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A Review on Performance and Sustainable Geopolymer Concrete Modified with Waste Glass Powder

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Abstract

The growing demand for low-carbon construction materials and effective utilization of industrial by-products has intensified research interest in geopolymer concrete as a sustainable alternative to ordinary Portland cement. Among various precursors, fly ash–based geopolymer systems have demonstrated significant potential; however, their performance is strongly influenced by the variability in fly ash availability, chemical composition, and reactivity. To overcome these limitations, the incorporation of supplementary aluminosilicate sources has become increasingly important. In this context, waste glass powder, characterized by its high amorphous silica content, has emerged as a promising modifier that not only enhances geopolymer performance but also contributes to sustainable solid waste management. This review critically examines recent advances in fly ash-based geopolymer concrete modified with waste glass powder, with particular emphasis on geopolymerization mechanisms, material reactivity, and performance enhancement strategies. Findings from the literature indicate that partial replacement of fly ash with waste glass powder commonly in the range of 20 to 30% promotes geopolymer gel development, refines pore structure, and enhances

1. Introduction

Concrete stands as a cornerstone of global infrastructure, traditionally relying on Ordinary Portland Cement (OPC) as its fundamental binder. The dual pressures of rapid industrialization and accelerating urbanization have necessitated massive infrastructural expansion, driving a continuous surge in concrete consumption [1]. This expansion comes at a significant environmental cost; construction activities frequently generate immense volumes of waste, much of which is relegated to open landfills, resulting in pervasive environmental degradation [2]. The ecological impact is compounded by high pollution levels in the vicinity of production and disposal sites [3]. In light of the dwindling availability of natural resources and increasing environmental scrutiny, the construction industry is transitioning toward more sustainable paradigms. This shift is characterized by the integration of circular economy principles and advanced waste management strategies, where industrial by-products are repurposed as viable substitutes for conventional raw materials [4]. A transformative solution in this context is Geopolymer Concrete (GPC), which facilitates the complete replacement of traditional cement. The adoption of geopolymer binders provides a twofold advantage: the efficient diversion of industrial waste from landfills and a substantial reduction in the carbon footprint associated with cement production [5]. Significant academic attention has recently been directed toward optimizing the mechanical characteristics, durability, and functional versatility of geopolymer composites. Diverse aluminosilicate precursors, including fly ash, red mud, dolomite, mine tailings, and lateritic clays, have been rigorously evaluated for their potential to enhance these systems [6-8]. Structural performance has been bolstered through the inclusion of various reinforcements, ranging from synthetic steel and polymer fibers to basalt and natural alternatives like flax, hemp, cotton, and corn stalks [9-14]. These reinforcements are instrumental in refining the toughness and long-term resilience of geopolymer matrices [15]. Ultimately, the utilization of these alternative materials not only advances the sustainability of the construction sector but also introduces superior material properties that broaden the application scope of geopolymer technology [16].

Keywords: Carbon Emissions ,Fly ash, Geopolymer , Glass powder, Sustainability

2. Geopolymer Synthesis: Methodologies and Technological Frameworks

2.1. Fundamental Components and Synthesis

As detailed by Kadhim et al. (2024) [18], the standard production of geopolymers necessitates two primary constituents: a solid aluminosilicate precursor (the Al-Si source) and a liquid alkaline activator, typically composed of alkali hydroxides or silicates based on sodium (Na), potassium (K), or calcium (Ca).1 The specific chemical profile of the source materials is a critical determinant of the final concrete performance. Furthermore, the efficiency of the geopolymerization process is dictated by several physicochemical factors, including the geological origin of the precursors, their calcium and amorphous content, the concentration of alkali metals, and the specific surface area or particle size of the raw materials [19].

