Volume 2, Issue 1, Jan – Jun 2026 Issue – Page no : 16-33

Integrated Journal of
Civil Engineering and Sustainable Technology

Experimental Investigation of Geopolymer Concrete Using Industrial Waste Materials for Sustainable Infrastructure Applications

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Abstract

The increasing demand for sustainable construction materials and the environmental challenges associated with conventional cement production have encouraged the development of alternative binder systems for concrete applications. Geopolymer concrete has emerged as a promising construction material that utilizes aluminosilicate-rich industrial by-products through alkaline activation instead of relying entirely on ordinary Portland cement. Industrial waste materials such as fly ash, ground granulated blast furnace slag (GGBS), and rice husk ash offer opportunities for producing geopolymer concrete while reducing industrial waste disposal and dependence on conventional cementitious materials. This paper presents an experimental investigation framework for evaluating the mechanical, physical and durability characteristics of geopolymer concrete incorporating industrial waste materials. The proposed experimental programme considers different combinations of fly ash, GGBS and rice husk ash as precursor materials, activated using sodium hydroxide and sodium silicate solutions. The investigation focuses on fresh concrete workability, setting behaviour, compressive strength, splitting tensile strength, flexural strength, water absorption, sorptivity and resistance to aggressive environmental conditions. The influence of precursor composition, alkaline activator characteristics and curing conditions is considered in evaluating concrete performance. The study also examines the potential applications of geopolymer concrete in sustainable infrastructure, including pavements, drainage components, precast elements and selected structural applications. Existing experimental literature indicates that appropriate combinations of industrial by-products can produce geopolymer concrete with promising mechanical and durability characteristics. However, performance depends strongly on precursor chemistry, activator composition, aggregate quality and curing conditions

Index Terms— Geopolymer concrete, industrial waste materials, fly ash, ground granulated blast furnace slag, rice husk ash, alkaline activation, compressive strength, sustainable infrastructure, concrete durability.

Received Date : 02.02.2026 **Publication Date : 12.02.2026**

I. INTRODUCTION

Concrete is one of the most widely used construction materials because of its strength, durability, availability and adaptability to different infrastructure applications. Residential buildings, transportation networks, bridges, industrial facilities and public infrastructure depend heavily on concrete for their construction and long-term operation. The continued growth of infrastructure development has increased the demand for

cement, fine aggregate and coarse aggregate, resulting in greater consumption of natural resources and increased environmental pressure.

Ordinary Portland cement is the principal binding material used in conventional concrete. However, cement manufacturing involves energy-intensive operations and the decomposition of limestone, both of which contribute to greenhouse gas emissions. The increasing recognition of the environmental impact of cement production has encouraged researchers to investigate alternative binder systems that can reduce dependence on conventional cement while maintaining acceptable engineering performance.

Geopolymer concrete has emerged as an alternative construction material developed using aluminosilicate-rich source materials activated through alkaline solutions. Unlike conventional Portland cement concrete, geopolymer systems can utilize industrial by-products as their principal binder precursors. The chemical activation of these materials produces a hardened binding structure capable of connecting fine and coarse aggregates into a concrete matrix.

Fly ash is one of the most widely investigated source materials for geopolymer concrete. It is generated during coal combustion in thermal power plants and contains silica and alumina that can participate in geopolymerization. Ground granulated blast furnace slag is produced during iron manufacturing and contains reactive calcium, silica and alumina components. Rice husk ash is obtained from the controlled combustion of rice husk and is recognized as a potentially useful silica-rich agricultural residue.

The combined utilization of these materials provides an opportunity to improve the resource efficiency of concrete production while addressing waste disposal challenges. However, industrial by-products differ in their chemical composition, particle size, reactivity and physical properties. These variations can significantly influence the fresh and hardened properties of geopolymer concrete.

Hardjito et al. [1] investigated the development of fly ash-based geopolymer concrete and demonstrated the importance of alkaline activation in developing an alternative cementitious binder. Their research examined the influence of mixture composition on the mechanical properties of geopolymer concrete. Subsequent investigations by Hardjito et al. [2] examined the influence of curing conditions, activator composition, water content and other mixture parameters on fly ash-based geopolymer concrete.

The incorporation of GGBS into fly ash-based geopolymer systems has received considerable attention because calcium-rich slag can influence setting behaviour and early-age strength development. Nath and Sarker [3] investigated the effect of GGBS on the workability, setting and early strength characteristics of fly ash-based geopolymer concrete under ambient curing conditions. Their findings demonstrated the importance of slag content in modifying the fresh and hardened behaviour of geopolymer concrete.

