

A Comprehensive Review of the Structural Performance of Reinforced Geopolymer Concrete Beams

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Abstract

In this review paper, the structural behavior of reinforced geopolymer concrete (GPC) beams is analyzed based on the synthesis of data obtained experimentally, numerically, and comparatively in peer reviewed literature from 2014 till 2025. Geopolymer concrete (a material synthesized from industrial aluminosilicate byproducts such as fly ash (FA), metakaolin (MK) and ground granulated blast furnace slag (GGBS) by means of alkaline activation) has generated significant research interests as an eco-friendly replacement of OPC concrete. LCA studies reveal reduction in carbon emissions from 30% to 60% with respect to OPC concrete. In this paper, various important parameters that influence the behavior of GPC beams with respect to flexural performance, shear strength, ductility, bond strength, seismic resistance, fire resistance, and durability will be reviewed. Fibers are found to enhance the post crack behavior and fracture energy of the beams. Seismic behavior of GPC beam-column joints have been found to satisfy the design codes. Important knowledge gaps still remain in long term creep and shrinkage properties, cyclic behavior, residual strength after fire exposure and standardization of design code for GPC structures.

Keywords: *Geopolymer Concrete (GPC); Reinforced Concrete Beams; Flexural Behavior; Sustainability.*

1. Introduction

The construction sector globally faces one major environmental challenge; conventional Portland cement (OPC) manufacturing is responsible for 6-8% of global man-made CO₂ emissions, generating about 0.8-0.9 tons of CO₂ for every ton of cement manufactured [1-3]. With the total annual global emissions being 2.46 Gt of CO₂ from cement usage, the need to find low-carbon binders that will still maintain good structural integrity is high. One of the most developed binders is geopolymer concrete (GPC), which are formed from aluminosilicate-rich industrial by-products like fly ash (FA), metakaolin (MK), and ground granulated blast furnace slag (GGBS) by an alkaline activation process [4, 5]. LCA analysis demonstrates reductions in carbon emissions in the range of 30-60% for FA and GGBS-based GPC when compared to OPC concrete of the same strength grade [2, 6, 7]. Reinforced GPC beams were proven to behave equally well in flexural and shear strength when compared to OPC beams, but showed greater resistance to chemical attacks, chloride ion permeability, and heat [8-12]; moreover, current studies have confirmed satisfactory

seismic response of GPC beam-column joints [13-18] and better bond characteristics between GPC and reinforcement [19]. Overall, there is consensus in the literature on the satisfactory structural performance of GPC [10, 20, 21]. In addition, there are brief reviews on the mechanical performance of GPC structures [22, 23].

There are still some challenges impeding the structural application of GPC widely. Such factors include the lack of GPC structural design standards, inconsistency due to material variability, sensitivity to curing conditions, and the absence of long-term performance data under both static and dynamic loads. This review article analyzes the results of the reviewed studies on GPC structure in the scope of structural performance parameters in peer-reviewed literature and suggests future research directions [5, 10, 20, 21].

2. Geopolymer Concrete: Definition, Chemistry, and Composition

2.1 Geopolymerization Chemistry

Geopolymerization occurs in three distinct, but at times concurrent, stages: (i) Dissolution of aluminosilicate source materials within the alkaline solution, which releases Si^{4+} and Al^{3+} monomers; (ii) polymerization to form oligomers; and (iii) hardening to produce a three-dimensional network of aluminosilicate gel [4, 5]. A geopolymer binder, depending on calcium content, can be sodium aluminosilicate hydrate (N-A-S-H) or calcium aluminosilicate hydrate (C-A-S-H). The former binder differs greatly from the C-S-H gel that forms when Portland cement hydrates [13, 24].

2.2 Precursor Materials

2.2.1 Fly Ash (FA)

Fly ash of class F ($\text{CaO} < 10\%$) is the most common material for making GPC because of its low amount of calcium oxide content, which makes possible creation of N-A-S-H gel and contributes to the formation of strength. Thermal treatment of the GPC made of fly ash is necessary for ensuring enough early strength (it occurs between 60° and 80°C) [5, 25]. For fast hardening, use of fly ash of class C is preferable due to its C-A-S-H structure formation.

