Geopolymer Concrete for Structural Use: Recent Findings and Limitations

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Abstract: **Geopolymer binders offer a possible solution for several problems that facing the current cement industry. These binders exhibit similar or better engineering properties compared to cement and can utilize several types of waste materials. This paper presents the recent research progress regarding the structural behavior of reinforced geopolymer concrete members including beams, columns and slabs. The reported results showed that the structural behavior of the reinforced geopolymer concrete members is similar to the known behavior of the ordinary reinforced concrete members. In addition, the currently available standards have been conservatively used for analysis and designing of reinforced geopolymer concrete structures. On the other hand, the main hurdles facing the spread of geopolymer concrete was the absence of standards and the concerns about the long-term properties. Other issues included the safety, cost and liability.**

Key Words: **Geopolymer binders, reinforced concrete, structural behavior, waste utilization, design standards, long-term performance.**

I. INTRODUCTION

Concrete is the primary construction material used globally, second only to water in consumption. The construction industry has become the largest consumer of the world's natural resources. According to the United Nations, by the year 2050, more than 65% of the global population is expected to live in urban areas [1]. This growth, particularly in developing countries, necessitates increased electricity use and the development of infrastructure and housing—in other words, a surge in the use of both electricity and concrete.

Ordinary Portland Cement (OPC) is the conventional binding material used in concrete production. It is estimated that the production of one ton of cement releases a comparable amount of carbon dioxide (CO_2) into the atmosphere. Overall, the cement industry accounts for approximately 5–8% of global CO_2 emissions [2]. Therefore, a technological shift is essential to reduce emissions in this sector. The reduction of CO_2 emissions is a global necessity, as continued emissions at current rates could pose a serious threat to future generations.

Geopolymer binders have emerged as promising green building materials capable of entirely replacing OPC in the concrete industry. Geopolymer technology can incorporate various industrial by-products, such as fly ash (FA), granulated blast furnace slag (GBFS), palm oil fuel ash, rice husk ash, and mining waste. Other sources include naturally reactive aluminosilicate powders or thermally activated aluminosilicates, offering sustainable and widely available alternatives for binder production.

The synthesis of geopolymers is based on inorganic alkali-activation chemistry. In this process, aluminosilicate-rich materials are activated using a strong alkali solution to form a three-dimensional aluminosilicate gel. This gel exhibits properties that can rival those of OPC. Geopolymer binders have demonstrated strong potential as OPC alternatives due to their superior characteristics, including higher early strength, dimensional stability, durability, fire resistance, and improved bonding with reinforcement and aggregates [3].

Currently, researchers worldwide are increasingly focused on this topic. The Geopolymer Institute has reported an exponential rise in the number of peer-reviewed journal publications featuring the keyword "geopolymer," with more than 400 publications recorded in 2013. The focus of research is now shifting from geopolymer chemistry toward engineering applications and commercial implementation.

II. STRUCTURAL BEHAVIOUR OF REINFORCED GEOPOLYMER CONCRETE

Geopolymer binders have shown increasing potential as cement-replacing materials in the concrete industry. These binders can be used to produce concrete with a wide range of physical and mechanical properties. To develop geopolymer concrete (GPC) with the desired characteristics, it is essential to control the silicon-to-aluminum (Si/Al) ratio, the alkali-to-silicon (M/Si) ratio—where *M* denotes alkali cations—and the water-to-binder ratio. Therefore, careful characterization of both the alkali activator and the source materials is necessary to determine and maintain these ratios.

GPC exhibits a different strength development mechanism compared to traditional cement-based concrete. As a result, the existing methods for the analysis and design of reinforced cement concrete (RCC) structures must be evaluated and validated before being applied to GPC structural members.

Although a significant amount of literature exists on the production, physical, mechanical, and durability properties of GPC, relatively little attention has been devoted to the structural behavior and applications of reinforced geopolymer concrete (RGPC).

2.1 Flexural behavior of RGPC beams

Kumaravel et al. [4] studied the flexural behavior of reinforced geopolymer concrete (RGPC) beams cast using fly ash (FFA) and granulated blast furnace slag (GBFS)-based geopolymer concrete, cured at 60°C for 24 hours. The beams were cast with grade 40 concrete, with dimensions of 125 × 250 × 3000 mm, and tested under a four-point flexural loading setup. The results were compared with reference reinforced cement concrete (RCC) beams of the same grade.