Rice husk ash provides another opportunity for utilizing agricultural waste in construction materials. Its incorporation into geopolymer binder systems has been investigated to understand the influence of additional reactive silica on strength development and durability. Arora et al. [4] experimentally investigated fly ash and rice husk ash-based geopolymer concrete with partial Portland cement substitution and evaluated workability, compressive strength, water absorption and resistance to aggressive environments.

The development of geopolymer concrete using industrial waste materials therefore requires an understanding of material characteristics, alkaline activator composition,

curing conditions and concrete performance. A material combination that produces acceptable compressive strength may not necessarily provide suitable workability or durability under all environmental conditions.

The present study proposes a systematic experimental investigation of geopolymer concrete incorporating fly ash, GGBS and rice husk ash. The primary objective is to evaluate how different industrial waste material combinations influence fresh concrete behaviour, mechanical performance and durability characteristics for sustainable infrastructure applications.

A. Research Objectives

The main objective of this study is to investigate the suitability of industrial waste-based geopolymer concrete as a sustainable construction material. The investigation considers the influence of different precursor combinations on the fresh properties, mechanical characteristics and durability performance of concrete. Particular attention is given to the contribution of fly ash, GGBS and rice husk ash to binder development and the influence of alkaline activator composition on geopolymerization.

The study also aims to evaluate the influence of curing conditions on strength development and examine the relationship between precursor characteristics and hardened concrete performance. Durability-related investigation is included to understand resistance to water penetration, sulphate exposure, acid exposure and chloride-related deterioration. A further objective is to examine the practical suitability of industrial waste-based geopolymer concrete for infrastructure applications where resource efficiency and long-term performance are important considerations.

B. Research Significance

The research is significant because it connects industrial waste utilization with sustainable construction material development. Thermal power plant fly ash, steel industry slag and rice husk ash can create storage and disposal challenges when they are not effectively utilized. Their incorporation into geopolymer binder systems provides an opportunity to convert selected industrial and agricultural residues into useful construction materials.

The proposed investigation also considers the technical limitations of geopolymer concrete rather than assuming that all industrial waste combinations automatically produce superior performance. Workability, setting behaviour, curing requirements, strength development and durability must be evaluated together to establish the practical suitability of the developed material.

II. LITERATURE REVIEW

A. Development of Geopolymer Concrete

Geopolymer concrete is produced by activating suitable aluminosilicate-rich materials using alkaline solutions. The process involves the dissolution of reactive silica and alumina from the precursor materials, followed by the formation and development of a hardened aluminosilicate-rich binding structure.

Unlike conventional Portland cement hydration, geopolymerization involves chemical reactions between the source materials and alkaline activators. The resulting binding structure depends on the available silica, alumina and calcium components, as well as the concentration and composition of the activating solution.

Provis [5] discussed the role of alkali-activated materials in sustainable construction and emphasized that their development requires careful consideration of source material availability, formulation, processing and environmental performance. The research also highlighted that alkali-activated materials should not be treated as universal direct replacements for Portland cement because their properties and practical suitability depend on the formulation and intended application.

Hardjito et al. [1] demonstrated that low-calcium fly ash could be chemically activated to produce geopolymer concrete without requiring Portland cement as the principal binder. Their research established an important foundation for the development of fly ash-based geopolymer systems.

The development of geopolymer technology has subsequently expanded to include different industrial by-products, including slag, rice husk ash, silica-rich residues and other aluminosilicate materials.

B. Fly Ash-Based Geopolymer Concrete

Fly ash is a widely available industrial by-product generated from coal-fired thermal power plants. Its chemical composition generally contains silica, alumina and iron oxide, with the proportions depending on the coal source and combustion conditions.

Low-calcium fly ash is frequently investigated in geopolymer concrete because its aluminosilicate components can participate in alkaline activation. The particle size distribution, glassy phase content, fineness and loss on ignition influence its suitability as a geopolymer precursor.

When exposed to suitable alkaline solutions, the reactive components of fly ash dissolve and participate in geopolymerization. The resulting reaction products contribute to the binding structure within the hardened concrete.

Hardjito et al. [2] investigated fly ash-based geopolymer concrete and examined the influence of mixture parameters, curing temperature, curing duration and water content. Their research demonstrated that compressive strength development is influenced by the characteristics of the activating solution and the curing process.

Fly ash-based geopolymer concrete may require controlled curing conditions, particularly when low-calcium fly ash is used as the principal precursor. Heat curing can accelerate geopolymerization, while ambient curing may provide greater practical flexibility for cast-in-place applications.

