

Flexural Behaviour and Durability of Geopolymer Reinforced Concrete Beams: A Review on Influence of Source Materials, Alkaline Activators, and Curing Methods

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Abstract: Industrial waste management remains a global environmental challenge, with traditional Portland cement production contributing significantly to CO₂ emissions. Geopolymer concrete, produced via alkali activation of aluminosilicate materials, offers a sustainable alternative. This review critically examines the flexural behaviour and durability of geopolymer reinforced concrete (GPC) beams, focusing on the influence of source materials, alkaline activator types, and curing methods. A comprehensive literature survey was conducted through major research databases to analyse previous experimental studies on reinforced geopolymer concrete beams. The review compares findings on flexural performance, failure modes, and durability characteristics across varying mix compositions and curing regimes. Results indicate that GPC beams exhibit structural behaviour comparable to ordinary Portland cement (OPC) beams in terms of flexural strength, crack pattern, and load-deflection characteristics. The use of optimized curing methods and activator concentrations enhances both mechanical and durability performance. Variability in source materials and activator types significantly affects strength and service life properties. Geopolymer reinforced concrete beams demonstrate promising flexural and durability performance, supporting their potential for structural applications. Further work should focus on long-term corrosion resistance and field scale validation.

Keywords: Alkali Activator, Curing Method, Geopolymer, Reinforced Concrete Beam, Source Material.

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I. INTRODUCTION

Portland cement concrete is produced by mixing Portland cement, water, sand, and crushed stone aggregate, which is referred to as "artificial stone." Over the last hundred years, concrete has gained global prominence as a building material; no other material has achieved such widespread acceptance as quickly as concrete. According to [1] and [2], it is the material used the most after water and requires a significant quantity of cement. Ordinary Portland cement is the primary component of concrete and the most famous building material worldwide [3]. One of the critical issues facing our environment nowadays is the change in climate

due to global warming. This is caused by global warming due to the emission of greenhouse gases, such as Carbon dioxide (CO₂), contributing to about 65% of global warming [4]. Ordinary Portland cement is a significant carbon dioxide-producing component used in conventional concrete production. One ton of carbon dioxide is produced during the production of one ton of cement [5], and the production of ordinary Portland cement (OPC) is rising at a rate of approximately 3% per year [4], the yearly global cement production of 1.6 billion tonnes is responsible for about 7% of the total CO₂ emission into the atmosphere. Portland cement production is one of the most energy-intensive processes responsible for enormous greenhouse gas

emissions. The production of one tonne of Portland cement utilises nearly 4 GJ energy [6].

Given this, the global concrete industry is under pressure to identify substitute binding materials to reduce the amount of cement used; this leads to the development of a more sustainable and less energy-intensive material called Geopolymer (GP) cement to reduce the energy required to produce OPC. The idea of environmentally friendly blending materials has been the subject of numerous studies conducted over the past ten years [7]. [1] and [8] reported that Davidovits formulated the name 'Geopolymer' in 1978. Geopolymer technology has been considered a substitute binder for traditional cement [9]. In order to create geopolymers, an aluminosilicate from various geological substances, such as Metakaolin and clay, or an industrial by-product, such as fly ash (FA) and ground granulated blast furnace slag (GGBS), and some agricultural wastes are mixed with an alkaline activator chemical solution. Some researchers have started replacing OPC with geopolymer to produce environmentally friendly cement. Their work has primarily focused on replacing cement in its entirety with fly ash and ground granulated blast-furnace slag (GGBS) activated with alkaline activators like potassium and sodium hydroxides [10] and [1].

While numerous studies have explored mix design optimization and mechanical performance of geopolymer concrete, there remains a lack of consolidated understanding of how source materials, alkali activators, and curing regimes collectively influence the flexural behaviour and durability of reinforced geopolymer concrete beams.