2.2.2 Ground Granulated Blast Furnace Slag (GGBS)

As a result of being an industrial waste product, GGBS contains CaO contents between 35 and 45%, which makes it possible for it to form the C-A-S-H gel when cured at normal temperatures; thus, it is possible to apply it in situ. The best mix ratio of the blend that consists of FA 20% and GGBS 80% has been found with regards to strength and workability [16, 17]. Tests done on blended GPC made from FA/GGBS mixture have shown that it has better chloride resistance, sulfate resistance, and sorptivity than OPC concrete [16].

2.2.3 Metakaolin (MK)

Metakaolin results from heating kaolin clay at temperatures between 600° and 800°C . Meta-kaolin has high reactivity at room temperature and produces a compact matrix with good compressive strength. Nevertheless, it is produced using heat, and LCA calculations suggest that the GPC made using metakaolin may have a global warming potential up to 68% greater than OPC concrete [1, 24].

2.2.4 Binary and Ternary Blends

The combination of FA, GGBS, and MK allows for the fine tuning of these parameters. As stated by Ansari et al. [10] and Saeed & Al Amlı [20], the blend ratios play an extremely important role in terms of mechanical resistance as well as in terms of durability. According to Al-Luhybi et al. [21], mix design is the key factor affecting the behavior of GPC beams.

2.3 Alkaline Activators

Sodium hydroxide solution (NaOH) and sodium silicate (Na_2SiO_3) are the most common activators. Geopolymerization degree is defined by the modulus of the activator ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) and NaOH concentration. According to LCA, up to 87.21% of GPC carbon footprint (CO_2 emissions) depend on the activator/binder ratio [1]; decreasing the ratio of siliceous sources (SS)/siliceous hydrogels (SH) from 4.0 to 2.0 reduces global warming potential by 23% [1, 7]. The use of different activator contents for the curing process of geopolymer concrete proves that 14 M NaOH causes [26].

3. Environmental Impact and Sustainability

Environmental benefits from GPC arise from the significant decrease in CO_2 emissions relative to OPC concrete. LCA calculations utilizing SimPro 9.4 software with Monte Carlo simulation confirm a 43% lower carbon emission for FA/GGBS-based GPC (228.34 kg CO_2 eq/ m^3) in comparison with OPC concrete [7]. The 95% confidence interval for OPC carbon emissions is 365.9–428.5 kg CO_2 eq/ m^3 [7]. Geopolymers result in decreased cost and reduced CO_2 in cases where only limited amounts of alkali activators are used; in aggressive chemical environments, savings amount to 90% [2].

The environmental merit of geopolymer concrete will depend on circumstances. Industrial production of alkaline activators (NaOH and Na_2SiO_3) is responsible for about 77% of GPC's CO_2 emissions due to high-energy consumption [7]. An AI-driven review of geopolymer LCA [6] concludes that ML techniques can be used to optimize activator proportions in order to reduce both environmental impact and cost at the same time. Superior environmental characteristics of GPC in terms of increased durability in aggressive conditions [16, 24] result in a longer service life and lower environmental costs due to decreased maintenance.

In addition to reduced CO_2 emissions, large quantities of industrial waste by-products are incorporated into GPC that will otherwise end up in the landfill [4, 27]. An analysis of the use of geopolymer concrete with recycled aggregates [4, 27] proves that the combined effect of GPC and recycled aggregates will result in lower embodied carbon and lower resource extraction costs. Zuaıter [23] analyzes glass-fiber-reinforced cement-free GPC.

4. Structural Behavior of Reinforced GPC Beams

4.1 Flexural Behavior

The most extensively studied GPC structural property is its flexural performance. Mamdouh et al. [28] performed extensive tests on ambient-cured geopolymer slag concrete beams under four-point bending while changing beam sizes and reinforcing proportions, proving their equivalent moment-carrying capacities and similar load-deformation behavior to those of OPC beams. In addition, size effects were observed according to models designed for OPC concrete beams.

Bayrak [8] examined the effect of fiber combination of hybrid and trio fibers on flexural strength of geopolymer concrete beams under four-point and three-point bending test setups. Adding trio fibers had the largest impact on increasing flexural capacity, particularly for the minimum proportion of reinforcement ratios. Importantly, this study found about a 25% error in estimating GPC beam's flexural capacity using ACI 318, EC2, TS500, and GB50010 design codes due to OPC-based formulation—indicating the need for calibration of OPC design code formulae for GPC beams. To address this deficiency, Kocaer and Aldemir [29] developed a GPC-specific compressive stress-strain relationship with high precision in calculating flexural capacity.

