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Ground waste glass as a supplementary cementitious material for concrete: sustainable utilization, material performance and environmental considerations

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This review article delves into the role, potential, and peculiarities of ground waste glass (GWG) as both a supplementary cementitious material (SCM) and a filler in concrete. Motivated by the increasing emphasis on sustainable construction practices, the article explores the potential of GWG in enhancing concrete performance while addressing environmental concerns associated with traditional materials. The comprehensive review encompasses the properties of GWG as an SCM, its global availability, its influence on various concrete properties, its compatibility with cementitious systems, optimization techniques, challenges, and practical applications. Key considerations such as particle size distribution, replacement levels, and chemical activation in optimizing recycled GWG incorporation are also highlighted. This comprehensive review underscores the potential of GWG as a sustainable additive in concrete, enhancing both environmental responsibility and structural performance.

Keywords: Ground waste glass; supplementary cementitious material; cementitious systems; concrete properties

1. Introduction

The construction industry is currently in the midst of a transformative shift, gravitating toward sustainable and eco-friendly practices to alleviate the environmental impact traditionally associated with conventional building materials. At the forefront of this movement is the nowadays popular use of supplementary cementitious materials (SCMs) as a pivotal strategy for bolstering the sustainability of concrete structures [1–5]. In this dynamic landscape, recycled and then ground waste glass (GWG), sourced from discarded glass materials, has been emerging as a promising SCM and filler with several studies already carried out but with limited applicability or substantial developments.

The motivation behind exploring the potential use of waste glass in concrete is threefold: (a) waste utilization, (b) reducing natural resource depletion, (c) improving concrete's sustainability credentials, and (d) potentially improving concrete properties. Delving into the historical context, the integration of glass waste into construction practices traces its roots back to the mid-twentieth century [6]. During this period, researchers embarked on a quest to identify alternative materials capable of mitigating the environmental repercussions inherent in conventional concrete production. GWG, with its pozzolanic properties akin to widely used SCMs like fly ash (FA) and silica fume, captured attention [7–9]. Since then, research endeavors have intensified, seeking to unravel the nuanced dynamics of performance, durability, and environmental impact associated with concrete formulations featuring GWG [10–13]. The inherent properties of GWG render it a potentially suitable material for fortifying concrete characteristics. Characterized by an amorphous structure, high silica content, and pozzolanic reactivity, GWG can become a catalyst in the development of concrete strength and durability. Furthermore, once finely ground, the distributed particle sizes of GWG can make it an appropriate filler material, enhancing the packing density within concrete mixes.

There are several environmental benefits of incorporating GWG into concrete [14–17]. A primary motivator for its adoption lies in its ability to curtail the carbon footprint linked to traditional cement and concrete production. By substituting a portion of Portland cement withGWG, not only is waste glass diverted from landfills but the energy-intensive process of clinker production is also alleviated. This dual environmental advantage aligns with the escalating demand for sustainable construction practices globally. Moving beyond its environmental merits, GWG can introduce a spectrum of technical advantages to concrete formulations: it may enhance workability, reduce permeability, and improve the long-term properties of concrete structures [18–21]. The pozzolanic reaction between GWG and cementitious materials facilitates the creation of additional cementitious compounds, culminating in heightened strength and durability of the resulting

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concrete. Conversely, the incorporation of GWG into concrete does not come without its challenges. Issues such as variability in glass composition, the potential for alkali-silica reactions, and concerns about color consistency have been identified [22–28]. To surmount these challenges, ongoing research endeavors are dedicated to optimizing the integration of GWG into concrete mixes. Simultaneously, the exploration of innovative methods for glass waste collection, processing, and standardization is underway to bolster the feasibility of wider adoption.

Glass powder can be categorized by particle size. Granular glass consists of coarse, irregular particles larger than 1 mm, resembling small pebbles or fragments, and is commonly used in filtration or as decorative aggregates. Sand-sized glass ranges from approximately 0.1 mm to 1 mm, with fine grains similar to natural sand, making it suitable for sandblasting, construction, and filler materials. Powdered glass features very fine, uniform particles typically less than 0.1 mm (100 μ), with a talc-like texture ideal for applications such as ceramics, polishing, or as a fine additive in various industrial and manufacturing processes.

The motivation behind crafting this review article lies in the imperative need to address the evolving landscape of sustainable construction within the concrete industry. As the construction sector pivots toward sustainable development, the role of SCMs, particularly GWG, demands comprehensive exploration. By delving into historical contexts, inherent properties, and environmental and technical advantages, this article aims to elucidate the potential of GWG as a transformative SCM and filler. Recognizing the urgency to mitigate environmental impacts, this review seeks to guide future research and industry practices toward a more sustainable and resilient future in concrete construction.

