waste recycling, circular economy, and sustainable resource management. Furthermore, geopolymer technology has the potential to reduce the carbon footprint of concrete production by minimizing the consumption of Portland cement and promoting the utilization of locally available industrial by-products.

THEORETICAL FRAMEWORK

1. Concept of Geopolymer Concrete

Geopolymer concrete is an innovative cement-free or low-cement construction material developed through the chemical activation of aluminosilicate-rich source materials. Unlike conventional Portland cement concrete, which relies on cement hydration, geopolymer concrete is primarily formed through geopolymerization reactions involving industrial by-products and alkaline activators. The process produces a hardened three-dimensional polymeric network that binds aggregates and provides mechanical strength and durability.

The primary source materials include fly ash, ground granulated blast furnace slag (GGBS), rice husk ash, silica fume, and metakaolin. These materials contain varying proportions of silica (SiO_2) and alumina (Al_2O_3), which are essential for geopolymer formation.

2. Theory of Geopolymerization

Geopolymerization is the fundamental chemical process responsible for the development of strength in geopolymer concrete. It involves the dissolution of reactive silica and alumina in an alkaline solution, followed by the formation of aluminosilicate oligomers and their subsequent polymerization.

The geopolymerization process generally involves three major stages:

1. Dissolution: Alkaline activators dissolve reactive silica and alumina from industrial waste materials.
2. Gel Formation: Dissolved silicate and aluminate species combine to form an aluminosilicate gel.
3. Polycondensation: The gel develops a three-dimensional network structure, resulting in hardening and strength development.

The resulting binding phases commonly include sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H), depending on the calcium content of the precursor materials.

3. Role of Industrial Waste Materials

Industrial waste materials play a significant role in determining the mechanical and durability characteristics of geopolymer concrete. Their chemical composition, particle size, fineness, and reactive silica-alumina content influence geopolymerization and the resulting microstructure.

Industrial Waste Material	Major Characteristics	Contribution to Concrete
Fly Ash	Rich in silica and alumina	Improves geopolymer formation
GGBS	Contains calcium, silica, and alumina	Enhances early strength development
Silica Fume	High silica content and fine particles	Improves density and reduces permeability
Rice Husk Ash	Rich in amorphous silica	Supports geopolymerization
Metakaolin	Highly reactive aluminosilicate	Improves binding properties

The combination of different industrial waste materials may produce synergistic effects, improving both strength development and resistance to environmental deterioration.

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4. Mechanical Strength Theory
Mechanical strength is one of the most important indicators for evaluating the structural performance of geopolymer concrete. The strength characteristics depend on precursor composition, alkaline activator concentration, curing temperature, and the development of the geopolymer gel structure.

The major mechanical properties include:

A. Compressive Strength
Compressive strength represents the ability of concrete to withstand compressive loading without failure. It is generally determined using standard cube or cylinder specimens.

$$f_c = \frac{P}{A}$$

Where:

- f_c = Compressive strength (MPa)
- P = Maximum applied load (N)
- A = Loaded cross-sectional area (mm²)

B. Split Tensile Strength
Split tensile strength measures the resistance of concrete to tensile stresses and provides information about its cracking behavior.

$$f_{ct} = \frac{2P}{\pi L D}$$

Where:

- f_{ct} = Split tensile strength
- P = Maximum applied load
- L = Length of specimen
- D = Diameter of specimen

C. Flexural Strength
Flexural strength indicates the resistance of concrete to bending stresses. It is particularly important for structural elements such as beams, slabs, and pavement systems.

PROPOSED MODELS AND METHODOLOGIES

1. Research Design and Methodological Approach
The proposed study adopts an experimental and comparative research methodology to investigate the strength and durability characteristics of geopolymer concrete incorporating industrial waste materials. The methodology focuses on selecting suitable industrial waste precursors, preparing geopolymer concrete mixtures, optimizing alkaline activator proportions, and evaluating mechanical and durability performance under different curing and exposure conditions.
The experimental investigation will compare geopolymer concrete with conventional ordinary Portland cement (OPC) concrete to determine the potential improvements in structural performance and environmental sustainability. Different combinations of fly ash, ground granulated blast furnace slag (GGBS), and silica fume will be considered to examine their influence on concrete properties.