Ozturk and Arslan [30] tested GPC beams made from ground granulated blast furnace slag and reported a marginal increase in their moment-carrying capacity over OPC ones. The Bulletin of Earthquake Engineering [31] paper also showed that a higher reinforcement ratio increases loading capacity but decreases ductility in GPC beams. Thumrongvut et al. [32] proved that rice husk ash incorporated into GPC beams provides an excellent balance in performance and carbon reduction compared to OPC beams.

The finite element modeling approach is another way of designing GPC beams. Tang et al. [33] verified the finite element models used to predict FRP-reinforced geopolymer concrete beams' properties through analyzing their parametric relationship between fiber reinforcement ratio and moment resistance. Liu and Yan [34] analyzed the use of geopolymer adhesive-bonded CFRP as external reinforcement for strengthening RC beams' flexural performance. Ansari et al. [10] and Saeed and Al Amlı [20] summarized existing literature and consistently showed the competitive flexural capacity of GPC beams compared to OPC.

4.2 Shear Behavior

Shear failure is sudden and brittle; therefore, reliable prediction of shear behavior becomes very crucial. Muhammad et al. [9] compared the slender GPC beams with the ratio's a/d equal to 4.5 and 5.0 to their OPC counterparts and found out that the cracking behavior of both beams was almost identical. Flexural cracking was noted at about 25–29% of the ultimate load, while inclined cracking occurred at about 65%. The stirrup reinforcement was seen to give identical shear strength to GPC and OPC beams.

According to Bayrak [8], one of the most serious defects of existing building codes is that the shear equations in the code give about an 82% average error in the prediction of the shear strength of GPC beams, while there is only a 25% error in flexural strength calculation. This claim was validated by Al-Luhybi et al. [21], who examined the flexural and shear strength behavior of reinforced GPC beams.

According to Liu and Su [35], there were 20–40% increases in the shear capacity of CFRP-reinforced beams bonded using geopolymer-based adhesive. As Ozturk and Arslan [36] found, the diagonal compressive struts' strength was somewhat increased when the GPC material was employed due to higher density and lower permeability and micro-cracking in the interfacial zones. The study by Aksoylu et al. [37] confirmed that shear strengthening was obtained by WSW additive optimization in both ambient and oven-cured beams.

4.3 Bond Behavior and Reinforcement Interaction

The interaction between the steel reinforcements and the GPC matrix is crucial for proper load transfer and serviceability performance. In their study of steel-concrete interfaces,

Hachem et al. [19] observed the bond strength behavior of GPC and found out that the bond behavior of GPC is better than that of OPC since GPC offers reduced interfacial porosity and micro-cracks.

In a recent investigation conducted by Luan et al. [38], models that predict tensile strength and bond strength of reinforcement-GPC have been created using significant mix ratios such as $\text{SiO}_2/\text{Al}_2\text{O}_3$, activator, and water contents. The models showed very good correlation with multiple sources of experimental data and are quite easy to use. According to Topark-Ngarm et al. [25], high-calcium fly ash GPC concrete performs better in terms of bond and compressive strength than OPC concrete owing to the formation of the extra binder phase, the C–A–S–H formed from the calcium fly ash.

Corrosion resistance is one of the durability aspects considered regarding bond strength. It has been shown that GPC matrix offers the best protection against corrosion due to the formation of the passive protective layer of alkalinity. Sobhan et al. [40] examined fiber-reinforced GPC in the marine environment and confirmed its better performance in chloride penetration and corrosion current density than OPC.

4.4 Ductility and Energy Absorption

Ductility, defined using displacement ductility indices ($\mu\delta = \delta u/\delta y$) and the capacity for energy dissipation, is generally similar for GPC and OPC beams of equal rebar ratio. Moazzenchi et al. [22] verified that the ductility ratios of GPC beams with FRP rebars were within $\pm 5\%$ of OPC beams. Nevertheless, it should be noted that the brittleness after the yield point in [31] shows that ductility properties rely on precursors and curing processes. In the context of buildings MDPI, it was found that the ductility coefficient of the GPC beams increased up to 50% more than normal concrete under cyclic loading. Guades et al. [41] found out that fiber-reinforced geopolymer composite (FRGC) jacketing enhanced not only the flexural capacity but also ductility by over 50%. Hybrid fiber types proved to control micro and macro cracks better. Parametric study carried out in [41] also confirmed that FRGC thickness and tensile strength are the predominant factors influencing energy absorption.