This review article aims to investigate the diverse roles of GWG in concrete, serving both as an SCM and a filler. With a focus on sustainable construction, the article explores how or worsens concrete performance while addressing environmental concerns linked to conventional materials. The review covers GWG properties as an SCM, its impact on concrete properties, compatibility with cementitious systems, optimization techniques, challenges, and practical applications. Key considerations such as particle size distribution, replacement levels, and chemical activation are highlighted. As importantly, an analysis of waste glass availability around the world is provided to identify locations that will benefit more profoundly from the reuse of waste glass in concrete. Further to this, an analysis of the current and ongoing standardization for GWG use in concrete is provided. The findings of this study provide valuable insights for industry professionals, researchers, and policymakers interested in sustainable concrete and circular economy, as well as underlying potential future research endeavors.

2. Methodology

In the current study, a comprehensive approach known as a systematic literature review (SLR) is employed to thoroughly investigate and evaluate the impact of incorporating GWG as SCM and filler in concrete. This method involves a systematic and organized review of existing literature to gather insights into the subject. The review process is depicted in the framework presented in Figure 1.

To conduct this literature review, widely recognized bibliometric databases such as Scopus, Web of Science, and Google Scholar were utilized. The search strategy involved the use of specific keywords related to the topic, including phrases like "ground glass in concrete," "waste glass in concrete," "waste glass powder (WGP) in concrete" and "recycled glass." These keywords were chosen to ensure a comprehensive exploration of relevant research on the subject. The subsequent steps involved a thorough examination and analysis of the identified research articles. The goal was to filter out studies that were most relevant to the influence of GWG on concrete properties. The selection process considered the quality, relevance, and significance of each article, resulting in a compilation of research findings that contribute to a deeper understanding of the role of GWG in enhancing concrete characteristics. This systematic and structured approach ensures a rigorous review, offering valuable insights into the current state of knowledge on the use of GWG in concrete applications.

3. Ground glass as a supplementary cementitious material (SCM)

3.1. Availability of GWG and the process of obtaining them

Waste glass, a byproduct of various industrial, commercial, and domestic activities, is a widely available resource due to the extensive use of glass in packaging, construction, and other applications. Common sources of waste glass include bottles, jars, windowpanes, and construction or demolition debris. A large portion of this waste being nonbiodegradable often ends up in landfills, creating environmental concerns. However, recycling waste glass into glass powder offers a sustainable solution, reducing landfill waste and providing a material with valuable applications in construction.

To use WGP as an SCM, several steps are required to ensure its suitability and performance. The process starts with the collection of waste glass, which is sorted to remove contaminants such as metals, plastics, and ceramics. Proper sorting is crucial to maintaining the quality and chemical composition of the final product. Once sorted, the glass is thoroughly cleaned to eliminate residues and impurities, ensuring it meets purity standards. The cleaned glass is then subjected to crushing and grinding, reducing it to a fine powder. Achieving a particle size of less than 75 μ is essential, as finer particles exhibit better pozzolanic activity. This activity occurs when the silica in the glass reacts with calcium hydroxide in cement to form additional cementitious compounds, enhancing the strength and durability of concrete. Following grinding, the glass powder is screened to ensure uniform particle size distribution. Consistency in size is critical for maintaining the performance and workability of the final concrete mixture. Comprehensive quality control tests are