Hence, this review critically evaluates experimental findings from existing literature to:

- Compare flexural performance and failure modes of GPC and OPC beams.
- Assess the influence of source materials and activator systems on mechanical properties.
- Examine the effects of curing methods on both strength development and durability performance.

This synthesis aims to establish a clearer basis for the safe structural application of geopolymer reinforced concrete beams and to identify future research directions in enhancing long-term performance and durability.

II. SUMMARY OF PUBLISHED INFORMATION

➤ *Geopolymer Concrete*

Joseph Davidovits first used the word "geopolymer" in 1978 to describe a class of binders that can be created through the interaction of an alkaline liquid with a source material that contains silicon (Si) and aluminium (Al). The source material may be a by-product such as fly ash or rice husk ash, or it may have a geological origin like Metakaolin. In essence, the chemical reaction that occurs between the alkaline liquid and the source material is a polymerisation process. As a result, these binders were referred to as "geopolymers" [11,12].

The fact that geopolymer concrete can be made without Portland cement adds relevance to its composition. Alkaline liquids and source materials are geopolymers' main components. Source materials based on aluminosilicate should have high silicon (Si) and aluminium (Al) concentrations.

➤ *Geopolymer Source Materials*

The primary raw elements for geopolymers have been identified to be amorphous silicon (Si) and aluminium (Al). Several criteria, including availability, pricing, and application type, influence the choice of a specific source material. These raw materials fall into three categories: natural, recycled, and industrial trash. The following is a list of the primary attributes of the raw materials:

➤ *Industrial Waste*

Various production processes generate a significant amount of industrial waste, such as metallurgical slag, mine and agricultural wastes, and ash from burned coal, some of these materials are added to PC to enhance its characteristics. However, massive amounts of other industrial wastes are landfilled and stored, including fly and bottom ash, rice husk ash (RHA), granulated blast-furnace slag, and steel slag. For fly ash, which is a by-product of coal-fired power stations, it has been estimated that over a billion tonnes of FA is currently produced worldwide with a utilisation rate of only 20% [13].

➤ *Recycling Materials*

The recent global consumption increase has resulted in increased waste and recycling of materials, including paper and water sludge, construction debris, and garbage. Even though these materials are smaller in bulk than heavy industrial trash, their presence has increased interest in lowering pollutants and other unwanted wastes into their utilisation in environmentally friendly materials for sustainability [7].

➤ *Natural Materials*

Numerous natural resources, such as silty clay, volcanic rock, and kaolin (china clay or kaolinite), could be used as raw materials for geopolymers. Limited quantities of these materials can be found in various geological locations. Alkaline liquids, which are typically dissolved alkali metals like sodium (Na) or potassium (K), and the two primary raw materials previously mentioned are considered to be the sources of geopolymer [14]. On the other hand, some researchers have discovered that combining calcined and non-calcined materials results in a notable increase in strength quickly [15].

➤ *Alkaline activators*

The activators required to complete the polymerization process of geopolymers are typically sodium silicate (SiO₂/Na₂O) and sodium hydroxide (NaOH) solutions. The higher the NaOH content, the higher the compressive strength [16]. Potassium-based hydroxide solutions can be used instead of NaOH solutions but are generally ignored due to the higher associated costs [16].

➤ *Benefits and Applications of Geopolymers*

According to [17,18,19,20,21,22 and 23] Geopolymer concrete as a construction material offers many benefits among which includes:

- Concrete made of geopolymer primarily helps to lower carbon emissions. Its production process releases merely 78 kg/m³ of CO₂, while the creation of OPC concrete results in 248 kg/m³ of CO₂ exhaustion.
- Essentially, it replaces OPC in concrete with elements derived from industrial by-products. As a result, it resolves the issue with these by-products' disposal.
- Because of the heat curing process's high temperature, geopolymer concrete achieves great early strength in a comparatively short time.
- When heat-cured, it has been demonstrated to show minimal shrinkage.
- Additionally, geopolymer has been shown to have outstanding durability and fire resistance.