However, the suitability of ambient curing depends on source material characteristics and the contribution of other reactive materials in the binder system.

C. Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag is produced by rapidly cooling molten slag generated during iron manufacturing and subsequently grinding the material into a fine powder.

GGBS contains silica, alumina, calcium oxide and other mineral constituents that contribute to its cementitious and alkaline activation characteristics. Its incorporation into geopolymer concrete can influence setting behaviour, workability and strength development.

Compared with low-calcium fly ash, GGBS generally contains a higher calcium content. This characteristic can influence reaction products and early-age hardening behaviour when combined with alkaline activators.

Nath and Sarker [3] investigated fly ash geopolymer concrete incorporating GGBS under ambient curing conditions. Their experimental work demonstrated that GGBS improved early strength development, while increasing slag content influenced setting time and workability. These findings suggest that the combination of fly ash and GGBS may provide a useful approach for developing geopolymer concrete suitable for practical construction conditions.

However, excessive slag incorporation may reduce workability and accelerate setting, creating difficulties during mixing, transportation and placement. Therefore, an appropriate balance between fly ash and GGBS is important when developing a geopolymer concrete mixture.

D. Rice Husk Ash as an Industrial and Agricultural By-Product

Rice husk ash is produced through the combustion of rice husk, an agricultural residue generated during rice processing. Depending on combustion conditions, the resulting ash may contain significant quantities of amorphous silica.

Its utilization in geopolymer concrete offers an opportunity to improve agricultural waste management while introducing an additional silica-rich material into the binder system.

The physical and chemical properties of rice husk ash depend on combustion temperature, burning duration, cooling conditions and grinding processes. Uncontrolled combustion may produce ash with high carbon content and variable reactivity, potentially reducing its suitability for geopolymer applications.

Arora et al. [4] investigated geopolymer concrete developed using fly ash and fine rice husk ash as primary binder materials. Their experimental study evaluated workability, compressive strength and several durability properties. The authors reported that the behaviour of the resulting material depended on the proportion of additional Portland cement used in the investigated hybrid binder system.

The use of rice husk ash in geopolymer concrete therefore requires material characterization and controlled incorporation to ensure consistent performance.

E. Effect of Alkaline Activator Composition

Alkaline activators play an essential role in geopolymerization because they provide the chemical environment required for dissolving reactive aluminosilicate components.

Sodium hydroxide and sodium silicate solutions are commonly used in fly ash-based geopolymer concrete. Sodium hydroxide supports the dissolution of reactive silica and alumina, while sodium silicate supplies additional soluble silica that contributes to the development of the binding structure.

The concentration of sodium hydroxide influences the dissolution behaviour of precursor materials. The relative quantity of sodium silicate and sodium hydroxide also affects reaction conditions, workability and hardened concrete properties.

The activator-to-binder proportion is another important consideration because it influences the available alkaline liquid, mixture consistency and pore structure.

Hardjito et al. [1], [2] investigated the influence of alkaline solution characteristics and mixture parameters on fly ash-based geopolymer concrete. Their studies demonstrate

that activator composition should be optimized according to the characteristics of the source materials rather than selected independently.

Excessive alkaline solution may create difficulties involving workability, efflorescence and material cost, while insufficient activation may restrict the development of the geopolymer binder.

F. Mechanical Properties of Geopolymer Concrete

The mechanical properties of geopolymer concrete are important for determining its suitability for construction applications.

Compressive strength is one of the principal characteristics used to evaluate hardened concrete performance. It is influenced by precursor composition, alkaline activator characteristics, water content, curing conditions and aggregate quality.

Splitting tensile strength provides information about the resistance of concrete to tensile cracking, while flexural strength helps evaluate its behaviour under bending-related loading conditions.

Arumugam and Soundarapandian [6] experimentally investigated fly ash–GGBS-based geopolymer concrete incorporating demolition waste fine aggregate. Their investigation considered compressive strength, splitting tensile strength, flexural strength, elastic modulus and other physical characteristics. The study reported that mechanical properties progressively declined as demolition waste fine aggregate content increased, although partial replacement levels produced smaller reductions than complete replacement in their investigated mixtures.

This study demonstrates that waste utilization should be balanced with the engineering characteristics of the resulting concrete.

G. Durability Characteristics of Geopolymer Concrete

Durability is an important consideration when selecting construction materials for long-term infrastructure applications.

Concrete structures may be exposed to water penetration, chloride contamination, sulphate environments, acidic conditions and repeated wetting and drying. The resistance of geopolymer concrete to these exposure conditions depends on precursor chemistry, microstructure, activator composition and curing conditions.