The RGPC beams exhibited load–deflection curves similar to those of the reference RCC beams. However, the RGPC beams demonstrated higher load capacities in terms of first crack appearance, service load, and ultimate load. Compared to the RCC beams, the RGPC beams showed increases in yield load, ultimate load, and maximum load by 3.57%, 2.7%, and 11.25%, respectively. Figure 1 illustrates the similar cracking patterns observed in both RGPC and RCC beams under flexural loading. All beams failed due to yielding of the reinforcement in the tension zone followed by crushing of concrete in the compression zone. Finite element simulations using ANSYS software predicted results that closely matched the experimental outcomes.

A similar study conducted by Dattatreya et al. [5] investigated RGPC beams cured under ambient conditions. In this study, the beam dimensions were 100 × 150 × 1500 mm, and the tensile reinforcement ratio varied between 82–110% of the balanced reinforcement ratio. The first crack load for RGPC beams was 9–11% of their ultimate load, while for RCC beams it ranged from 13–16%. The average service loads were 12% lower for RGPC beams compared to RCC beams. Despite this, the cracking patterns—including crack number, spacing, width—and the failure modes were largely similar for both types of beams.

Predictions using ACI 318 code [6] equations for cracking moment, ultimate moment, and maximum deflection showed good correlation with the experimental data. However, the degree of agreement varied across different cases. The study suggested incorporating an additional reduction factor to improve prediction accuracy. Further research was recommended to investigate the stress block shape in RGPC members.

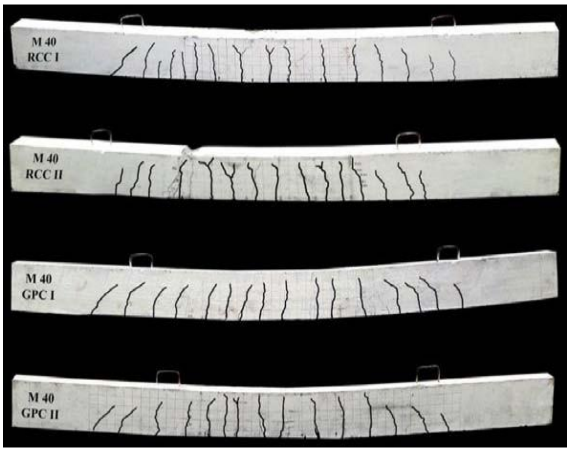

Figure1.Cracking patterns of RCC (RCCI&II) and RGPC (GPCI&II) beams [4].

An interesting study by Yost et al. [7, 8] investigated the flexural behavior of full-scale RGPC beams. The beams were cast using fly ash (FFA)-based geopolymer concrete with dimensions of 305 × 152 × 3200 mm, and were cured at 60°C for 24 hours using a newly developed system known as the *environmental curing chamber*. This system utilized halogen lamps as the heat source for temperature elevation. The resulting compressive strength of the concrete ranged from 52 to 57 MPa.

The beams were reinforced using three different reinforcement configurations representing under-reinforced (U), over-reinforced (O), and shear-critical (S) conditions. All beams were tested under a four-point loading setup, and the results were compared with those of reference RCC beams.

The U-type beams from both RGPC and RCC specimens exhibited nearly identical load–deflection curves. In both cases, the reinforcement yielded at slightly higher loads than predicted. A fully ductile behavior was observed until the concrete in the compression zone failed due to crushing. However, RGPC beams exhibited a more brittle failure mode, where the concrete disintegrated and the load dropped sharply at the point of failure. In contrast, RCC beams were able to sustain load for a short period even after initial failure. RGPC beams also recorded higher deflection values at maximum load.

Strain gauge measurements along the beam sides indicated that the position of the neutral axis could be characterized in three phases: transition, elastic, and inelastic. The theoretical predictions and experimental measurements for the neutral axis location during these stages showed close agreement, suggesting that the ACI 318 code [6] equations, including the Whitney rectangular stress block, may be applicable to RGPC beam design.

For the O-type beams, a linear load–deflection response was observed up to failure. In contrast, RCC beams exhibited a slight curvature in the load–deflection plot prior to failure. The ultimate load of the RGPC beams was 8% higher than predicted values. The failure mode for these beams was diagonal shear. Both RGPC and RCC beams exhibited similar cracking patterns, indicating comparable shear transfer mechanisms in both types of concrete.

2.2 Shear behavior of RGPC beams

The shear behavior of reinforced geopolymer concrete (RGPC) beams was investigated by Chang [9], who cast nine beams using FFA-based geopolymer concrete, with dimensions of 200 × 300 × 1680 mm. The study observed that the failure modes and cracking patterns were similar for both RGPC and reinforced cement concrete (RCC) beams. It was found that the shear capacity of the beams was influenced by the longitudinal reinforcement ratio. Shear cracking loads and ultimate shear strength were predicted using the ACI 318 code [6], which yielded conservative estimates. Additionally, the VecTor2 program was employed to simulate cracking patterns, failure modes, and shear strength. The predictions showed a strong correlation with the experimental data.