➤ *Limitations of Geopolymers*

Despite the numerous advantages of geopolymer and its wide range of applications, particularly as an alternative to OPC binders, it does come with certain limitations. In other words, there are specific issues to be addressed with these materials. Some of the limitations as observed by [22] include:

- Workability is reduced since the combination feeds on low water content
- The proper setup must be available because geopolymer must be cured at high temperatures.
- Because geopolymer mixes contain caustic alkalis, it is imperative to take safety precautions and possess the necessary handling expertise.
- Alkalis may lead to efflorescence on the surface of the concrete, which could detract from its aesthetic appeal.

The long-term viability of geopolymer has yet to be thoroughly established. More thought must be given, in particular, to the study on the corrosion of steel reinforcement in geopolymer concrete buildings.

III. LITERATURE REVIEW FINDINGS

➤ *Research Overview on Geopolymer Reinforced Concrete Beams*

All the research work reviewed in this article is categorised into the following headings: Research Authors, Structural element, Precursor or geopolymer source material, alkaline activator, curing method adopted for the geopolymer, testing variable and the research findings, which are all presented in Table 1.0.

Table 1: Research Findings from the literature

Author	Element	Precursor	Activators	Curing Method	Testing Variables	Remark
[1]	Beam	Metakaolin	NaOH and Na ₂ SiO ₃	Oven Curing	Bending Strength	Bending strength for the geopolymer RC beam is superior to that of the OPC RC beam.
[13]	Beam and Column	Fly Ash	NaOH and Na ₂ SiO ₃	Steam Curing (60° C)	Reinforcement Ratio	The elastic properties of hardened concrete and the behaviour and strength of reinforced structural members are similar to those of Portland cement concrete.
[24]	Beam	Fly Ash	NaOH and Na ₂ SiO ₃	Heat curing at a temperature of 75°C	Flexural Strength	The geopolymer concrete beams exhibit increased flexural strength. The deflections at different stages including service and peak load stages are higher for GPC beams.
[25]	Beam	Fly Ash & Slag	NaOH and Na ₂ SiO ₃	Ambient Temperature	Fly Ash-Slag Ratio	GPC beams exhibited more significant deflections at distinct stages. Nonetheless, the ductility factor was comparable to that of traditional concrete beams.
[26]	Beam	GGBS	NaOH and Na ₂ SiO ₃	Ambient Temperature	Reinforcement Ratio (Steel and GFRP)	The results showed that the crack width and deflection at failure were notably reduced by increasing the GFRP and steel bars' reinforcement ratio.
[27]	Beam	Fly Ash	NaOH and Na ₂ SiO ₃	Heat curing at a temperature of 70°C	Reinforcement ratio, compressive stress and concrete type	They concluded that while GPC beams had a smaller crack width than normal concrete beams, they showed a slight increase in deflection and almost the same ultimate load.
[28]	Beam	Fly Ash	NaOH and Na ₂ SiO ₃	Hot air Curing at a temperature of 65°C to 70°C	Reinforcement Ratio	The defalcation, stiffness and crack patterns are found similar to conventional concrete beam