Nagajothi et al. [7] investigated the durability of fly ash-based geopolymer concrete incorporating slag and alkaline solutions under ambient curing conditions. Their study examined water absorption, sulphate resistance, acid resistance, chloride penetration and sorptivity. The researchers reported favourable performance in selected durability measurements compared with conventional concrete under their specific experimental conditions.

These findings highlight the importance of evaluating geopolymer concrete using multiple durability indicators rather than relying exclusively on compressive strength.

H. Utilization of Construction and Demolition Waste

Construction and demolition activities generate large quantities of discarded concrete, masonry and other mineral-based materials.

The recovery of suitable construction waste for use as aggregate or precursor material can contribute to resource conservation and reduce landfill disposal.

Ren and Zhang [8] experimentally investigated geopolymer concrete produced from waste concrete using waste concrete fines, Class F fly ash and recycled coarse and fine aggregates. Their research examined the effects of material proportions, alkaline activation and curing conditions on the properties of the resulting geopolymer concrete.

I. Research Gap

Existing research demonstrates that fly ash, GGBS and rice husk ash can be incorporated into geopolymer binder systems. However, their combined influence depends on the chemical composition and physical properties of the source materials.

Different precursor combinations may produce variations in workability, setting behaviour, compressive strength, tensile behaviour and durability. Curing conditions further influence the development of the geopolymer matrix.

There is a need for an integrated experimental evaluation that considers fresh concrete properties, mechanical performance, durability and practical construction requirements within a consistent mix-design programme.

The present study addresses this need through a proposed experimental investigation of fly ash, GGBS and rice husk ash-based geopolymer concrete, with emphasis on sustainable infrastructure applications.

III. MATERIALS AND CHARACTERIZATION

A. Fly Ash

Fly ash is selected as the primary aluminosilicate precursor in the proposed geopolymer concrete investigation. The material should be obtained from a reliable thermal power plant source and evaluated before use.

The chemical composition of fly ash should be determined through X-ray fluorescence analysis. Particular attention should be given to silica, alumina, calcium oxide, iron oxide, magnesium oxide and loss on ignition.

The physical characteristics should also be examined, including fineness, particle size distribution, specific gravity and moisture content.

The classification of fly ash should be based on its verified chemical and physical characteristics rather than relying only on the supplier's designation.

B. Ground Granulated Blast Furnace Slag

GGBS is selected as a calcium-containing supplementary precursor for combination with fly ash.

Its physical and chemical properties should be evaluated to determine its suitability for geopolymer production.

The material should be examined for fineness, specific gravity, moisture condition and chemical composition. The calcium content is particularly relevant because it may influence setting and early-age strength development.

The selected GGBS should be stored under dry conditions to prevent uncontrolled moisture exposure and changes in material characteristics.

C. Rice Husk Ash

Rice husk ash is selected as an additional silica-rich agricultural by-product.

The ash should be collected from a controlled combustion process and processed to obtain consistent particle characteristics. Unburnt carbon and other impurities should be minimized.

The chemical composition and particle fineness should be examined because both factors influence the reactivity of rice husk ash.

The material should be incorporated only after confirming that its physical and chemical properties are suitable for the selected geopolymer binder system.

D. Fine and Coarse Aggregates

The aggregates should be evaluated for particle size distribution, specific gravity, water absorption, bulk density and moisture condition.

The grading should be maintained consistently across different geopolymer mixtures to ensure that observed changes in concrete behaviour can be associated primarily with binder composition and activation conditions.

Recycled aggregate or demolition waste aggregate may be introduced as an additional investigation after establishing the performance of the primary geopolymer mixtures.

E. Alkaline Activator Solution

Sodium hydroxide and sodium silicate solutions are proposed as the principal alkaline activators.

The sodium hydroxide solution should be prepared at a selected concentration based on preliminary trials. Sodium silicate solution should be incorporated according to the selected activator composition.

The activating solution should be prepared sufficiently in advance to allow cooling and stabilization before concrete mixing.

Preparation and handling require appropriate laboratory safety procedures because concentrated alkaline solutions can cause severe chemical burns. Protective gloves, eye protection and suitable laboratory equipment should be used throughout the preparation and mixing process.

F. Superplasticizer and Mixing Water

A suitable chemical admixture may be used to improve the workability of geopolymer concrete.

The compatibility of the selected admixture with the alkaline activator system should be checked through preliminary trials because admixture performance may differ from its behaviour in conventional Portland cement concrete.

Additional water should be controlled carefully because it can influence workability, pore structure and hardened concrete properties.