4.5 Fiber-Reinforced GPC Beams

4.5.1 Steel Fibers

Fracture mechanics test on slag-based GPC reinforced with steel fiber has been done by Ding & Bai [42]. The result showed improved fracture energy, toughness modulus and post peak loading capacity. The steel fiber contents of 1–2% were found to be ideal to achieve optimum mechanical improvement without compromising its workability. Further support can be seen from the work of Ozturk & Arslan [36].

4.5.2 Polypropylene Fibers

Effect of fiber factor (volume fraction \times aspect ratio) of polypropylene fiber on self-compacting GPC was studied systemically by Pu et al. [43]. The threshold of fiber factor was determined such that mechanical properties improvement would be reduced due to formation of fiber balls at higher level. Below the threshold, fibers were able to improve compressive, tensile and flexural strength along with fire resistance [43].

4.5.3 Hybrid and Natural Fibers

In addition, Bayrak [8] confirmed that the combination of fibers into trios (all three fiber types together) greatly surpasses hybridization (combination of two fiber types) in terms of efficiency in flexural and shear tests. On comparing natural fibers like jute, sisal, and coir and synthetic fibers on the basis of their use with GPC, Azevedo et al. [44] showed that the former gives better mechanical properties with better ecological compatibility. Moreover, Michael et al. [45] tested hybrid PP-R fiber-reinforced ferro-geopolymer pavers.

4.5.4 FRP Reinforcement in GPC Beams

Combining FRP reinforcement bars with GPC matrices is a successful symbiosis for developing corrosion-resistant buildings. It has been numerically shown by Nofal et al. [11] that finite element model predictions concerning FRP-reinforced beams in terms of failure behavior, capacity, and deflection response coincide well with test results. Tang et al. [33] validated numerically the models of FRP-reinforced GPC beams and found the parameter dependence between the reinforcement ratio of fibers and resistance to bending. Liu and Yan [34] successfully showed flexural strengthening of RC beams by means of geopolymer-based adhesively bonded CFRP plates.

4.6 Seismic Performance of GPC Beam–Column Joints

The performance of exterior beam-column joints using 20% FA + 80% GGBS GPC concrete under quasi-static cyclic loading was examined by Maniarasan et al. [17]. It revealed satisfactory performance concerning energy dissipation capacity, stiffness degradation, and ductility. Further extension of this study [18] to the investigation of the performance of interior beam-column joints under cyclic loading indicated different hysteresis patterns compared to OPC joints yet satisfying seismic code requirements regarding energy dissipation capacity and drift. On the other hand, another study on the effect of GPC beam flexural reinforcement bonds in beam-column joints [18] in the journal "Engineering Structures" proved the appropriateness of applying existing provisions of bond design.

Overall, the above-reviewed seismic studies proved the adequacy of the design of beam-column joints with GPC concrete in accordance with seismic code provisions and also identified the need to incorporate GPC material constitutive models into joint shear and bond-slip performance analysis. Superior fire resistance of GPC [13, 14, 15] offers a further safety margin in case of fire following earthquake events.

4.7 Fire Resistance

Fire resistance in geopolymer concrete is much better than that of OPC concrete. The aluminosilicate structure is relatively more heat resistant compared to C-S-H gel because of dehydration above 300-500°C. It has been proven that GPC has significant compressive strength even at 1000-1200°C temperatures [13]. The compressive strength of GPC increases up to 150-350°C but starts decreasing at more than 400°C as a result of thermal expansion cracking.

Hassan et al. [13] gave an extensive overview regarding fire resistance of GPC by presenting facts that (1) GPC based on fly ash has no explosive spalling when used with polypropylene fiber; (2) residual tensile strength is higher than OPC up to a 300°C temperature; and (3) inclusion of recycled tire fiber in an optimal value of 1.2-2 kg/m³

enhances fire resistance. The Environment, Development, and sustainability paper [14] confirms a denser microstructure of GPC after fire and a lower number of macrocracks in comparison to OPC concrete. Shen et al. [15] have done experiments with GHPC prefabricated staircases according to the ISO-834 standard and found very good fire behavior without any spalling.