2. Selection of Raw Materials
The first stage involves identifying and characterizing the materials required for geopolymer concrete production.

Material	Function in Concrete	Important Properties
Fly Ash	Primary aluminosilicate precursor	Silica and alumina content
GGBS	Calcium-rich precursor	Calcium oxide and fineness
Silica Fume	Supplementary reactive material	High silica content
Sodium Hydroxide	Alkaline activator	Molar concentration
Sodium Silicate	Silicate source	Silica-to-sodium oxide ratio
Fine Aggregate	Filler material	Grading and specific gravity
Coarse Aggregate	Structural skeleton	Size, strength, and density
Water	Workability adjustment	Quality and quantity

The chemical composition of industrial waste materials will be determined using X-ray fluorescence (XRF), while particle characteristics and physical properties will be evaluated through standard laboratory procedures.

3. Proposed Geopolymer Concrete Mix Design Models
Three major mix design models are proposed to investigate the influence of different industrial waste combinations.

Model 1: Fly Ash-Based Geopolymer Concrete
This model uses fly ash as the primary aluminosilicate source material. Sodium hydroxide and sodium silicate solutions are employed as alkaline activators. The model is intended to evaluate the strength development and durability characteristics of fly ash-based geopolymer concrete.

Model 2: Fly Ash-GGBS-Based Geopolymer Concrete
This model incorporates different proportions of fly ash and GGBS. The addition of GGBS introduces calcium-rich compounds that can accelerate early-age strength development and influence the formation of binding gels.

Model 3: Hybrid Industrial Waste-Based Geopolymer Concrete
This model combines fly ash, GGBS, and silica fume to investigate the combined effects of different industrial waste materials. The objective is to achieve improved particle packing, reduced pore connectivity, and enhanced mechanical and durability performance.

4. Proposed Mix Proportions
The following preliminary mix combinations are proposed for experimental investigation. The proportions represent the percentage of total binder materials by mass and should be finalized through trial mixes.

Mix ID	Fly Ash (%)	GGBS (%)	Silica Fume (%)
GPC-1	100	0	0
GPC-2	80	20	0
GPC-3	70	30	0
GPC-4	60	30	10
GPC-5	50	40	10
GPC-6	40	50	10

A conventional OPC concrete mixture will also be prepared as a control specimen. The alkaline activator-to-binder ratio, sodium silicate-to-sodium hydroxide ratio, aggregate proportions, and curing conditions will be optimized through preliminary experimental trials.

RESULTS & ANALYSIS

The results and analysis of the study entitled **"Strength and Durability Assessment of Geopolymer Concrete Incorporating Industrial Waste"** focus on evaluating the mechanical strength, durability characteristics, microstructural properties, and environmental benefits of geopolymer concrete. The investigation considers the influence of different industrial waste materials, alkaline activator proportions, and curing conditions on the overall performance of geopolymer concrete compared with conventional Ordinary Portland Cement (OPC) concrete.

Note: The following results represent an illustrative research-analysis framework. Actual experimental values should be established through laboratory testing.

1. Compressive Strength Analysis
Compressive strength is one of the most important parameters for assessing the structural performance of geopolymer concrete. The incorporation of fly ash and Ground Granulated Blast Furnace Slag (GGBS) can significantly influence strength development.

- Fly ash-based geopolymer concrete generally exhibits improved strength under suitable curing conditions.
- GGBS incorporation can accelerate early-age strength development.
- A combination of fly ash and GGBS may provide a balanced strength-development profile.
- Excessive alkaline activator concentration may negatively affect concrete performance.

The compressive strength is evaluated at 7, 28, and 56 days to understand early-age and long-term strength development.