2.2 Mechanism of Geopolymerizatio*n*

The development of GPC is rooted in the intricate chemistry of geopolymerization. This process is initiated when aluminosilicate precursors react with highly alkaline solutions, such as sodium or potassium hydroxide mixed with silicates. These activators catalyze the dissolution of the raw materials, triggering a sequence of chemical transformations that culminate in a stable, three-dimensional polymeric network. According to Provis and Bernal (2014), this resulting network is primarily amorphous in nature [20]. It is this unique microstructural arrangement that provides GPC with its enhanced mechanical strength and long-term durability, distinguishing it from the crystalline hydrated phases found in traditional Portland cement systems. The procedural steps involved in the industrial manufacturing of GPC emphasize the precision required in mixing and curing to achieve these optimal properties. The chemical transformation of aluminosilicate precursors into a stable geopolymer binder is a complex, multi-stage process initiated by alkaline activation. Although the specific polymerization kinetics may vary depending on the chemical composition of the raw materials, the fundamental mechanism remains essentially consistent [21]. This process generally proceeds through four integrated stages that often occur simultaneously:

- Dissolution Phase: Upon contact with the high-pH alkaline activator, the covalent bonds within the silicon oxide (SiO_2) and aluminum oxide (Al_2O_3) phases of the precursor are severed. This results in the release of silicate and aluminate monomers into the aqueous phase [21].
- Diffusion and Equilibrium: These liberated monomers migrate away from the solid particle surfaces into the surrounding medium. Driven by the principles of chemical equilibrium, this diffusion reduces the ionic concentration at the interface, thereby promoting further dissolution of the aluminosilicate source [21].
- Polycondensation (Gelation): The concentrated monomers undergo a polymerization reaction, where silicate and aluminate tetrahedra interconnect to form a complex, amorphous -Si-O-Al-O- network or, in specific conditions, microcrystalline zeolite structures [21].
- Dehydration and Hardening: As the reaction progresses, a dehydration phase occurs where excess water is expelled from the system. This leads to the final setting and development of a hardened geopolymer matrix characterized by high structural density and significant mechanical strength [21].

2.3 Chemical Activation and Material Reactivity

Unlike conventional concrete which depends on hydration, GPC utilizes a mechanism where water is not a primary binding reagent. According to Al-Shathr et al. (2015) [22], the binding matrix is instead developed through the chemical interaction between an alkaline medium and the aluminosilicate (Si-Al) minerals present in the precursors. This polymerization is characterized by an exceptionally swift chemical reaction triggered by the high-pH environment. The efficiency of this process and the resulting structural performance are dictated by several critical parameters:

Precursor Composition: The mineralogical makeup of the raw materials determines the chemical equilibrium of the system.

Activator Concentration: The molarity of the alkaline solution governs the rate of ionic dissolution.

Curing Regimes: Thermal and temporal conditions influence the kinetics of the hardening phase.

Alkali-to-Binder Ratio: This ratio is fundamental to the workability and densification of the matrix.

As noted by Provis and Bernal (2014), the selection of the precursor is perhaps the most influential factor in determining geopolymer reactivity [20]. Materials characterized by high amorphous (non-crystalline) content, such as fly ash or metakaolin, are preferred because they demonstrate superior solubility in alkaline activators. This increased solubility facilitates a more robust reaction, leading to enhanced mechanical and durability properties in the final geopolymer product. To professionally convert this section into a review paper while eliminating plagiarism and maintaining academic rigor, I have rephrased the technical content and organized it into thematic sub-sections. happens when the surface chemistry and mineral makeup of a rock are unpredictable [6].

3. Waste Glass Powder as a Sustainable Geopolymer Precursor

The escalating global consumption of glass has resulted in a substantial increase in non-biodegradable waste, the majority of which is relegated to landfills. This disposal method is increasingly viewed as unsustainable due to its long-term environmental footprint and potential hazards to ecosystems [23]. Given that glass occupies significant landfill volume without decomposing, recycling waste glass into construction materials has emerged as a critical strategy for urban waste management [24].

3.1. Chemical Reactivity and Particle Size Effects

WGP is frequently utilized as a reactive additive in GPC. Its efficacy is highly dependent on fineness; research indicates that a particle size of approximately 75 µm yields the most favorable results [25]. Fine-grinding WGP enhances its pozzolanic activity, as smaller particles provide a larger surface area for chemical interaction [26]. The high amorphous silica content in WGP acts as a catalyst, accelerating the geopolymerization process and fostering the rapid development of silico-aluminate gels, which are essential for structural hardening [27].

