



Performance, Mechanisms, and Optimization of Glass Fiber– Reinforced Geopolymer Concrete: A Comprehensive Review

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Abstract- Geopolymer concrete (GPC) — an emerging low-carbon alternative to Portland cement concrete — has attracted considerable attention for its reduced CO₂ footprint and excellent chemical resistance. The growing demand for sustainable construction materials has intensified research into geopolymer concrete as an environmentally friendly alternative to conventional Portland cement concrete. Although geopolymer concrete exhibits excellent compressive strength, chemical resistance, and thermal stability, its inherently brittle nature and limited tensile performance restrict broader structural applications. The incorporation of glass fibers has emerged as an effective strategy to enhance the mechanical performance and durability of geopolymer matrices. This review paper presents a comprehensive synthesis of existing research on glass fiber–reinforced geopolymer concrete (GFRGPC), with a focus on performance characteristics, underlying reinforcement mechanisms, and optimization strategies. The effects of glass fiber on fresh properties, compressive strength, tensile strength, and flexural behavior. Durability aspects such as alkali resistance of glass fibers, chloride penetration, chemical attack, and high-temperature performance are also reviewed, highlighting both the benefits and limitations of glass fiber incorporation in highly alkaline geopolymer environments. The review identifies optimal ranges of fiber content that maximize mechanical performance while minimizing adverse effects on workability and fiber dispersion. Furthermore, current challenges, including long-term durability of glass fibers, lack of standardized mix design procedures, and variability in experimental methodologies, are discussed. Based on the analyzed literature, future research directions are proposed, focusing on long-term performance evaluation, and life-cycle assessment. The findings demonstrate that, with proper optimization, glass fiber–reinforced geopolymer concrete has strong potential as a high-performance and sustainable material for future structural and infrastructure applications.

Keywords: Geopolymer concrete; Glass fibres; Compressive strength; Split tensile strength; Flexural strength; Durability; Sustainable construction; Mechanical performance.

I. INTRODUCTION

The global shift toward sustainable construction materials has spurred the adoption of geopolymers as low-carbon binders. Unlike OPC, geopolymer binders rely on polymerization reactions between aluminosilicate precursors and alkaline activators, producing a rigid, three dimensional network of Si–O–Al bonds (Siddika et al., 2021). However, GPC's brittle failure behavior limits its ductility and post-cracking load capacity (Wang et al., 2023). The inclusion of glass fibers (GF) in geopolymer matrices provides a reinforcing mechanism through crack bridging, energy absorption, and improved tensile behavior (Hakeem et al., 2024).

Recent work by Li et al. (2025, Elsevier) demonstrated that hybrid reinforcement with GF and polypropylene fibers improved fracture toughness and energy absorption capacity of alkali-activated



composites derived from industrial waste tailings. Similarly, Raza et al. (2025, Taylor & Francis) observed enhanced durability and reactivity of GFRGPC incorporating calcined bauxite residue and blast furnace slag, emphasizing synergy between precursor composition and fiber reinforcement.

II. FRESH AND RHEOLOGICAL PROPERTIES

Workability

Workability is significantly influenced by fiber content, length, and surface roughness. Glass fibers reduce slump flow due to increased interparticle friction (Benfratello et al., 2025). Optimum fiber content ranges between 0.5%–1.25%, balancing workability and reinforcement benefits (Samal & Blanco, 2021). Beyond 1.5%, fiber agglomeration increases air voids and reduces homogeneity (Sharma et al., 2024). The workability of geopolymer concrete is governed primarily by the activator concentration, precursor fineness, and fiber content.

According to Wang et al. (2023, Polymers), adding 0.5–1.0% glass fiber volume reduces the slump flow by 10–20% compared to control mixes. This is attributed to fiber interlocking and clustering, which increases internal friction. The high specific surface area of fibers that absorbs part of the free water or activator solution. Benfratello et al. (2025, Engineering) found that increasing glass fiber content beyond 1.5% leads to “balling” or non-uniform dispersion, significantly reducing workability and causing entrapped air voids. Optimal fiber content was identified at 0.75–1.0% by volume for maintaining workable consistency without segregation.

Setting and Flowability

$\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio affects the polymerization rate. Ratios of 2.0–2.5 result in stable rheology and uniform fiber dispersion (Rupwate & Kulkarni, 2025). Heat-curing accelerates setting by 20–30%, improving early-age strength, but may cause differential shrinkage if fiber dispersion is uneven. Li et al. (2025, Theoretical and Applied Fracture Mechanics) observed that the addition of glass fibers accelerates the setting reaction by ~15% due to the nucleation effect on geopolymeric gels. The fibers act as heterogeneous nucleation sites for aluminosilicate polymerization, resulting in quicker network formation.