[29]	Beam	Fly Ash	NaOH and Na ₂ SiO ₃	Steam Curing at a temperature of 60°C	Longitudinal reinforcement ratio	Geopolymer reinforced concrete beams fracture pattern and relevant failure mode were comparable to those of the conventional concrete beams
[30]	Beam	Fly Ash & GGBS	NaOH and Na ₂ SiO ₃	Ambient Temperature 24°C-32°C	Reinforcement ratio and Compressive strength	Increasing the longitudinal steel ratio and concrete grade enhanced the first cracking, service, and ultimate load.
[31]	Beam	Fly Ash	NaOH and Na ₂ SiO ₃	Heat curing at 65°C	Longitudinal and shear steel reinforcement	GC beams' ductility, as determined by their load-deflection response, is comparable to that of conventional RC beams
[32]	Beam	Fly Ash & GGBS	NaOH and Na ₂ SiO ₃	Ambient Temperature	Shear span to depth ratio	GC beams' load-deflection behaviour is generally comparable to that of regular RC beams
[33]	Beam	MK & GGBS	NaOH and Na ₂ SiO ₃	Ambient Temperature	Flexural Strength	it was concluded that up to 70% GGBS + 30% MK, the load-deflection response of GC beams is the same as that of the reference specimen.
[34]	Beam	GGBS & Fly Ash	NaOH and Na ₂ SiO ₃	Open Air Curing	Wire mesh configuration	The results demonstrated that the compressive strength surpassed the target compressive strength.
[35]	Beam	GGBS	NaOH and Na ₂ SiO ₃	Ambient Temperature	Molar concentrations	The load-carrying capacity of GPC beams increases as the molarity of sodium hydroxide concentration increases
[36]	Beam	GGBS & Fly Ash	NaOH and Na ₂ SiO ₃	Ambient Temperature	Flexural strength	that the GRC and CRC beams exhibited comparable quantities and types of cracks in flexure.
[37]	Beam	Rice husk ash	NaOH and Na ₂ SiO ₃	Room temperature of 25 ± 2 °C	Rice husk ash ratio	According to the test results, the compressive strength of the PC-RHA and GC-RHA decreased when there was a higher proportion of RHA replacement in the concrete.

*GGBS = Ground granulated blast furnace slag, *MK = Metakaolin

➤ Influence of Source Materials on Flexural Behaviour

The choice and characteristics of source materials exert a fundamental influence on the mechanical, durability, and microstructural performance of geopolymer concrete (GPC) beams. Variations in the chemical composition, fineness, and amorphous content of precursor materials directly affect geopolymerization kinetics, strength gain, and long-term structural stability. Consequently, proper selection, characterization, and proportioning of these materials—along with suitable curing and activator systems—are essential to achieving consistent and reliable performance across varying service conditions.

The aluminosilicate precursor serves as the principal binder source in the geopolymer matrix, and its type largely determines the rate and extent of reaction. Among the widely studied precursors, fly ash (FA) and ground granulated blast furnace slag (GGBS) remain the most prevalent, used either singly or in blended systems.

- High-calcium materials such as GGBS promote rapid geopolymerization and high early strength, particularly under ambient curing conditions [25,30,33].
- Low-calcium precursors, including fly ash and rice husk ash (RHA), typically require heat or steam curing to

achieve comparable strength due to their slower reaction rates [24,27,37].

- Metakaolin-based systems demonstrate high reactivity and produce consistent early strength even at moderate curing temperatures, making them suitable for structural applications requiring rapid strength development [1,33].

Blended or hybrid systems—such as 70% GGBS + 30% metakaolin (MK) or FA–GGBS composites—often exhibit enhanced mechanical and microstructural performance arising from the synergistic interaction between calcium-assisted and aluminosilicate-based geopolymerization mechanisms. These combinations foster denser gel formation, reduced porosity, and improved flexural stiffness.

However, over-reliance on industrial by-products introduces variability in oxide composition, particularly in SiO₂, Al₂O₃, and CaO content, which influences gel structure formation (N–A–S–H, C–A–S–H, or mixed phases). Such compositional variations can lead to inconsistencies in flexural strength and stiffness among different batches. Therefore, consistent material preprocessing—such as controlled calcination for metakaolin or standardized grinding for fly ash—is essential to ensure reproducible reactivity and structural performance.

➤ *Effect of Alkaline Activator*

Alkaline activators play a pivotal role in the synthesis and performance of geopolymer concrete (GPC). They initiate and sustain the geopolymerization reaction, wherein reactive aluminosilicate materials dissolve and subsequently polycondense to form a three-dimensional polymeric network. The type, concentration, and ratio of these activators profoundly affect the reaction kinetics, gel composition, microstructural development, and ultimately the mechanical and durability characteristics of the resulting geopolymer matrix. Consequently, optimizing activator parameters is critical to achieving high-performance and durable geopolymer systems.