2. Split Tensile and Flexural Strength Analysis
Split tensile strength and flexural strength indicate the resistance of concrete against tensile stresses and bending forces. The incorporation of industrial waste materials can improve the bonding characteristics and density of the geopolymer matrix. GGBS and silica-rich materials may contribute to the development of a compact binding structure.

The analysis indicates that:

- Optimized geopolymer mixtures can demonstrate improved tensile strength.
- Appropriate fly ash and GGBS combinations can enhance flexural performance.
- Poorly optimized mixtures may develop microcracks due to shrinkage and curing-related effects.
- The quality of the interfacial transition zone influences the overall mechanical performance.

3. Water Absorption and Porosity Analysis

Water absorption is an important indicator of concrete permeability and durability. Lower water absorption generally indicates a denser concrete structure with fewer interconnected pores.

Geopolymer concrete incorporating properly proportioned industrial waste materials can exhibit reduced water absorption due to the formation of aluminosilicate and calcium-aluminosilicate hydrate-based binding products.
The analysis considers:

- Percentage of water absorption.
- Open porosity and pore connectivity.
- Influence of alkaline activator concentration.
- Effect of curing temperature and duration.

A reduction in water absorption can improve resistance against moisture penetration and environmental deterioration.

4. Chloride and Sulfate Resistance Analysis

The resistance of geopolymer concrete against chloride and sulfate attacks is essential for structures exposed to marine environments, industrial wastewater, and chemically aggressive soils.

Geopolymer concrete may demonstrate improved resistance to chloride penetration because of its dense microstructure and suitable pore structure.

Similarly, the incorporation of GGBS and fly ash can improve sulfate resistance when the mixture is properly designed.
The major observations include:

1. Reduced chloride ion penetration in suitably optimized mixtures.
2. Improved resistance to sulfate-induced deterioration.
3. Lower permeability under appropriate curing conditions.
4. Better potential for long-term performance in aggressive environments.

However, chemical resistance varies depending on precursor composition, activator chemistry, and exposure conditions.

COMPARATIVE ANALYSIS IN TABULAR FORM

The comparative analysis evaluates the mechanical strength, durability, environmental performance, and practical applicability of conventional Ordinary Portland Cement (OPC) concrete and geopolymer concrete incorporating different industrial waste materials, including fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and rice husk ash.

Table 1. Comparative Analysis of Different Concrete Mixtures

Parameters	**OPC Concrete**	**Fly Ash Geopolymer**	**GGBS Geopolymer**	**Fly Ash + GGBS Geopolymer**
Compressive strength	Conventional baseline	High potential	High potential	High potential
Early-age strength	Moderate	Often slower at ambient temperature	Generally high	Generally improved
Split tensile strength	Conventional	Good potential	Good potential	Improved potential
Flexural strength	Conventional	Moderate to high	High potential	High potential
Water absorption	Mixture-dependent	Potentially low	Potentially low	Potentially reduced
Chloride resistance	Variable	Good potential	Good potential	Good potential
Sulfate resistance	Cement-dependent	Good potential	Good potential	Good potential
Acid resistance	Generally limited	Potentially improved	Variable	Potentially improved
Thermal stability	Variable	Good potential	Composition-dependent	Composition-dependent
Environmental impact	Higher cement-related emissions	Potentially lower	Potentially lower	Potentially lower

Table 2. Comparison of Mechanical Strength Properties

Mechanical Properties	**OPC Concrete**	**Fly Ash-Based Geopolymer**	**Fly Ash + GGBS Geopolymer**
Compressive strength	Conventional reference	Depends on curing and activation	Potentially enhanced
Tensile strength	Conventional reference	Improved potential	Improved potential
Flexural strength	Conventional reference	Moderate to high	Moderate to high
Elastic modulus	Conventional reference	Mixture-dependent	Mixture-dependent
Strength development	Gradual	Curing-dependent	Often faster at early ages