4.8 Long-Term Behavior: Creep and Drying Shrinkage

The issue of time-dependent deformations is crucial for ensuring the proper serviceability of structures. For instance, Negahban et al. [26] performed a year-long study on restrained shrinkage and creep for GPC slabs through photogrammetric measurements to verify the fact that 14 M NaOH solutions resulted in 26.5% smaller shrinkage compared to 16 M solutions, showing the significance of activator molarity for time-dependent deformation control. Similarly, Seneviratne et al. [46] estimated a one-year creep coefficient of ~0.97 for geopolymer aggregate concrete, which is significantly lower than those predicted by AS 3600 and CEB-FIP models (~1.5–2.5).

The currently existing design standards and guidelines for estimation of time-dependent deformation (creep and shrinkage) of concrete (AS 3600, CEB-FIP, and ACI 209) apply to OPC only and do not provide adequate estimates for GPC materials. It has direct impacts on the calculation of deformations of GPC RC beams. According to numerous durability studies [16, 24], the low permeability of GPC results in reduced corrosion caused by chlorides, as well as shrinkage cracks resulting from moisture transport. Specifically, Nagajothi et al. [16] confirmed durability of FA/GGBS-based GPC with manufactured sand under ambient curing conditions.

5. Comparative Performance: GPC vs. OPC Concrete

Table 1 elaborately compares these parameters for both GPC and OPC concrete. The performance attributes mentioned have been verified by experimental results and life cycle analysis presented in the literature references as well [1, 2, 7, 8, 10, 13-16, 19-21, 25, 26, 29, 38, 46].

Table 1: Comparative Performance of Geopolymer Concrete vs. Ordinary Portland Cement Concrete

Property	OPC Concrete	Geopolymer Concrete	Assessment
Compressive Strength	25–80 MPa	Comparable or higher [5, 10]	Equivalent/Superior
Flexural Strength	Standard per ACI 318	Comparable [8, 29]	Equivalent
Shear Capacity	ACI 318 / EC2	Comparable; codes overpredict by ~82% [8]	Code gap
Bond to Steel	Reference	Equal or superior [19, 38]	GPC advantage
CO ₂ Emissions	~0.85 t CO ₂ /t cement	30–60% reduction [1, 2, 7]	Major advantage GPC

Property	OPC Concrete	Geopolymer Concrete	Assessment
Fire Resistance	Degrades >300°C	Stable to 1000–1200°C [13, 14, 15]	Major GPC advantage
Chloride Resistance	Moderate	Superior, lower permeability [16, 40]	GPC advantage
Creep Coefficient	1.5–2.5 (AS 3600)	~0.97; lower than OPC [26, 46]	GPC advantage
Curing Requirement	Ambient	Ambient (GGBS/MK) or thermal (FA) [25]	Precursor-dependent
Design Codes	ACI 318, EC2, etc.	No dedicated standard yet [10, 20, 21]	OPC advantage

6. Summary of Literature Review

The list of relevant research papers in Table 2 is an exhaustive summary of all significant research works discussed in the present study. These studies have been sourced from renowned peer-reviewed scientific journals.

Table 2: Summary of Selected Studies on Structural Performance of Reinforced GPC Beams

Source / Reference	Study Focus	Key Findings
[8] Bayrak (2024)	Trio/hybrid fiber effect on flexural and shear behavior of GPC beams with minimum/maximum reinforcement ratios	Trio fibers increased flexural capacity significantly; ACI318/EC2/TS500 showed ~25% error (flexure) and ~82% error (shear); EC2 was the best among codes.
[9] Muhammad et al. (2023)	Shear behavior of slender steel-reinforced GPC beams ($a/d = 4.5-5.0$) with and without stirrups vs. OPC beams	Similar crack propagation and failure mechanisms in GPC and OPC; stirrups provided equivalent shear enhancement in both systems.
[37] Aksoylu et al. (2025)	Shear and flexural of GPC beams cured under ambient/oven conditions with waste steel tire wire (WSW) additives	10% GBFS + 3% WSW was optimum; 20% GBFS reduced load capacity; oven curing was marginally superior for shear.
[31] Özbayrak et al. (2025)	Structural behavior of heat-cured FA-based GPC beams: experimental, numerical	Higher reinforcement ratio increased capacity but reduced ductility; GPC showed more brittle post-yield behavior; OPC-based