Among the commonly employed activator systems, sodium-based combinations of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) dominate current research due to their wide availability, cost-effectiveness, and proven efficiency in promoting aluminosilicate dissolution. Studies such as [24], [25], and [30] have reported that molarity ranges between 10 and 14 M yield optimal reactivity, leading to the formation of denser matrices and higher compressive and flexural strengths. Excessively high molarities, however, may induce brittleness, efflorescence, or microcracking due to excessive alkali concentration.

In contrast, potassium-based activators ($\text{KOH} + \text{K}_2\text{SiO}_3$), though less frequently explored, have demonstrated superior mechanical and thermal performance. The larger ionic radius of potassium (K^+) facilitates the development of a more open yet thermally stable K–A–S–H gel structure, which enhances structural integrity at elevated temperatures and improves long-term stability compared to sodium-based systems.

A well-balanced silicate-to-hydroxide ratio (typically between 1.5 and 2.5) has been identified as a crucial factor influencing workability and setting behaviour. Ratios below this range can result in insufficient polymeric network formation, whereas excessively high ratios increase solution viscosity, leading to reduced workability, shrinkage, and cracking tendencies despite possible short-term strength gains.

The activator system governs not only the early-age reaction kinetics but also the long-term microstructural stability of geopolymer concrete. Proper selection and optimization of activator type, concentration, and silicate-to-hydroxide ratio are therefore essential to balance strength, workability, durability, and thermal performance, ensuring that GPC beams attain reliable structural and service performance comparable to or exceeding that of conventional OPC systems.

➤ *Influence of Curing Method*

The curing regime plays a decisive role in determining the geopolymerization kinetics, microstructural development, and mechanical performance of geopolymer concrete (GPC). Heat and steam curing within the temperature range of 60–80 °C have been widely reported to accelerate the dissolution of aluminosilicate species and enhance the formation of

geopolymeric gels, resulting in rapid early-age strength development, improved matrix densification, and reduced porosity [24, 27, 29]. However, excessively high curing temperatures may promote thermal shrinkage or microcracking, necessitating controlled thermal exposure to maintain structural integrity.

In contrast, ambient curing offers an energy-efficient and environmentally sustainable approach but typically results in slower strength development and slightly lower ultimate strength values compared to thermally cured systems. The inclusion of calcium-rich precursors such as ground granulated blast furnace slag (GGBS) has been shown to mitigate this limitation by facilitating calcium-assisted geopolymerization and improving mechanical performance under ambient conditions [25, 33].

Hybrid curing regimes—comprising an initial period of heat curing followed by ambient exposure—have demonstrated an effective balance between early age strength gain and long-term durability [30]. This approach promotes efficient early geopolymerization while minimizing energy consumption and reducing the risk of thermal-induced defects.

➤ *Durability and Corrosion Resistance of Geopolymer*

While most studies have primarily focused on the mechanical performance of geopolymer concrete (GPC), growing evidence highlights its superior durability compared to ordinary Portland cement (OPC) systems. The improved resistance of GPC to aggressive environments stems from its distinct aluminosilicate-based gel structure, low calcium content, and refined pore network, all of which contribute to long-term stability under chemical, thermal, and physical stressors.

• *Chemical and Acid Resistance*

Geopolymer binders exhibit excellent resistance to acid and sulfate environments, primarily due to the absence of calcium hydroxide ($\text{Ca}(\text{OH})_2$), which is highly susceptible to acid dissolution. Previous studies [18,19,34] have reported negligible mass loss and minimal compressive strength reduction when GPC specimens were exposed to sulfuric and hydrochloric acid solutions, in contrast to the severe degradation typically observed in OPC systems. This superior chemical resistance is attributed to the stable Si–O–Al framework and the formation of chemically inert reaction products.