IV. EXPERIMENTAL METHODOLOGY

A. Proposed Experimental Programme

The proposed experimental programme is designed to investigate the influence of industrial waste material combinations on geopolymer concrete performance.

Fly ash is considered the primary precursor, while GGBS and rice husk ash are introduced at different replacement levels.

The initial control mixture is prepared using fly ash as the sole principal precursor. Additional mixtures are prepared by incorporating increasing quantities of GGBS to investigate its influence on setting behaviour and strength development.

A further series of mixtures incorporates rice husk ash into selected fly ash–GGBS combinations to examine the contribution of additional reactive silica.

For experimental clarity, a practical trial programme may consider a fly ash control mixture, fly ash with 10% GGBS, fly ash with 20% GGBS and fly ash with 30% GGBS. Selected mixtures may then incorporate 5% and 10% rice husk ash by replacement of the total precursor mass.

These are proposed starting proportions and should be adjusted following preliminary material characterization and trial batches. They are not experimentally established optimum compositions.

The total precursor quantity, aggregate grading and selected activator conditions should be maintained consistently wherever possible to enable meaningful comparison between mixtures.

B. Activator Optimization

The alkaline activator composition should be optimized through preliminary experimental trials.

Different sodium hydroxide concentrations and sodium silicate-to-sodium hydroxide proportions may be evaluated to identify combinations that provide suitable workability and strength development.

The selected activator condition should be based on the chemical characteristics of the precursor materials and the practical requirements of the concrete mixture.

Activator preparation procedures and material temperatures should be documented because these factors can influence mixing consistency and reaction behaviour.

C. Concrete Mixing Procedure

The mixing process begins with the measurement and preparation of fly ash, GGBS, rice husk ash, fine aggregate and coarse aggregate.

The dry precursor materials should be blended to achieve a reasonably uniform distribution before the activating solution is introduced.

The fine and coarse aggregates should then be incorporated according to the designed mixture proportions.

The prepared alkaline solution is added gradually while mixing continues until a uniform geopolymer concrete mixture is obtained.

Where required, the compatible superplasticizer should be incorporated according to preliminary workability trials.

The mixing duration and sequence should be maintained consistently across all mixtures.

Fresh concrete should be examined immediately after mixing to record its consistency, flow behaviour and visible segregation characteristics.

D. Specimen Casting and Curing

After fresh concrete evaluation, the mixtures should be placed into appropriately prepared moulds.

Specimen preparation should follow the relevant concrete testing procedures and ensure adequate compaction without introducing unnecessary air voids.

After the specified initial curing period, the specimens should be demoulded and transferred to the selected curing environment.

Ambient curing should be considered as the primary curing approach where practical construction applications are the main objective.

A separate heat-curing investigation may be conducted for selected mixtures to understand the influence of curing temperature and duration on strength development.

The curing conditions should be controlled and recorded to ensure consistency between the different mixture groups.

Specimens should be examined at appropriate testing ages, such as 7, 28, 56 and 90 days, to evaluate the development of mechanical and durability characteristics.

E. Workability and Fresh Concrete Evaluation

Workability is an important fresh-state property because it determines the ease of mixing, transportation, placement and compaction.

Geopolymer concrete may exhibit different flow characteristics depending on precursor fineness, activator composition, liquid content and setting behaviour.

Slump or an appropriate flow-based test should be conducted immediately after mixing.

Fresh density and visible segregation characteristics should also be recorded.

The influence of increasing GGBS content should be examined carefully because faster setting may reduce the time available for concrete placement.

The use of suitable admixtures may help improve consistency, provided that their compatibility with the alkaline activator is established.

F. Compressive Strength Evaluation

Compressive strength is a principal mechanical performance indicator for geopolymer concrete.

Concrete cube or cylindrical specimens should be prepared and tested according to the selected applicable standard.

The compressive strength evaluation should be conducted at different curing ages to examine strength development.

The results should be compared across the fly ash control mixture and modified mixtures incorporating GGBS and rice husk ash.

At least three specimens should be tested for each mixture and selected testing age, with additional specimens included where required to improve reliability.

The average strength, specimen-to-specimen variation and failure characteristics should be documented.

G. Splitting Tensile Strength

Splitting tensile strength provides an indication of concrete resistance to tensile cracking.

Cylindrical concrete specimens should be prepared and tested using a suitable diametral compression procedure.

The failure pattern should be examined to understand crack development and the influence of binder composition on tensile behaviour.

Variations in precursor composition may influence the bond between the geopolymer matrix and aggregates, which can affect tensile performance.

H. Flexural Strength

Flexural strength is important for evaluating the performance of concrete under bending conditions.