3.2. Workability and Microstructural Characteristics

The rheological properties of GPC modified with WGP are influenced by the powder's geometry, surface texture, and the specific geopolymer system employed [28]. Generally, increasing WGP substitution levels leads to reduced fluidity; this is attributed to the angular and irregular shape of glass particles compared to the spherical morphology of fly ash (FA) [25]. Microstructural evaluations via Scanning Electron Microscopy (SEM) reveal that WGP particles possess sharp, prismatic edges and smooth surfaces, contributing to a high-density matrix [29]. Although minor microcracking may occur in some regions, WGP typically exhibits excellent interfacial bonding with FA, resulting in a cohesive and stable microstructure [29].

3.3. Mechanical Strength and Durability Enhancements

The inclusion of WGP significantly bolsters the mechanical performance of GPC. Specimens cured under ambient conditions have demonstrated marked improvements in compressive and flexural strengths when WGP content is increased up to 20% [30]. This strength gain is driven by the synergistic effect of WGP's pozzolanic reactivity and its physical role as a micro-filler, which densifies the matrix and creates a more homogeneous gel network [31]. Optimizing the WGP content specifically at a 20% replacement level results in peak compressive and bonding strengths [24]. The durability of the composite is enhanced as the fine powder reduces porosity. This structural densification significantly lowers the rate of water absorption and chemical ingress compared to traditional OPC concrete [31]. The inherently impermeable nature of glass further contributes to this resistance, making WGP-based GPC highly resilient against chemical attack [32].

3.4. Thermal Performance and Comparative Analysis

Beyond mechanical strength, WGP contributes to the fire resistance of GPC, an essential factor for structural safety during high-temperature exposure [33]. Recent academic work has consolidated these findings, evaluating variables such as activator molarity, alkali-to-binder (AL/B) ratios, and curing regimes to identify optimal mix designs for industrial application.

4. Comparative Analysis: Geopolymer Concrete vs. Conventional Cement Systems

The global construction industry is increasingly mandated to meet stringent sustainability requirements. The significant carbon footprint associated with OPC production, coupled with the escalating challenges of global warming, has led to a critical re-evaluation of its widespread application [34]. In this context, GPC has gained substantial traction within the scientific and engineering communities due to its environmentally superior profile and robust performance characteristics.

4.1 Environmental and Ecological Advantages of Geopolymer Systems

4.1.1 Mitigation of Greenhouse Gas Emissions

The global construction sector's reliance on OPC presents a significant sustainability challenge, with cement manufacturing accounting for approximately 25% to 35% of industrial CO_2 emissions [35]. Current projections suggest that global cement production, which stood at 2.55 billion tons in 2006, could escalate to between 3.7 and 4.4 billion tons by 2050 [1]. In response to the intensifying climate crisis, researchers are prioritizing the development of "green" binders that facilitate a carbon-neutral construction cycle. Geopolymer technology offers a transformative advantage in this area, potentially reducing CO_2 emissions by 80% to 90% compared to traditional OPC, as the chemical synthesis does not inherently release carbon during the curing phase [16, 36, 37]

4.1.2 Industrial and Local Waste Valorization

GPC aligns with the circular economy by repurposing industrial, agricultural, and geological waste as primary binders [19, 38]. This approach not only diverts hazardous waste from landfills but also conserves natural virgin resources [36]. Common precursors include industrial by-products like Ground Granulated Blast Furnace Slag (GGBFS) and FA, as well as agricultural residues such as rice husk ash and sugarcane residue ash [21, 39]. The integration of demolition waste including recycled glass, ceramics, and clay bricks highlights the versatility of GPC in transforming low-value waste into high-performance aluminosilicate raw materials [40].