• *Corrosion Resistance*

The dense, low permeability microstructure of GPC minimizes chloride ion ingress and moisture penetration, effectively reducing the risk of reinforcement corrosion. Furthermore, the absence of portlandite and the presence of chemically stable gels enhance the passivation of embedded steel. GGBS and metakaolin based geopolymer systems have demonstrated significantly lower corrosion current densities and higher electrical resistivity compared to OPC counterparts [26,33], confirming their superior electrochemical stability.

- *Thermal Stability*

Geopolymer concrete exhibits remarkable thermal resistance, maintaining a substantial proportion of its compressive strength even after exposure to temperatures approaching 800°C. This resilience is linked to the formation of thermally stable aluminosilicate and potassium-based gel networks, which resist microstructural breakdown and prevent spalling under high-temperature conditions [16,17].

- *Water Absorption and Permeability*

Reduced permeability and lower water absorption values have been consistently reported for heat- and steam-cured geopolymer concretes. This improvement is attributed to enhanced geopolymerization reactions, which refine pore structure and yield a denser, less interconnected matrix, contributing to the long-term durability and service life of GPC.

IV. CONCLUSION

This review highlighted the structural behaviour and durability performance of reinforced geopolymer concrete (GPC) beams, emphasizing the influence of source materials, alkaline activator composition, and curing regimes. The findings revealed that GPC beams exhibit mechanical responses—such as cracking patterns, load–deflection behaviour, and ultimate load capacity comparable to those of conventional ordinary Portland cement (OPC) beams, affirming GPC as a sustainable structural-grade alternative.

High-calcium precursors, such as GGBS, enhance early strength under ambient curing, while low calcium systems like fly ash, metakaolin, and rice husk ash require heat curing for optimal reactivity. The type and molarity of alkaline activators, particularly sodium- and potassium-based systems, significantly affect strength and durability, with potassium activators providing improved thermal resistance. Curing temperature and method critically govern microstructural development, with heat and hybrid curing yielding superior densification and early-age performance.

Geopolymer concrete also demonstrates excellent durability, characterized by reduced permeability, improved acid and corrosion resistance, and high thermal stability up to 800°C. Overall, the review establishes GPC as a promising, eco-efficient alternative to OPC, capable of achieving high mechanical performance and long-term durability when mix composition and curing parameters are properly optimized.

V. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the promising mechanical and durability performance of geopolymer reinforced concrete beams, several critical research gaps remain that must be addressed to enable large-scale adoption and code integration:

- *Standardization and Design Guidelines*

There is currently no universally accepted standard or design code for geopolymer structural elements. Future research should aim to establish standardized mix design

frameworks and structural design equations, validated through comprehensive experimental and numerical investigations.

- *Long Term Durability Assessment*

Existing studies are predominantly short-term and laboratory based. Extended field exposure and accelerated aging tests are needed to assess the long-term durability of reinforced geopolymer concrete beams, including corrosion resistance, carbonation depth, and chloride ion penetration under real environmental conditions.

- *Reliability and Probabilistic Evaluation*

Due to the inherent variability of local precursors such as rice husk ash and metakaolin, probabilistic approaches such as the Monte Carlo Simulation (MCS) and First Order Reliability Method (FORM) should be incorporated into structural reliability assessments to quantify uncertainty in strength and serviceability.

- *Microstructural Mechanical Correlation*

Further investigation using advanced characterization techniques (e.g., SEM, FTIR, XRD) is necessary to establish quantitative correlations between gel phase composition, porosity, and mechanical properties. Such relationships will enhance mix optimization and predictive modeling accuracy.

- *Sustainability and Life Cycle Assessment*

Holistic life-cycle and cost–benefit analyses comparing geopolymer and OPC structures are essential to validate the claimed environmental and economic advantages, particularly in developing regions rich in agricultural and industrial by-products.

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