Table 3. Comparative Durability Assessment

Durability Parameters	**OPC Concrete**	**Geopolymer Concrete Incorporating Industrial Waste**
Water absorption	Depends on water-cement ratio and curing	Can be reduced through pore refinement
Chloride penetration	May permit chloride ingress	Potentially lower penetration
Sulfate attack	Vulnerable depending on cement composition	Potentially improved chemical resistance
Acid attack	Generally susceptible	Often better resistance, depending on acid type
Drying shrinkage	Depends on mixture proportions	Can vary with precursor and activator composition
Freeze-thaw resistance	Depends on air entrainment and saturation	Requires mixture-specific evaluation
High-temperature exposure	May experience cracking and strength loss	Thermal performance depends on binder chemistry
Long-term durability	Established performance history	Promising but requires further field validation

Table 4. Influence of Industrial Waste Materials

Industrial Waste Material	**Major Characteristics**	**Contribution to Concrete**	**Potential Benefits**
Fly ash	Aluminosilicate-rich material	Geopolymer binder formation	Improved long-term strength
GGBS	Calcium-rich industrial by-product	Accelerates binding reactions	Enhanced early-age strength
Silica fume	High amorphous silica content	Improves matrix density	Reduced permeability
Rice husk ash	Silica-rich agricultural residue	Participates in binder reactions	Improved microstructure
Waste glass powder	Silica-containing material	Supplementary reactive precursor	Waste utilization and resource conservation

LIMITATIONS & DRAWBACKS

Although geopolymer concrete incorporating industrial waste offers significant advantages in terms of sustainability, mechanical strength, and durability, several limitations and technical challenges restrict its widespread application in the construction industry. These challenges are associated with raw material variability, alkaline activators, curing requirements, long-term performance, economic considerations, and standardization.

1. Variability in Industrial Waste Materials

The chemical and physical properties of industrial waste materials, such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and rice husk ash, vary depending on their sources and manufacturing processes.

- Variations in silica and alumina content can affect geopolymerization.
- Different particle sizes may influence workability and strength development.
- Impurities and unreactive materials can reduce binder efficiency.
- Consistent quality control is required before industrial application.

2. High Cost of Alkaline Activators
Geopolymer concrete generally requires alkaline activators such as sodium hydroxide and sodium silicate to initiate chemical reactions.

- Sodium silicate can increase overall production costs.
- Concentrated sodium hydroxide requires careful handling.
- Transportation and storage of alkaline chemicals increase operational expenses.
- Activator preparation may require additional energy and processing.

3. Workability and Setting Time Challenges
The workability of geopolymer concrete depends on precursor composition, alkaline solution concentration, and liquid-to-binder ratio.

- Some mixtures exhibit rapid setting.
- High activator concentrations may reduce workability.
- Improper proportions can cause segregation and inconsistent mixing.
- Maintaining uniform fresh-concrete properties can be challenging.

4. Curing Requirements
Certain fly ash-based geopolymer concrete mixtures require elevated-temperature curing to achieve satisfactory strength development.

- Heat curing increases energy consumption.
- Temperature-sensitive reactions may affect strength development.
- Large structural components may be difficult to heat uniformly.
- Ambient-cured mixtures may require optimized proportions to achieve comparable performance.

CONCLUSION

The study entitled “Strength and Durability Assessment of Geopolymer Concrete Incorporating Industrial Waste” highlights the potential of geopolymer concrete as a sustainable and environmentally friendly alternative to conventional Ordinary Portland Cement (OPC) concrete. The incorporation of industrial waste materials, such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and other aluminosilicate-rich residues, provides an effective approach to reducing industrial waste disposal, conserving natural resources, and minimizing the environmental impact of construction activities.

The investigation demonstrates that the mechanical and durability performance of geopolymer concrete is strongly influenced by the chemical composition of precursor materials, alkaline activator concentration, liquid-to-binder ratio, and curing conditions. Appropriate combinations of fly ash and GGBS have considerable potential to improve compressive strength, split tensile strength, and flexural strength. The presence of suitable reactive materials also contributes to the formation of a dense geopolymeric matrix, which can reduce porosity and improve resistance to water absorption, chloride penetration, sulfate attack, and other aggressive environmental conditions.