Zhang et al. (2024, Construction and Building Materials) noted that heat-cured specimens (70°C for 24 hours) with 1% glass fiber showed 20% higher early strength but required longer mixing times to achieve uniform dispersion.

III. MECHANICAL PERFORMANCE

Compressive

Compressive strength gains of 15–25% are typical with 1% glass fiber incorporation (Liu et al., 2024; Wang et al., 2023). Zhang et al. (2024) found that fiber–matrix bonding leads to improved microcrack control, confirmed through SEM imagery showing fiber pull-out and dense interfacial zones. Compressive strength of GFRGPC typically improves by 10–25% at optimal fiber dosages (0.5–1.25%). Wang et al. (2023) reported a peak strength of 63 MPa for fly-ash-based GPC with 1% GF, compared to 52 MPa for unreinforced GPC. Raza et al. (2025, Sustainable Cement-Based Materials) found a 22% increase in compressive strength due to better stress transfer and microcrack arrest. However, beyond 1.5% fiber content, excessive void formation and poor compaction reduce strength by up to 10% (Benfratello et al., 2025). Fibers bridge internal microcracks, delay crack coalescence, and redistribute internal stresses. The interfacial transition zone (ITZ) becomes denser



due to enhanced geopolymer gel formation around the fibers (Liu et al., 2024, Arabian Journal for Science and Engineering).

Flexural and Tensile Strength

Flexural strength: Flexural strength improvements of 35–50% have been recorded due to fiber bridging (Blazy et al., 2022). Li et al. (2025) reported that the synergistic effect of GF and PPF increased fracture energy by 60%, attributed to better energy dissipation across the fiber–matrix boundary.

Glass fiber incorporation markedly improves the tensile and flexural strength of geopolymer concrete due to effective crack-bridging and pull-out mechanisms.

0.5% 7.2 +22% Wang et al., 2023

1.0% 8.4 +38% Li et al., 2025

1.5% 8.1 +34% Zhang et al., 2024

Tensile Behaviour: The split tensile strength increased by 20–30% at 1% fiber content (Hakeem et al., 2024, Heliyon). The improvement is attributed to load transfer via fibers across the crack plane and a higher energy absorption during failure.

Fracture Energy and Ductility

The energy absorption mechanism involves three phases: microcrack initiation, fiber pull-out, and matrix rupture (Raza et al., 2025). Optimal performance occurs at 1.0% GF volume fraction, where fibers provide sufficient crack bridging without compromising matrix cohesion. The fracture energy of GFRGPC increased from 65 to 110 J/m² when fiber volume rose from 0% to 1%, indicating improved toughness (Li et al., 2025). Raza et al. (2025) reported similar trends, where hybrid glass–polypropylene reinforcement achieved 65% higher fracture energy.

Contrary to compressive strength, the elastic modulus exhibits marginal variation ($\pm 5\%$) with fiber addition. Glass fibers mainly influence the non-linear phase of deformation, improving toughness rather than stiffness (Blazy et al., 2022, Materials).

IV. DURABILITY AND ENVIRONMENTAL PERFORMANCE

Alkali Resistance

The high alkalinity of geopolymer matrices can attack glass fibers, causing surface leaching and strength loss. However, E-glass fibers treated with silane coupling agents exhibit improved chemical stability (Shafei et al., 2021). Surface coatings such as zirconia-based layers mitigate alkali corrosion (Siddika et al., 2021).

Chloride Penetration and Chemical Resistance

Hakeem et al. (2024) demonstrated a 45% reduction in chloride permeability in GFRGPC compared to unreinforced GPC. The dense microstructure and crack arrest mechanisms of fibers inhibit ion transport, improving durability in marine environments.

High-Temperature Performance

GFRGPC retains 70–80% of compressive strength up to 800°C (Zhang et al., 2024). The absence of calcium hydroxide decomposition in geopolymer gels prevents catastrophic thermal degradation observed in OPC-based systems.



V. REINFORCEMENT MECHANISMS

Glass fibers enhance geopolymer concrete through:

1. Crack Bridging: Arrests microcracks and delays macrocrack propagation (Wang et al., 2023).
2. Fiber Pull-out: Absorbs fracture energy, increasing toughness (Li et al., 2025).
3. Stress Redistribution: Reduces localized stress concentrations (Benfratello et al., 2025).
4. Matrix Densification: Fibers act as nucleation sites enhancing geopolymeric gel bonding (Liu et al., 2024).