4.1.3. Energy Efficiency and Carbon Footprint Reduction

Traditional cement production is an energy-intensive process, requiring approximately 4.7 million BTUs (roughly 400 pounds of coal) to produce a single ton, which in turn generates nearly an equivalent ton of CO_2 [41]. As noted by Abbas et al. (2022), cement emissions are both direct stemming from the chemical calcination of limestone (which contributes 50% of the total emissions) and indirect resulting from the combustion of fossil fuels to heat kilns [1]. Geopolymers entirely circumvent the calcination process, significantly lowering the embodied energy of the material while providing structural performance and durability that often exceed those of conventional concrete [42, 43].

4.1.4. Alignment with Green Construction and Economic Viability

To meet modern green construction goals, innovative strategies such as the use of Supplementary Cementitious Materials (SCMs) like silica fume, metakaolin, and waste glass powder are being implemented to reduce the ecological impact of infrastructure [16,44]. Beyond environmental resilience, geopolymers exhibit superior fire resistance and lower permeability, enhancing the lifecycle of structural assets [45,46]. From an economic standpoint, transitioning from OPC to GPC is highly favorable; studies indicate that the utilization of local waste as binders can result in cost savings ranging from 12% to 30% [47,48]. Consequently, geopolymer technology represents a dual-benefit strategy that optimizes both economic expenditure and environmental stewardship. To ensure your review paper maintains high academic standards and avoids plagiarism, I have rephrased this section on Mechanical Performance Comparison. I have organized the technical details into structured sub-sections and integrated all your original citations.

4.2 Mechanical Performance and Comparative Analysis

The mechanical integrity of GPC is a fundamental criterion for its adoption in the construction sector. For geopolymers to serve as viable structural materials, they must demonstrate mechanical and volumetric stability, with a particular emphasis on consistent compressive strength development [49]. Extensive research has shown that GPC derived from low-calcium (Class F) FA possesses mechanical properties that are either comparable or superior to those of conventional OPC concrete (Hassan & Arif, 2019) [50].

4.2.1. Compressive Strength Development

Compressive strength is the most vital mechanical parameter in concrete design and is influenced by several variables, including the aluminosilicate source type, the chemical composition of the alkali activator, and the curing regime [55, 56]. Key determinants for achieving high strength include the Si/Al ratio, curing duration, temperature, and the presence of calcium or other impurities [49]. Specifically, an increase in aluminum content relative to silicon often enhances strength due to the accelerated formation of aluminosilicate networks [57]. A denser, less porous microstructure yields a more compact matrix, which correlates with higher compressive strength and reduced permeability [58]. The molarity of the sodium hydroxide (NaOH) solution is also a critical factor. Studies by Chami et al. (2022) indicate that higher molarity (ranging from 8M to 16M) promotes ionic dissolution and speeds up the geopolymerization reaction, leading to increased strength [59]. Abdullah et al. (2021) observed that while strength increases as molarity rises from 6M to 12M, a subsequent decline may occur beyond this threshold due to excessive alkalinity [60].

4.2.2. Flexural Strength and Fiber Reinforcement

Fly ash-based GPC frequently exhibits higher flexural strength than OPC of similar compressive grades, a phenomenon attributed to its inherently denser microstructure [61]. Research by Bellum et al. (2019) demonstrated that increasing NaOH concentration from 8M to 14M can enhance flexural strength by as much as 42.5%. Optimal performance is typically achieved through a balance of chemical activation (e.g., 14M NaOH) and thermal curing (e.g., 60°C for 24 hours) [33].

Partial replacement of FA with WGP (up to 30%) triggers a pozzolanic reaction that generates additional geopolymer gel, significantly boosting flexural resilience [33].

4.2.3. Modulus of Elasticity

The modulus of elasticity is critical for evaluating structural stability and a material's resistance to stress-induced deformation [62]. While the modulus for OPC concrete typically ranges between 30 and 34 GPa, GPC of similar strength often falls between 10 and 18 GPa, though low-calcium FA-based variants can reach 23 to 30 GPa [63]. Similar to compressive strength, the elastic modulus is positively influenced by heat treatment and higher compressive grades [50,61] . Conversely, the excessive use of chemical admixtures like plasticizers may reduce the modulus by increasing the volume of voids within the structure [64].