Madheswaran et al. [10] studied the shear behavior of thin-webbed T-beams cast using FFA + GBFS-based geopolymer concrete. The results indicated that both RGPC and RCC beams exhibited similar shear behavior, where the shear capacity was significantly affected by stirrup spacing and the shear span-to-effective depth ratio. All beams failed by diagonal tension—a typical shear failure mode. One of the flexural cracks within the shear span progressed into an inclined crack that propagated toward the loading and support points, ultimately causing a sudden brittle shear failure.

The load–deflection diagrams revealed a linear response up to cracking, with a continued linear relationship in the post-cracking phase. However, the experimental deflections were greater than those calculated using ACI 318 code provisions for RCC, which could be attributed to the lower modulus of elasticity of geopolymer concrete. The study concluded that ACI 318 code provisions for shear design are valid for RGPC beams and provide conservative estimates.

The same researchers later conducted a similar investigation on rectangular RGPC beams [11]. Twelve shear-deficient beams with a span of 1600 mm were cast and tested. The strain compatibility method was used to predict the ultimate moment capacity, and a non-linear stress–strain model was employed to estimate the full load–deflection response. Both methods showed excellent correlation with the experimental results for RGPC and ordinary Portland cement (OPC) concrete beams.

In a separate study, Laskar et al. [12] examined the performance of RGPC beams under cyclic loading. The results demonstrated that RGPC beams exhibited approximately 30% higher load-carrying capacity compared to RCC beams. Additionally, RGPC beams showed reduced stiffness degradation over time and 45% greater energy dissipation capacity, indicating improved resilience and suitability for seismic applications.

2.3 Behaviour of RGPC columns

Sarker [13] analyzed the behavior of short slender RGPC columns subjected to combined compression and uniaxial bending. The study concluded that the analytical methods used for reinforced cement concrete (RCC) column analysis could be conservatively applied to RGPC columns as well. However, modifications to the stress–strain relationship were suggested for improved accuracy. The predicted values of ultimate load, mid-height deflection, load–deflection curves, and deflected shapes showed good correlation with the experimental results.

Rahman et al. [14] investigated the behavior of slender columns subjected to axial compression and biaxial bending. The columns were cast using FFA-based geopolymer concrete, and the parameters studied included concrete grade, reinforcement ratio, and eccentricity distance. All columns failed due to the spalling of the concrete cover followed by crushing of the core concrete. For smaller eccentricities, failure occurred in a more brittle manner, with a shorter post-peak region in the load–deflection response. As the eccentricity increased, mid-height deflections also increased. Similarly, higher deflection was observed with an increase in reinforcement ratio and compressive strength. Overall, the failure modes and load–deflection behavior were similar to those observed in RCC columns.

Bresler's reciprocal load formula and the stress block formula provided by the Australian Standards were used to estimate column load capacity. These predictions were found to be conservative and reasonably close to experimental results, especially for columns with smaller eccentricities. A similar study conducted by Sumajouw et al. [15] confirmed the conservative nature of predictions made using Australian Standard AS3600 and ACI 318 code provisions, with an average experimental-to-estimated load ratio of 1.15.

In another study, Sujatha et al. [16] compared the axial load behavior of short, slender RGPC columns with that of RCC columns. The specimens were 1800 mm in height with circular cross-sections. The RGPC columns demonstrated a 30% higher load-carrying capacity than their RCC counterparts, along with lower mid-height deflections, indicating improved performance under axial compression.

2.4 Behaviour of RGPC slabs

The flexural behavior of reinforced geopolymer concrete (GPC) solid slabs made using GBFS + FA-based binders has been reported to be comparable to that of ordinary Portland cement (OPC) reinforced concrete slabs [17]. Slab strips with dimensions of 1300 × 650 × 75 mm were cast and reinforced with 8 mm diameter bars. The slabs were tested under various support conditions and loading types. The mid-span deflections at failure ranged between 4 mm and 30 mm. When compared to analytical predictions based on standard OPC concrete design equations, the experimental results showed good agreement in terms of maximum deflection. However, the calculated deflections at first crack loading were generally higher than the measured values.