Microscopic studies reveal chemical bonding between silicate phases of the matrix and the fiber surface, improving load transfer (Hakeem et al., 2024).

V. OPTIMIZATION STRATEGIES

Fiber Content and Geometry

A volume fraction of 0.75–1.25% with aspect ratios of 600–900 provides optimal reinforcement (Blazy et al., 2022). Excess fiber (>1.5%) leads to void formation and reduced strength.

Activator Composition

$\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios between 2.0–2.5 optimize geopolymerization kinetics (Rupwate & Kulkarni, 2025). Hybrid activators (NaOH + KOH) further enhance silica dissolution and bond strength (Raza et al., 2025).

Curing Method

Thermal curing at 70°C for 24 hours yields high early strength but increases energy consumption. Hybrid curing (ambient + low heat) provides eco-efficient alternatives (Siddika et al., 2021).

VI. CHALLENGES AND FUTURE

Perspectives

Key research gaps include:

- Long-term Alkali Resistance: Need for 10+ year performance data.
- Standardized Mix Design: Absence of unified procedures for GFRGPC mix proportioning.
- Hybrid Reinforcement: Combining GF with basalt or carbon fibers for synergistic strength.
- Machine Learning Optimization: Predictive modeling of GFRGPC mechanical and durability behavior (Hakeem et al., 2024).
- Lifecycle Assessment: Quantifying embodied energy and CO_2 reductions for sustainable certification (Raza et al., 2025).

Microstructural Analysis and Fiber–Matrix Interaction

Microscale analysis via SEM, XRD, and FTIR provides key insights into how glass fibers interact with geopolymer gels. Liu et al. (2024) observed a dense calcium–silicate–hydrate (C–S–H) and sodium–aluminosilicate–hydrate (N–A–S–H) gel layer at the fiber–matrix interface. Wang et al. (2023) confirmed that this layer increases interfacial shear strength, reducing fiber pull-out at early ages. Pan et al. (2023, Journal of Building Engineering) found that E-glass fiber treatment with silane enhanced the geopolymerization interface by promoting covalent bonding between silanol groups and aluminosilicate networks, improving flexural performance by 42%.



VIII. Thermal and Fire Resistance Mechanisms

Hussin et al. (2023, Fire and Materials) demonstrated that GFRGPC retains over 80% compressive strength at 600°C due to glass fiber's high softening point and its ability to prevent pore pressure buildup. Zhang et al. (2024) confirmed that at elevated temperatures, glass fibers promote controlled microcracking, dissipating thermal stresses that would otherwise cause explosive spalling. Furthermore, Wang & Qu (2023, Construction and Building Materials) showed that glass fibers delay heat penetration, reducing thermal conductivity by 25% compared to plain GPC.

IX. LONG-TERM DURABILITY AND ALKALI ATTACK

Glass fibers face degradation in highly alkaline media, forming silica leaching zones. Shi et al. (2024, Cement and Concrete Composites) evaluated surface coated fibers using zirconia and found that coated glass fibers retained 95% of their tensile capacity after 90 days of immersion in 10 M NaOH. Raza et al. (2025) validated that hybrid blends with blast furnace slag + calcined bauxite residue reduced pore alkalinity, improving glass fiber stability and reducing weight loss by 30% over 180 days.

Sustainability and Life Cycle Assessment

Compared with OPC concrete, geopolymer binders reduce CO₂ emissions by 50–80% (Siddika et al., 2021; Benfratello et al., 2025). When reinforced with glass fibers, embodied energy rises marginally (~5%), but service life extension offsets this environmental cost.

Rahman et al. (2024, Journal of Cleaner Production) reported that GFRGPC structures achieve a 40% reduction in lifecycle cost due to reduced maintenance and superior durability.

Emerging AI-driven optimization tools (e.g., genetic algorithms and neural networks) are being employed to model fiber dispersion and optimize activator ratios (Hakeem et al., 2024).

Future Directions with Smart Composites

Recent works explore hybridization of glass fibers with:

- Basalt fibers - to enhance alkali resistance (Pan et al., 2023).
- Polypropylene fibers - to improve post-crack ductility (Li et al., 2025).
- Carbon fibers - to achieve self-sensing electrical conductivity for smart infrastructure applications (Chen et al., 2024, Sensors and Actuators A).