Furthermore, microstructural investigations using Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), and Fourier-Transform Infrared Spectroscopy (FTIR) provide valuable insights into geopolymerization reactions, chemical bonding, and the development of binding products responsible for mechanical strength and durability. These investigations help establish the relationship between material composition, microstructural characteristics, and overall concrete performance.

REFERENCES

1. ACI Committee 232. (2004). Use of fly ash in concrete (ACI 232.2R-03). *American Concrete Institute*.
2. ACI Committee 239. (2018). *Ultra-high-performance concrete: An emerging technology report (ACI 239R-18).* American Concrete Institute.
3. ACI Committee 242. (2019). *Report on alkali-activated binders (ACI 242R-13).* American Concrete Institute.
4. Azad, N. M., & Samarakoon, S. M. K. M. (2021). Utilization of industrial by-products/waste to manufacture geopolymer cement/concrete. *Sustainability, 13*(2), 873. https://doi.org/10.3390/su13020873
5. Davidovits, J. (1991). Geopolymers: Inorganic polymeric new materials. *Journal of Thermal Analysis, 37,* 1633–1656.
6. Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & van Deventer, J. S. J. (2007). Geopolymer technology: The current state of the art. *Journal of Materials Science, 42*, 2917–2933. https://doi.org/10.1007/s10853-006-0637-z

7. Hardjito, D., & Rangan, B. V. (2005). *Development and properties of low-calcium fly ash-based geopolymer concrete*. Curtin University of Technology.
8. John, S. K., Nadir, Y., & Girija, K. (2021). Effect of source materials, additives on the mechanical properties and durability of fly ash and fly ash-slag geopolymer mortar: A review. *Construction and Building Materials, 280*, 122443. https://doi.org/10.1016/j.conbuildmat.2021.122443
9. Khawaji, M. (2023). Hydration, microstructure, and properties of fly ash-based geopolymer: A review. *Materials Science-Poland, 41*(2), 263–287. https://doi.org/10.2478/msp-2023-0006
10. Kolade, A. S., Ikotun, B. D., & Oyejobi, D. O. (2025). A review of the chemistry, waste utilization, mix design and performance evaluation of geopolymer concrete. *Iranian Journal of Science and Technology, Transactions of Civil Engineering, 49*, 5421–5454. https://doi.org/10.1007/s40996-025-01801-w
11. Kurtoğlu, A. E., Alzeebaree, R., Aljumaili, O., Niş, A., Gülşan, M. E., Humur, G., & 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
12. Mehta, A., & Siddique, R. (2016). An overview of geopolymers derived from industrial by-products. *Construction and Building Materials, 127*, 183–198. https://doi.org/10.1016/j.conbuildmat.2016.09.136
13. Nath, P., & 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.
14. Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research, 29*(8), 1323–1329.
15. Podolsky, Z., Liu, J., Dinh, H., Doh, J. H., Guerrieri, M., & Fragomeni, S. (2021). State of the art on the application of waste materials in geopolymer concrete. *Case Studies in Construction Materials, 15*, e00637. https://doi.org/10.1016/j.cscm.2021.e00637
16. Provis, J. L., & van Deventer, J. S. J. (Eds.). (2009). *Geopolymers: Structures, processing, properties and industrial applications*. Woodhead Publishing.
17. Rathnayaka, M., Karunasinghe, D., Gunasekara, C., Wijesundara, K., Lokuge, W., & Law, D. W. (2024). Machine learning approaches to predict compressive strength of fly ash-based geopolymer concrete: A comprehensive review. *Construction and Building Materials, 419*, 135519.
18. Rangan, B. V. (2008). *Fly ash-based geopolymer concrete*. Curtin University of Technology.
19. Shi, C., Krivenko, P. V., & Roy, D. (2006). *Alkali-activated cements and concretes*. Taylor & Francis.
20. Singh, B., Ishwarya, G., Gupta, M., & Bhattacharyya, S. K. (2015). Geopolymer concrete: A review of some recent developments. *Construction and Building Materials, 85*, 78–90.