Beam specimens should be prepared and tested using an appropriate flexural testing procedure.

The results should be examined in relation to compressive and splitting tensile strength to identify differences in the mechanical response of the selected geopolymer mixtures.

This parameter is particularly relevant for pavement applications, precast concrete elements and infrastructure components subjected to bending stresses.

I. Water Absorption and Sorptivity

Water absorption provides information about the accessible pore structure of hardened concrete.

The specimens should be dried under controlled conditions and subsequently subjected to an appropriate saturation procedure.

The difference between dry and saturated conditions can be used to evaluate the tendency of concrete to absorb water.

Sorptivity testing should also be considered to investigate the rate of water movement into the concrete through capillary action.

These tests are important because higher moisture transport may increase the exposure of concrete to aggressive environmental conditions.

J. Chemical Resistance

The chemical durability of geopolymer concrete should be investigated under selected aggressive exposure conditions.

Sulphate exposure testing can be used to examine the stability of the hardened geopolymer matrix in sulphate-containing environments.

Acid exposure may also be considered to understand material deterioration under chemically aggressive conditions.

Chloride-related testing is important for concrete applications involving reinforced infrastructure exposed to saline water or marine environments.

The assessment should include changes in appearance, mass, compressive strength and other appropriate durability indicators following controlled exposure.

K. Microstructural Characterization

Microstructural analysis provides additional understanding of geopolymer reaction products and hardened matrix characteristics.

Scanning Electron Microscopy can be used to examine the morphology and compactness of the geopolymer matrix.

Energy Dispersive X-ray Spectroscopy can help identify the distribution of important chemical elements within selected specimens.

X-ray Diffraction may be used to investigate crystalline phases and changes in precursor-related mineral characteristics.

Fourier Transform Infrared Spectroscopy can provide information about chemical bonding and changes associated with geopolymerization.

The combined interpretation of these techniques can help explain differences in concrete performance between different precursor combinations.

V. RESULTS AND DISCUSSION

The proposed investigation should distinguish between the effects of precursor composition, activator characteristics and curing conditions.

Since actual laboratory measurements have not been supplied, this section provides a literature-supported interpretation framework rather than fabricated experimental findings for the proposed mixtures.

A. Influence of Precursor Composition on Workability

Workability in geopolymer concrete is influenced by precursor fineness, particle shape, surface area, liquid availability and alkaline activator composition.

Fly ash particles are often relatively spherical, which can contribute to favourable flow characteristics in certain mixtures.

GGBS has different physical and chemical characteristics, and its incorporation may influence setting behaviour and the time available for concrete placement.

Nath and Sarker [3] reported that the inclusion of GGBS in fly ash geopolymer concrete enhanced early strength development under ambient curing conditions. Their experiments also showed that increasing GGBS content influenced workability and setting time.

Rice husk ash may influence water demand and flow behaviour depending on its fineness, porosity and processing conditions.

Therefore, workability results should be examined alongside material fineness, activator quantity and admixture dosage rather than treating precursor replacement as the only controlling factor.

B. Influence on Compressive Strength

Compressive strength development depends on the availability of reactive aluminosilicate components and the effectiveness of alkaline activation.

In fly ash-based geopolymer concrete, the dissolution and subsequent formation of reaction products contribute to the hardened binding structure.

The addition of GGBS may modify the reaction process due to its calcium-containing constituents and can influence early-age strength development.

The incorporation of rice husk ash may provide additional reactive silica, although its contribution depends on ash quality and processing.

Arora et al. [4] investigated fly ash and fine rice husk ash geopolymer concrete and reported that the performance varied with the level of Portland cement substitution in their specific hybrid binder formulations.

These findings indicate that the selection of precursor proportions should be based on experimental evaluation rather than assuming that increasing the quantity of any individual industrial by-product automatically improves compressive strength.

C. Influence on Tensile and Flexural Performance

Tensile and flexural properties are important for understanding the cracking behaviour of geopolymer concrete.

The bond between aggregates and the geopolymer binder influences stress transfer and fracture development.

A compact geopolymer matrix may support improved load transfer, while inadequate activation or excessive porosity may contribute to weaker interfaces.

The influence of GGBS and rice husk ash on tensile and flexural performance should therefore be examined alongside compressive strength and microstructural observations.

Arumugam and Soundarapandian [6] demonstrated the relevance of evaluating compressive strength, splitting tensile strength and flexural strength together when investigating fly ash–GGBS-based geopolymer concrete incorporating demolition waste aggregate.

D. Influence on Water Absorption and Porosity

Water absorption and effective porosity provide useful information about the internal characteristics of hardened concrete.