Such multi-fiber-geopolymer systems exhibit multifunctional properties, including crack self-monitoring and improved seismic resilience, aligning with the global "smart materials" initiative.

X. CONCLUSIONS

Glass fiber-reinforced geopolymer concrete (GFRGPC) exhibits outstanding mechanical and durability properties, bridging the performance gap between brittle geopolymers and ductile composites. Optimization of fiber content, curing regime, and activator composition is essential for achieving balanced performance. Future advancements in surface-treated fibers, hybrid systems, and digital design optimization will enable large-scale structural adoption of GFRGPC as a sustainable construction material.



REFERENCES

1. Benfratello, S., Palizzolo, L., Sanfilippo, C., &Valenza, A. (2025). The structural performance of fiber reinforced geopolymers: A review.Engineering, 6(7), 159.DOI: 10.3390/eng6070159
2. Blazy, J., Blazy, R., &Drobiec, Ł. (2022). Glass fiber reinforced concrete as a durable material for smart cities: A review.Materials, 15(8), 2754.DOI: 10.3390/ma15082754
3. Chen, Z., Yue, H., & Zhao, P. (2024). Self-sensing geopolymer composites with carbon–glass hybrid fibers.Sensors and Actuators A: Physical, 371, 115632.DOI: 10.1016/j.sna.2024.115632
4. Hakeem, I.Y., Zaid, O., Arbili, M.M., Alyami, M., &Alhamami, A. (2024). Durability and microstructure behavior of ultra-high-performance geopolymer concrete.Heliyon, 10(3), e27294.DOI: 10.1016/j.heliyon.2024.e27294
5. Hussin, M.W., Rahman, M.A., & Ismail, M. (2023). Fire resistance behavior of glass fiber reinforced geopolymer composites.Fire and Materials, Wiley.DOI: 10.1002/fam.3096
7. Li, J., Zhang, S., Jin, H., Chen, M., Liu, X., & Zhu, X. (2025). Flexural and fracture properties of fiber reinforced alkali activated composites derived from waste tailings.Theoretical and Applied Fracture Mechanics, Elsevier.DOI: 10.1016/j.tafmec.2025.103991
8. Liu, X., Shi, C., Yao, Y., Wei, Y., & Huang, C. (2024). Strengthening mechanism of geopolymer lightweight cellular concrete reinforced with glass fibers.Arabian Journal for Science and Engineering, Springer.DOI: 10.1007/s13369-024-08517-9
9. Pan, Y., Wang, J., &Qu, C. (2023). Silane-modified glass fiber reinforcement in geopolymer concrete for improved durability.Journal of Building Engineering, 68, 107548.DOI: 10.1016/j.jobe.2023.107548
11. Rahman, A., Karim, M.R., & Chowdhury, S. (2024). Life cycle assessment of geopolymer concretes reinforced with recycled glass fibers.Journal of Cleaner Production, 438, 140567.DOI: 10.1016/j.jclepro.2024.140567
13. Raza, A., Elhag, A.B., &Ghazouani, N. (2025). Enhanced performance of fiber-reinforced engineered geopolymer composites incorporating blast furnace slag and calcined bauxite residue.Journal of Sustainable Cement-Based Materials, Taylor & Francis.DOI: 10.1080/21650373.2025.2471835
15. Rupwate, A.B., & Kulkarni, S.A. (2025). Geopolymer Concrete Optimization: A Critical Review.Journal of Mines, Metals & Fuels.DOI: 10.18311/jmmf/2025/5638
16. Shi, C., Liu, X., & Yao, Y. (2024). Chemical stability of coated glass fibers in high-alkaline geopolymer matrices.Cement and Concrete Composites, 146, 106960.DOI: 10.1016/j.cemconcomp.2023.106960
17. Siddika, A., Hajimohammadi, A., Mamun, M.A.A., &Alyousef, R. (2021). Waste glass in cement and geopolymer concretes: A review.Polymers, 13(13), 2071.DOI: 10.3390/polym13132071
18. Wang, T., Fan, X., Gao, C., Qu, C., Liu, J., & Yu, G. (2023). The influence of fiber on the mechanical properties of geopolymer concrete: A review.Polymers, 15(4), 827.DOI: 10.3390/polym15040827
19. Zhang, M., Yue, F., & Chen, B. (2024). Optimizing toughness in one part geopolymers via fiber reinforcement.Construction and Building Materials, Elsevier, 395, 136587.DOI: 10.1016/j.conbuildmat.2024.136587
20. 10.1016/j.conbuildmat.2024.136587



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