Source / Reference	Study Focus	Key Findings
	(SAP2000), and code-based assessment	FEM was good linearly but diverged post-yield.
[10] Ansari, Shariq & Mahdi (2023)	Review of structural behavior of reinforced GPC beams	GPC achieves comparable structural performance to OPC; design codes require GPC-specific calibration for reliable application.
[11] Nofal et al. (2023)	Numerical FEM of GPC beams with steel and GFRP bars using ANSYS: two dispersed fiber types	FEM agreed with experimental results for failure mode, load, and deflection; GPC with FRP bars performed similarly to OPC beams.
[12] Al-Janabi et al. (2026)	Flexural performance of GPC beams under monotonic and cyclic loading: experimental investigation	GPC beams showed ~50% higher ductility coefficient than normal concrete under cyclic loading; comparable or superior structural performance was confirmed.
[22] Moazzenchi et al. (2023)	Flexural behavior of RC beams with GPC and OPC using steel and FRP bars—four-point bending	GPC beams with FRP rebar performed similarly to OPC cement beams, with ductility ratios within 5% of OPC values.
[42] Ding & Bai (2018)	Fracture properties of steel fiber-reinforced slag-based GPC mortar and concrete	Steel fibers significantly enhanced fracture energy, toughness, and post-peak load retention; bi-linear softening curves observed.
[44] Azevedo et al. (2021)	Natural vs. synthetic fibers in geopolymer matrix reinforcement: comparative review	Natural fibers (jute, sisal) viable for low-to-medium strength applications; eco-friendly with enhanced mechanical properties.
[35] Liu & Su (2023)	Shear performance of CFRP-strengthened RC beams bonded with geopolymer adhesive	CFRP-GPC bonded beams showed 20–40% shear capacity enhancement; geopolymer adhesive comparable to epoxy systems.
[45] Michael et al. (2024)	Hybrid fiber-reinforced low-calcium ferro-geopolymer paver block development	Polypropylene + rubber fibers reduced brittleness and improved energy absorption; ferro-GPC paver viable as eco-friendly alternative.
[39] Manoj et al. (2024)	Corrosion inhibitor performance on steel	GPC matrix proved most effective corrosion inhibitor; formed

Source / Reference	Study Focus	Key Findings
	reinforcement in geopolymer concrete	alkaline passive layer around reinforcement bars.
[20] Saeed & Al Amlı (2023)	Structural behavior of GPC beams: short review	GPC demonstrates comparable mechanical properties to OPC; standardized design guidelines urgently needed.
[21] Al-Luhybi et al. (2024)	Flexural and shear performance of reinforced GPC beams: systematic review	GPC beams show promising structural performance; gaps in design codes and long-term behavior data are identified.
[17] Maniarasan et al. (2023)	Seismic behavior of exterior beam-column joints with slag-based GPC (20%FA+80%GGBS)	20%FA+80%GGBS mix improved mechanical properties and joint ductility; ambient curing was validated for seismic applications.
[18] Mao et al. (2023)	Seismic performance of interior beam-column joints using reinforced slag-based GPC under cyclic loading	GPC joints met code requirements; distinct hysteresis from OPC; existing seismic code provisions applicable with modifications.
[19] Hachem et al. (2023)	Physical, mechanical, and transfer properties at the steel-concrete interface: review	GPC demonstrated improved bond behavior over OPC; lower porosity at ITZ reduces crack widths and improves serviceability.
[13] Amran et al. (2022)	Fire resistance of GPC: critical review	GPC retains structural integrity to 1000–1200°C; residual compressive strength peaks at 150–350°C and declines beyond 400°C.
[14] Hassan et al. (2022)	Fire resistance characteristics of GPC: review of thermal, mechanical, and microstructure properties	GPC shows superior thermal stability over OPC; microstructure remains denser post-fire; tensile strength maintained to 300°C.
[15] Shen et al. (2024)	Fire resistance of GHPC prefabricated stairs using ISO-834 protocol	GHPC showed no bursting or spalling and less strength degradation than OPC; exceptional fire performance confirmed.
[28] Mamdouh et al. (2022)	Size and reinforcement ratio effects on ambient-cured geopolymer slag concrete beams	GPC beams showed equivalent flexural performance to OPC; size effect was consistent with OPC concrete design models.