4.2.4. Interfacial Bond Strength

The efficacy of reinforced concrete depends on the bond strength between the matrix and the steel reinforcement [65]. GPC has been found to exhibit superior bonding behavior compared to OPC, with pullout tests showing up to 21% higher bond strength in FA-based GPC [66]. This superior performance is attributed to the excellent adhesion and mechanical interlocking between the GPC matrix and the ribs of deformed steel bars [66].

4.2.5. long – term Strength Gain

The rate of geopolymerization is highly sensitive to temperature. Elevated curing temperatures accelerate the reaction, facilitating the rapid development of early-age strength [67]. In contrast, ambient-temperature curing can be slow and often impractical for industrial needs, as low temperatures decelerate the solubility of aluminosilicate compounds [50,51]. To achieve adequate early-age performance, curing temperatures between 40°C and 75°C are typically recommended [52, 53]. Additionally, employing a higher molarity of NaOH has been shown to significantly boost the rate of early-age strength gain (Ryu et al., 2013) [54].

4.3 Durability and Transport Properties

Durability represents the capacity of concrete to maintain its structural integrity and engineering performance throughout its design life, despite exposure to deleterious conditions such as weathering, corrosion, and chemical degradation [55]. In practical structural applications, the long-term resilience of a binder is dictated by its transport properties specifically ion diffusivity and permeability which are fundamentally shaped by the microstructural development during the hardening stage. Central to this development is the material's porosity and pore size distribution [68]. Long-term assessments conducted by Wallah and Rangan (2010) have confirmed that FA-based GPC demonstrates exceptional durability compared to traditional systems [48].

4.3.1. Resistance to Sulfate Attack

Sulfate-induced degradation remains a critical concern for infrastructural serviceability, occurring either through internal sources (binder or aggregate contaminants) or external environmental exposure. Such attacks typically manifest as expansion, cracking, spalling, and a loss of structural load-bearing capacity [69]. GPC has emerged as a superior alternative to OPC due to its inherently high resistance to these mechanisms [70]. Experimental evaluations involving magnesium sulfate ($MgSO_4$) and sodium sulfate (Na_2SO_4) have highlighted the distinct behaviors of geopolymer matrices. For instance, Ismail and Bernal (2013) observed that while Na_2SO_4 primarily affects the grain surface, $MgSO_4$ exposure is more severe, leading to both grain degradation and the dissolution of the aluminosilicate framework [71]. Despite these challenges, GPC consistently outperforms OPC; while OPC can suffer compressive strength losses between 9% and 38% under sulfate exposure, FA-based GPC typically exhibits significantly lower loss rates, often ranging from 2% to 29% [72].

4.3.2. Acid Resistance and Chemical Stability

Acid attack is a primary driver of material deterioration, significantly increasing repair and maintenance costs for global infrastructure [73]. GPC is highly regarded for its chemical stability in acidic environments [74]. Research comparing FA-based GPC to OPC under sulfuric acid exposure (5% concentration) demonstrated that geopolymers maintain superior structural integrity even after five months of immersion [75]. Extended longitudinal studies further support these findings. Ariffin et al. (2013) reported that GPC specimens submerged in a 2% sulfuric acid solution for 18 months showed performance vastly superior to OPC [76]. After 24 weeks of sulfuric acid exposure, GPC samples have been found to retain between 29.4% and 54.8% of their original compressive strength. Resistance is most pronounced in samples with low porosity and water absorption, as higher sorptivity facilitates deeper acid penetration and subsequent strength loss [70]. The acid resistance of geopolymer binders is significantly higher than that of OPC, making them ideal for specialized industrial and wastewater applications where chemical durability is paramount [73].

4.4. Performance at Elevated Temperatures

The structural resilience of concrete under thermal distress, such as fire, is a critical safety consideration. The response of concrete to extreme heat is primarily governed by its constituent materials, particularly the choice of aggregates and the chemical nature of the binder [77]. For GPC to be considered a viable alternative to OPC, it must demonstrate the capacity to withstand the deleterious effects of high temperatures without catastrophic failure.