Madheswaran et al. [18] explored the performance of reinforced GBFS + FA-based GPC solid slabs under impact loading, comparing them to equivalent OPC concrete slabs. The GPC slabs demonstrated higher energy absorption at both the cracking and failure stages, attributed to their lower modulus of elasticity, which reduced overall stiffness. Interestingly, the inclusion of steel fibers enhanced the energy absorption capacity of OPC concrete slabs more significantly than GPC slabs, resulting in similar performance between the two materials when fiber reinforcement was introduced.

Ganesan et al. [19] studied the one-way flexural behavior of FA-based GPC panels in comparison with OPC concrete panels. Both types of panels exhibited similar cracking patterns and failure modes. Failure occurred by crushing of the concrete near the edges, accompanied by large lateral deflections, with maximum values at mid-span. The load–deflection curves displayed linear behavior until the formation of the first cracks, followed by a nonlinear response. GPC panels showed steeper curves, indicating lower ductility compared to OPC panels. This reduced ductility was attributed to the higher content of fine particles in GPC mixes, which contributed to a softening effect.

However, the analytical results for GPC panels consistently underestimated the experimental values, with errors ranging from 20% to 35%, depending on the aspect ratio and slenderness of the panels. This suggests the need for applying additional safety margins when predicting the ultimate load capacities of GPC slabs and panels.

III. STRESS-STRAIN RELATIONSHIP

The stress–strain behavior of fly ash (FA)-based geopolymer concrete (GPC) has been found to be generally comparable to that of normal-strength ordinary Portland cement (OPC) concrete [20, 21]. The existing analytical models for OPC concrete have been used successfully to approximate the stress–strain relationship and to predict the strain at peak stress for GPC, with acceptable levels of accuracy [7, 22].

Up to the point of ultimate strength, the FA-based GPC exhibits a stress–strain profile similar to that of OPC concrete. However, a notable difference arises in the post-peak region. While OPC concrete typically undergoes a gradual decline in stress after reaching its peak strength (strain softening), GPC tends to exhibit a more sudden stress drop, indicating a brittle failure pattern [20, 21]. This behavior is attributed to the presence of distributed microcracks in the geopolymer matrix, which compromise its post-peak ductility [23, 24].

Sarker [13] proposed a modified model to improve the accuracy of post-peak behavior predictions. By adapting the curve-fitting parameter nnn from the Thorenfeldt et al. [25] model—originally developed for high-strength concrete—a better correlation with experimental data was achieved. Reported peak strain values for different GPC mixes ranged from 0.0015 to 0.0026 [7, 22, 26, 27], which are lower than the commonly assumed value of 0.003 used in conventional OPC concrete design.

In a broader investigation involving 25 FA-based GPC mixes with varying fly ash sources, the ultimate strain was generally found to be less than 0.002, while compressive strengths ranged from 20 to 55 MPa [28]. It was also reported that the Si/Al molar ratio plays a critical role in defining the ductility of GPC. Mixes with a Si/Al ratio greater than 24 exhibited more ductile behavior with failure characterized by larger deformations rather than abrupt fracturing [29].

Prachasaree et al. [30] developed a simplified empirical stress–strain model specifically for GPC design, using the Thorenfeldt model [25] as a foundation. They recommended using the strain at peak stress rather than peak compressive strength when estimating the modulus of elasticity and other stress block parameters. Although a minor deviation was observed in the post-peak region, the proposed model aligned well with experimental data. Furthermore, this model was used to derive equivalent rectangular stress block parameters, which were then applied in flexural capacity calculations according to ACI 318 provisions. The model demonstrated strong predictive performance, with errors ranging from 9% to 16%, compared to errors as high as 34% when using existing ACI 318 models. This validation was specifically applicable to FA-based GPC with compressive strength below 75 MPa.

Ganesan et al. [21] also reported that, for the same strain values, FA-based GPC generated higher stresses than OPC concrete. Additionally, GPC exhibited a slower rate of deformation up to 80% of the ultimate load, followed by a rapid increase in deformation, indicating a sharper transition from elastic to inelastic behavior compared to OPC concrete.

IV. LIMITATIONS AND CHALLENGES

Despite the extensive research conducted on geopolymer concrete (GPC), several challenges hinder its widespread adoption in the construction industry. One of the primary limitations is the absence of universally accepted standards. The development of such standards should ideally be led by a global consortium of experts and organizations. Unlike technical barriers, the lack of institutional and regulatory flexibility poses a significant obstacle to the adoption of geopolymer-based concrete. Establishing performance-based standards that evaluate concrete based on durability, strength, and serviceability may provide a viable pathway for incorporating GPC into mainstream practice.