Source / Reference	Study Focus	Key Findings
[32] Thumrongvut et al. (2022)	Comparative study of reinforced OPC and GPC beams using rice husk ash (RHA)	GPC-RHA beams showed competitive performance, load-deflection consistent with OPC, and significant carbon footprint reduction achieved.
[29] Kocaer & Aldemir (2022)	Compressive stress-strain model for flexural capacity estimation in reinforced GPC members	Proposed model achieved high accuracy, superior to OPC-derived models for GPC-specific flexural capacity prediction.
[30] Ozturk & Arslan (2023)	Flexural behavior of GBFS-based geopolymer-reinforced concrete beams	GBFS-GPC beams exhibited comparable flexural performance to OPC; a denser GBFS matrix enhanced moment capacity marginally.

7. Research Gaps and Future Directions

Despite great progress, lack of knowledge in many areas precludes universal implementation of GPCs in structures [5, 10, 20, 21].

7.1 Standardized Design Provisions

There is currently no universally accepted design code dealing with reinforced GPC structural members. This was reported by Bayrak [8] who showed that there is ~82% shear error in the current equations for code design; the same problem was shown by Ansari et al. [10] and Al-Luhybi et al. [21].

7.2 Long-Term Creep and Shrinkage

Long-term experimental data relating to the behavior of GPC beams under sustained load conditions are not abundant. Some preliminary work by Negahban et al. [26] and Seneviratne et al. [46] is available; however, there are no prediction models specific to the behavior of GPCs based on long-term studies. The present AS 3600, CEB-FIP, and ACI 209 methods overestimate the deformation of GPC's time-dependent deformations.

7.3 Fatigue Behavior Under Cyclic Loading

Cyclic properties of fatigue life and stiffness deterioration of GPC beams have not been adequately investigated. As observed from the work done by Mao et al. [18] and Maniarsan et al. [17], investigations have mainly been carried out to study seismic quasi-static cyclic behavior only; high cycle fatigue behavior has not been studied yet.

7.4 Post-Fire Residual Structural Capacity

Whereas fire resistance at the material level is extensively studied [13-15], there are no studies regarding residual capacity of the reinforced GPC beams and GPC frames under real-world fire exposure conditions. The load-bearing capacity, bonding strength, and ductility of GPC members under real fires should be assessed.

7.5 Source Material Variability

The properties of GPC are extremely sensitive to the chemistry and physics of the precursor, which differs greatly from one industry source to another. This fact is acknowledged in the durability tests [16, 24]. It is imperative to have quality assurance systems and characterization methods for the precursors.

7.6 Advanced Numerical Modeling

A general constitutive model capable of predicting GPC material nonlinearity under multiaxial loading conditions, such as those associated with softening, compressive/tensile interactions, and temperature effects, does not currently exist. However, finite-element work has been done for materials [11, 31, 33]; yet no general framework has been developed.

8. Conclusions

Conclusions about the structural behavior of reinforced geopolymer concrete beams have been drawn based on the analysis of scientific publications. Based on the results of the literature review, the following key statements are made:

1. Geopolymer concrete provides a 30–60% reduction in carbon emissions relative to OPC concrete, depending on optimal activator chemistry. Thus, this material can be used as an effective technical solution.
 2. Reinforced GPC beams show equal or higher flexural and shear capacities as compared to OPC beams with similar reinforcement configurations, possessing bond capacity comparable to that of OPC concrete.
 3. Currently available equations for calculating reinforced OPC beams yield prediction errors up to 25% (flexure) and up to 82% (shear) for reinforced GPC beams. It is necessary to develop separate design codes for reinforced GPC.
 4. Fiber reinforcement of GPC (steel, polypropylene, glass, or natural) significantly increases post-cracking ductility, energy absorption capacity, fire resistance, and crack control capacity of GPC. Hybrid and trio fibers show better performance.
 5. Fire resistance of geopolymer concrete is much higher than that of OPC concrete, and the GPC beams do not spall up to 1000-1200°C of fire temperature.
 6. The creep of GPC is considerably lower than OPC concrete and does not coincide with the predictions given by existing codes. Drying shrinkage of GPC depends on activator concentration. It is important to develop one's own time-dependent deformations model for GPC design.
 7. Fire-resistance of geopolymer concrete beams in seismic-resistant joint connections is sufficient to satisfy modern code requirements on energy dissipation and ductility.
 8. Recycling GPC with aggregates from recycled concrete and using cement-free glass-fiber-reinforced systems additionally contribute to sustainable properties of GPC.
- To conclude, geopolymer concrete is a technically well-developed alternative to conventional concrete, and its sustainable use in reinforced concrete structures is expected.

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