Geopolymer concrete containing well-reacted precursor materials may develop a relatively compact matrix. However, insufficient activation, unsuitable liquid content and inadequate curing can result in a more porous structure.

The incorporation of industrial by-products should therefore be evaluated in relation to the resulting pore structure rather than only the quantity of waste material utilized.

Nagajothi et al. [7] investigated water absorption, acid resistance, sulphate resistance and chloride penetration in fly ash–slag-based geopolymer concrete under ambient curing conditions. Their research provides a useful basis for understanding the relationship between binder composition and durability characteristics.

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E. Influence on Chemical Resistance

Geopolymer concrete may exhibit useful resistance to selected chemical environments because its hardened binding system differs from conventional Portland cement hydration products.

However, chemical resistance depends on precursor composition, curing quality, activator chemistry and the particular aggressive environment.

Sulphate exposure and acid exposure may produce different deterioration mechanisms. Chloride-related deterioration is also important where concrete is used in reinforced infrastructure.

Therefore, durability should not be established from a single chemical exposure test.

A combination of water absorption, sorptivity, sulphate resistance, acid exposure and chloride-related evaluation provides a more complete understanding of concrete durability.

F. Influence of Curing Conditions

Curing conditions strongly influence geopolymerization and the development of hardened concrete properties.

Heat curing can accelerate the activation of certain low-calcium fly ash systems. This approach may be useful for precast concrete production where controlled curing facilities are available.

However, heat curing may create practical difficulties for large-scale cast-in-place applications.

The incorporation of GGBS may improve the feasibility of ambient-cured systems by modifying reaction behaviour.

Nath and Sarker [3] demonstrated the influence of GGBS on ambient-cured fly ash geopolymer concrete, highlighting its relevance for practical construction applications.

The proposed investigation should therefore evaluate curing conditions as an important factor when selecting geopolymer mixtures for infrastructure use.

G. Comparative Interpretation with Conventional Concrete

The performance of geopolymer concrete should be evaluated against conventional Portland cement concrete prepared with comparable aggregate quality and target engineering requirements.

The comparison should consider workability, setting behaviour, compressive strength, tensile strength, flexural performance and durability.

Such comparisons are meaningful only when specimen preparation, curing age and testing conditions are sufficiently consistent.

Arumugam and Soundarapandian [6] and Nagajothi et al. [7] provide examples of experimental comparisons between geopolymer concrete and conventional concrete in mechanical and durability investigations.

The results from these studies demonstrate that material combinations and curing conditions significantly influence the comparative performance of geopolymer concrete.

H. Overall Experimental Interpretation

The expected experimental evaluation should identify whether the combined use of fly ash, GGBS and rice husk ash produces a suitable balance between workability, strength and durability.

A mixture with higher compressive strength may not necessarily provide the best workability or lowest water absorption.

Similarly, a mixture that utilizes a larger quantity of industrial by-products may require more alkaline activator or additional processing, which can affect cost and environmental performance.

The final mixture selection should therefore be based on a balanced assessment of mechanical characteristics, fresh concrete behaviour, durability, production feasibility and environmental considerations.

VI. SUSTAINABILITY AND INFRASTRUCTURE APPLICATIONS

The use of industrial waste materials in geopolymer concrete provides an opportunity to reduce the disposal burden associated with selected industrial and agricultural residues.

Fly ash generated by thermal power plants, GGBS from iron production and rice husk ash from agricultural processing can be incorporated into alternative binder systems when their physical and chemical characteristics are suitable.

This approach supports the conversion of selected waste streams into construction materials and contributes to resource efficiency.

However, the environmental advantages of geopolymer concrete should be evaluated across the complete production process. The manufacture of alkaline activators, transportation of precursor materials, processing requirements and curing energy can influence the overall environmental impact.

Provis [5] emphasized that alkali-activated materials have important sustainability potential, but their performance and environmental advantages depend on formulation, locally available source materials and careful consideration of activator-related impacts.

A. Road and Pavement Infrastructure

Geopolymer concrete may be considered for selected pavement and road infrastructure applications after appropriate mechanical and durability evaluation.

Pavement systems require suitable compressive and flexural properties because they experience repeated traffic loading and environmental exposure.

The suitability of geopolymer concrete for pavements should therefore be established through flexural strength, fatigue-related performance and durability evaluation.

B. Precast Concrete Components

Precast concrete production provides an opportunity to investigate geopolymer concrete under controlled manufacturing conditions.

Elements such as paving blocks, drainage components, kerbs, non-critical structural components and selected precast products may be evaluated using industrial waste-based geopolymer systems.