4.4.1. Thermal Stability and Compositional Influence

Unlike OPC concrete, which undergoes significant dehydration and structural disintegration when heated, GPC maintains a higher level of structural integrity. Its solid, three-dimensional inorganic matrix can remain stable at temperatures reaching between 1000°C and 1200°C [78]. This fire resistance is largely influenced by several factors: the mineralogical composition of fine and coarse aggregates, the calcium content of the precursors, and the molarity of the alkaline activator [13]. The superior performance of GPC at extreme temperatures often exceeding 800°C is attributed to its interconnected silicate-aluminate network, which experiences less dehydration compared to the calcium-silicate-hydrate (C-S-H) gels in OPC [24]. Jiang et al. (2020) observed that the bond strength between steel reinforcement and the FA-based GPC matrix remains significantly more robust than in OPC systems during high-temperature exposure [24].

4.4.2. Mechanical Transitions Under Heat Exposure

The compressive strength of GPC undergoes distinct phases as temperatures escalate:

Initial Strength Gain (100°C – 200°C): Moderate heating can actually improve compressive strength. Tayeh et al. (2021) noted improvements between 100°C and 150°C [13], while Kishanrao & Narasimhan (2012) reported a residual strength increase of up to 10% at 200°C, likely due to further promotion of geopolymerization [79].

Moderate Degradation (400°C – 600°C): A significant decline in strength begins above 150°C. Residual strength typically drops to approximately 71% at 400°C and falls sharply to about 30% of its initial value as it nears 600°C [79].

Severe Deterioration (800°C– 000°C): The most critical strength loss occurs at these extremes. By 800°C, the rate of loss accelerates significantly [13], eventually leaving the material with only 9% to 10% of its original compressive capacity as temperatures approach 1000°C [79].

4.5 Resistance to Chloride Ingress and Corrosion

The intrusion of chloride ions is the leading catalyst for the corrosion of reinforcing steel and the subsequent degradation of structural integrity. Maintaining concrete durability is particularly challenging in marine and industrial zones, where structures are perpetually subjected to aggressive chemical exposure [80].

4.5.1. Chloride Transport Mechanisms

In marine settings, chloride ions penetrate the concrete matrix via three primary pathways: capillary absorption, hydrostatic pressure, and diffusion [81]. While ions can enter through large voids and microcracks, diffusion through the interconnected capillary pores of the paste remains the most dominant transport mechanism. This process is driven by a concentration gradient, where high external chloride levels force ions to migrate toward the embedded steel reinforcement [82]. Consequently, the rate of chloride ingress is fundamentally governed by the concrete's internal porosity.

4.5.2. Passivation and Electrochemical Stability

Reinforcing steel within concrete is typically protected by a thin oxide layer, known as the passivation layer. Corrosion initiates when chloride ions penetrate this barrier and destabilize it.3 Research suggests that FA-based GPC effectively passivates steel reinforcement, with the stability of this protective layer being highly dependent on the concentration of the alkaline activator used [83]. Several factors contribute to the superior corrosion resistance of GPC compared to OPC:

- Alkalinity and pH: The high pH and alkalinity inherent in FA-based GPC provide a robust chemical environment that maintains the passivity of the steel bars [80].
- NaOH Molarity: Increasing the molarity of sodium hydroxide (NaOH) further bolsters the alkalinity of the concrete, thereby enhancing the electrochemical resistance of the reinforcement [64].
- Matrix Density: GPC often exhibits a greater structural density than OPC, which acts as a physical barrier to the migration of deleterious ions (Emad et al., 2024).

4.5.3. Carbonation and Pore Structure

Carbonation represents another significant threat to reinforcement longevity. This occurs when CO2 and oxygen permeate the concrete pores, lowering the pH and potentially triggering corrosion.7 The depth of carbonation is highly sensitive to environmental humidity and the concrete's specific pore architecture, as these factors determine the rate at which CO2 can diffuse through the binder (Pau et al., 2018).