A further complication arises from the broad classification of materials under the term "geopolymers," which encompasses a diverse range of aluminosilicate source materials. This variability can lead to confusion among designers and specifiers. Hence, the correct categorization and specification of source materials are essential for their effective use in construction applications.

Developing new design codes and testing standards for GPC will require substantial investment and collaboration between government bodies, industry stakeholders, and the research community. Although sustainability and environmental concerns are often cited as key motivations for adopting GPC, they may not be compelling enough to influence market behavior on their own. Greater global awareness, coupled with regulatory incentives such as carbon taxes or emission-related credits, may be necessary to shift industry preferences.

End-users tend to prioritize tangible performance metrics such as strength, durability, and cost over environmental considerations. While the relatively low cost of by-product materials such as fly ash (FA) and ground granulated blast furnace slag (GBFS) initially suggested that GPC could be 10–30% cheaper than conventional concrete [29], this advantage has not been consistently realized. Much of the raw material supply is locked in through long-term contracts with cement companies, limiting its availability. Additionally, the cost and environmental burden of alkaline activator solutions remain significant. Innovations are needed to develop low-cost, low-emission activators and reduce the overall demand for alkaline reagents.

The question of long-term performance remains a major barrier to acceptance. Design professionals typically require 20–30 years of real-world performance data before endorsing new materials for structural applications. In the absence of such data, concerns about user safety and reliability persist. Although laboratory-based durability tests offer insights into potential performance, a standardized and definitive long-term evaluation method is urgently needed.

Another critical issue is the variability in mechanical and physical properties caused by inconsistencies in raw material quality and composition [31]. This variability complicates comparative analysis across different studies and undermines the predictability of performance. For widespread industry acceptance, GPC must demonstrate consistent and reproducible behavior in both fresh and hardened states. This necessitates a shift toward chemical and rheological property-based evaluation methodologies.

The requirement for elevated-temperature curing presents another limitation, restricting GPC's application primarily to precast environments. To enable broader use in cast-in-situ applications, ambient-cured GPC formulations and one-part (just-add-water) geopolymer binders are essential. Some researchers have attempted to improve the reactivity of FA by increasing its fineness [32] or adding calcium-rich source materials [33, 34]. However, these modifications may affect both the cost and the long-term durability of GPC. Further investigation is needed to understand the role and location of calcium in the geopolymer matrix [3], as well as the influence of other oxides such as Fe, Mg, and others on the overall performance.

A recent survey by Heidrich et al. [35] in Australia involving a broad range of stakeholders in the concrete industry identified the main barriers to GPC adoption. More than 60% of respondents cited the absence of standards as the most critical issue. Concerns about long-term durability ranked second, followed by productivity and safety. Interestingly, cost and liability were perceived as relatively minor concerns, indicating that technical and regulatory hurdles are of greater significance to industry stakeholders.

V. CONCLUSIONS

This review has evaluated the structural behavior of reinforced geopolymer concrete (RGPC) elements—including beams, columns, and slabs—in comparison with conventional ordinary Portland cement (OPC) reinforced concrete members. The findings indicate that fly ash (FA) and ground granulated blast furnace slag (GBFS)-based geopolymer concrete (GPC) can exhibit mechanical and physical properties comparable to those of conventional cement concrete. However, due to the limited long-term performance data, it is advisable to incorporate additional safety factors when designing with GPC to account for potential variations over time.

In terms of stress–strain behavior, FA-based GPC shows a similar trend to OPC concrete up to the point of ultimate strength. However, after reaching this point, GPC undergoes a rapid decline in stress, indicating a more brittle post-peak response compared to the gradual softening seen in OPC concrete. The peak strain values for various GPC mixtures typically fall within the range of 0.0015–0.0026, which is lower than the 0.003 strain value commonly used for OPC concrete in structural design.

Despite the growing body of research, significant gaps remain in understanding the comprehensive structural behavior of RGPC. There is a need for more in-depth studies to establish clear and reliable relationships among its key properties, including the elastic modulus, Poisson's ratio, tensile strength, flexural strength, compressive strength, shear strength, and bond strength. Addressing these gaps is critical to developing accurate design models and ensuring the safe application of GPC in structural engineering.

One of the most pressing barriers to the widespread acceptance of GPC is the lack of standardized codes and guidelines. The variability in raw materials and mixture designs further complicates its application. Therefore, adopting a performance-based evaluation approach appears to be the most promising path forward. Such an approach would allow for the rational design and implementation of geopolymer concrete in structural systems, ensuring safety, reliability, and sustainability.

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