Controlled mixing and curing conditions can improve production consistency and permit more systematic quality assessment.

C. Bridges and Transportation Infrastructure

Bridge infrastructure and transportation components may involve exposure to moisture, chloride contamination and other environmental conditions.

Geopolymer concrete may be considered for selected applications where appropriate mechanical and durability requirements are established.

The suitability of the material should be assessed through project-specific structural design and exposure evaluation rather than assuming universal replacement of conventional concrete.

D. Drainage and Wastewater Infrastructure

Drainage channels and wastewater-related components may be exposed to moisture and aggressive chemical environments.

The resistance of geopolymer concrete to selected chemical conditions may make it relevant for investigating such applications.

However, the performance should be validated using appropriate acid and sulphate exposure studies, together with long-term service testing.

E. Sustainable Building Components

Industrial waste-based geopolymer concrete may also be evaluated for selected building applications, including precast wall components, non-critical structural components and architectural concrete products.

The final application should depend on the measured performance, curing requirements and relevant construction specifications.

F. Environmental and Economic Considerations

The environmental assessment of geopolymer concrete should consider precursor collection, processing, transportation, activator production, concrete manufacturing and curing energy.

Although the use of industrial by-products may reduce reliance on Portland cement, alkaline activator production can contribute to environmental impacts.

A life-cycle assessment should therefore be undertaken before claiming a specific reduction in carbon emissions or total environmental impact.

Economic evaluation should also consider material availability, transport distance, processing cost, activator cost, labour requirements and curing facilities.

VII. LIMITATIONS AND FUTURE RESEARCH

The proposed experimental investigation has several important considerations.

First, industrial waste materials may exhibit considerable variations in chemical composition and physical characteristics depending on their production source. This variation can influence geopolymerization and the consistency of the resulting concrete.

Second, alkaline activators require careful preparation and handling. Their concentration and composition must be controlled to obtain consistent concrete properties.

Third, curing requirements may vary depending on the precursor combination. Heat curing can be effective for selected fly ash-based mixtures, whereas ambient curing may require an appropriate contribution from calcium-rich materials such as GGBS.

Fourth, geopolymer concrete may exhibit differences in shrinkage, creep and long-term performance compared with conventional concrete. These characteristics should be investigated before recommending the material for critical infrastructure applications.

Fifth, the environmental benefits of geopolymer concrete should be established through life-cycle assessment that includes the production and transportation of alkaline activators.

Future research should investigate additional industrial by-products, including bottom ash, silica fume, ferrochrome slag and construction demolition waste, as potential components of geopolymer concrete.

Microstructural investigations should also be expanded to understand the relationship between precursor composition, reaction products, pore structure and durability performance.

Long-term structural studies are required to evaluate the performance of geopolymer concrete under sustained loading, repeated loading and different environmental exposure conditions.

Further research should also investigate standardized mix-design procedures, quality control requirements and practical production methods to support wider implementation of industrial waste-based geopolymer concrete.

VIII. CONCLUSION

This paper presented an experimental investigation framework for evaluating geopolymer concrete incorporating industrial waste materials for sustainable infrastructure applications. The proposed approach considers fly ash, ground granulated blast furnace slag and rice husk ash as alternative precursor materials activated using alkaline solutions.

The literature indicates that industrial waste-based geopolymer concrete has the potential to reduce dependence on conventional Portland cement while supporting the utilization of industrial and agricultural residues. However, successful material development depends on the characteristics of the precursor materials, alkaline activator composition, aggregate quality and curing conditions.

The proposed experimental programme examines fresh concrete workability, setting behaviour, compressive strength, splitting tensile strength, flexural strength, water absorption, sorptivity and resistance to selected aggressive environments. These properties provide a comprehensive basis for evaluating the suitability of different geopolymer mixtures.

The reviewed literature also demonstrates that GGBS can influence early-age strength development and ambient curing behaviour, while fly ash and rice husk ash provide important aluminosilicate and silica-rich precursor components. Appropriate combinations may improve selected mechanical and durability characteristics, although the response depends on the specific material proportions and processing conditions.

The study further highlights the importance of balancing industrial waste utilization with concrete performance, production feasibility and environmental considerations. Geopolymer concrete should be evaluated through a complete performance assessment rather than relying exclusively on compressive strength or the percentage of waste materials incorporated.

Overall, industrial waste-based geopolymer concrete represents a promising alternative construction material for selected sustainable infrastructure applications. Further experimental validation, long-term durability investigation, environmental assessment and mix-design optimization are necessary to establish reliable recommendations for practical engineering use.

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