4.6. Transport Properties: Water Absorption, Porosity, and Sorptivity

Water is the primary medium for the transport of deleterious substances, playing a fundamental role in the degradation of concrete structures. The infiltration of moisture through the internal pore system facilitates the ingress of chloride ions, triggers reinforcement corrosion, and exacerbates damage from freeze-thaw or wetting-drying cycles. The durability of a binder is inherently linked to its pore architecture, which governs its transport characteristics [84]. Sorptivity is a critical metric used to assess the connectivity of the capillary network within a material. It serves as a reliable indicator of how easily aggressive ions can penetrate concrete in harsh environments, such as marine zones. A low sorptivity coefficient suggests a high resistance to water ingress, whereas elevated values signify a highly interconnected pore structure with low tortuosity, allowing for faster moisture migration [85].

Research consistently demonstrates that low-calcium FA-based GPC outperforms OPC in terms of transport resistance. GPC typically exhibits lower water absorption, reduced sorptivity, and a smaller volume of permeable voids [55]. The efficiency of this transport resistance is highly dependent on curing protocols; for instance, Noushini & Castel (2016) found that thermal curing at 75°C for 18 to 24 hours significantly minimizes permeable voids and lowers the sorptivity coefficient [85]. A direct inverse relationship exists between the porosity of geopolymer systems and their mechanical integrity. Increasing the volume of internal pores results in a quantifiable reduction in compressive strength [25]. Mustofa & Pintowantoro (2017) noted that high compressive strength is indicative of a denser and more homogeneous microstructure. This densification reduces the capacity for water absorption, effectively sealing the matrix against environmental ingress [68].

5. Conclusions

1. This study comprehensive reviewed recent research on geopolymer concrete made from fly ash and replacing with recycled glass powder, focusing on geopolymerization mechanisms, material performance, and sustainability implications. Several key conclusions can be drawn from the analyzed studies.

2. Most experimental studies report optimal WGP replacement levels in the range of approximately 20–30%, resulting in notable improvements in compressive and flexural strengths. These outcomes are highly dependent on alkaline activator composition, molarity, and curing regime.
3. Compared with conventional OPC-based concrete, WGP-modified geopolymer concrete generally exhibits superior resistance to chemical attack, chloride penetration, and elevated temperatures, primarily due to its dense aluminosilicate matrix and reduced calcium content.
4. Sustainable Alternatives: GPC has established itself as a robust and eco-friendly successor to OPC. It effectively mitigates the ecological degradation and high carbon intensity inherent in traditional cement manufacturing while offering comparable or superior structural performance.
5. Synergistic Effects of WGP: The inclusion of WGP within FA-based systems provides a dual-benefit strategy. It enhances the mechanical properties of the binder while simultaneously addressing environmental waste management challenges.
6. Chemical Reactivity: Due to its high amorphous silica content, WGP functions as a highly reactive pozzolanic agent. It serves as an essential supplementary precursor, particularly in geographical regions where the supply of high-quality Fly Ash is scarce or inconsistent.
7. Long-term strength and Microstructural Refinement: Research indicates that partially substituting FA with WGP can accelerate the geopolymerization process. While FA particles provide long-term strength development
8. through gradual reaction, the high silica content in WGP promotes the rapid formation of additional geopolymer gels. This synergy results in a more compact matrix, reduced internal porosity, and improved early-age strength.
9. Enhanced Durability: Microstructural evaluations consistently demonstrate that WGP-modified mixes exhibit denser gel phases and a refined pore structure. This denser architecture is fundamental to the material's superior resistance to aggressive environmental ions and chemical attacks.
10. Circular Economy Alignment: The utilization of WGP facilitates significant industrial waste reduction and minimizes the embodied carbon footprint of construction projects. This practice directly supports the global transition toward circular economy principles within the built environment.
11. Most available studies are confined to laboratory-scale testing, while field applications, large-scale structural validation, and real exposure conditions are rarely reported.
12. The absence of standardized mix design procedures, durability assessment protocols, and design codes represents a major barrier to the practical implementation of fly ash–waste glass powder geopolymer concrete.

Future Outlook: Using WGP as a supplementary precursor not only optimizes the technical performance of GPC but also validates the feasibility of sustainable construction practices that rely on recycled industrial by-products

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