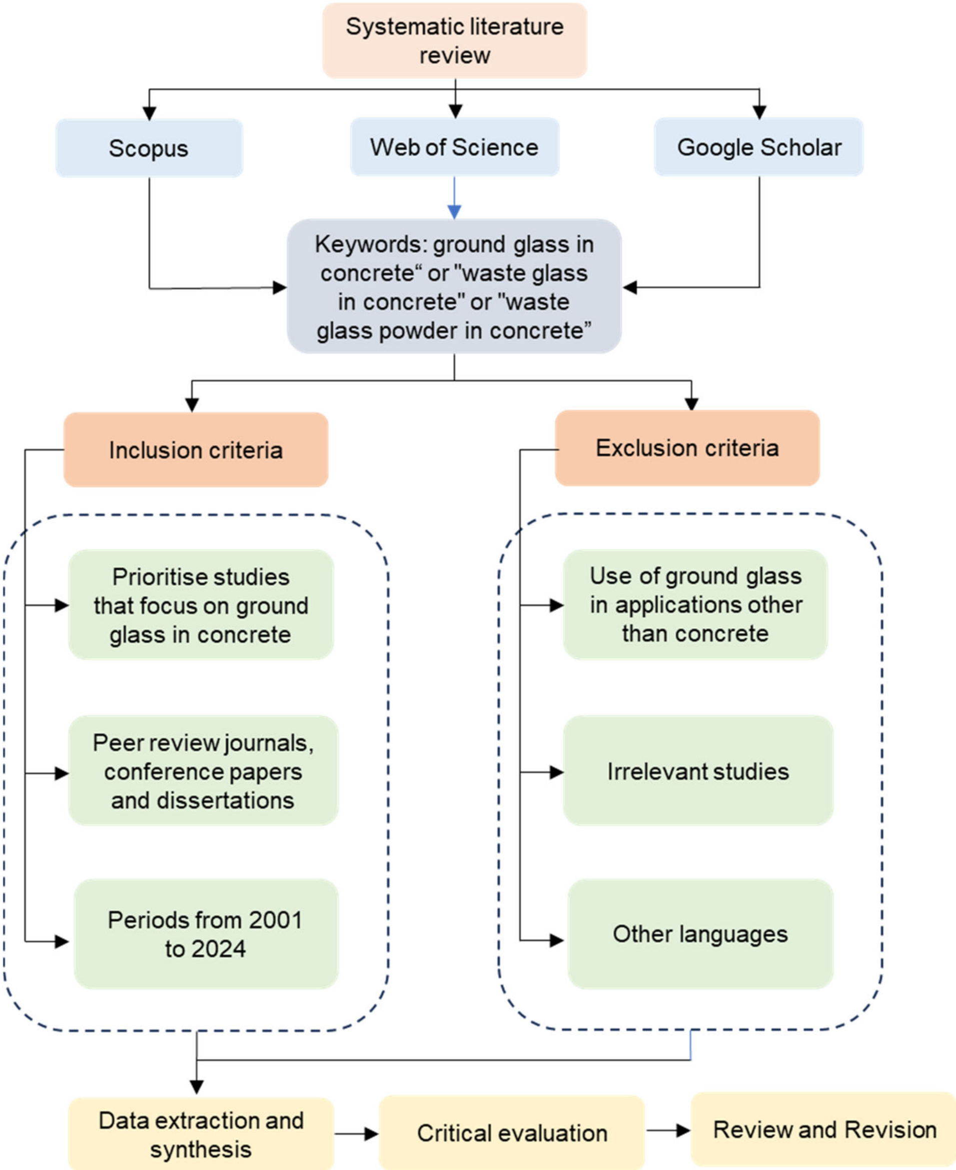


Figure 1. Systematic literature review methodology.

then conducted to confirm the chemical composition and compliance with standards for SCMs. This includes verifying silica content and assessing the material's potential reactivity to ensure compatibility with cementitious systems. Processed WGP demonstrates significant pozzolanic properties, making it an effective partial replacement for cement. Its use in concrete production not only reduces reliance on traditional cement, lowering greenhouse gas emissions, but also diverts waste glass from landfills. Additionally, incorporating glass powder enhances the durability and sustainability of concrete structures, contributing to greener construction practices and a circular economy.

3.2. *Properties of GWG as an SCM*

GWG, when employed as an SCM, imparts a range of characteristics to concrete that can enhance its overall performance. GWG has been known to exhibit pozzolanic reactivity, where it chemically reacts with calcium hydroxide in the presence of moisture. This reaction generates cementitious compounds, contributing to the concrete's strength and long-term durability. The finely ground nature of glass powder is pivotal in influencing concrete properties [29–32]. It allows for a meticulous control of particle size distribution, impacting the workability of concrete and promoting optimal packing density. This control not only affects the structural integrity but also contributes to a reduction in material porosity, thereby enhancing the overall durability of the concrete. Functioning as a filler, GWG occupies interstitial spaces between cement particles, resulting in a denser microstructure [33–35]. This filler effect can go beyond reducing permeability as it can improve concrete's general durability properties.

Internal chemical activation is another significant effect, where the alkaline environment generated by Portland cement activates the pozzolanic reaction of GWG [36–39]. This activation fosters the formation of additional binding materials, positively influencing the mechanical properties of the concrete and enhancing its overall performance. Moreover, the incorporation of GWG is beneficial in reducing the heat of hydration during the concrete-setting process. This is particularly advantageous in massive concrete elements where excessive heat generation could lead to thermal cracking, compromising the structural integrity. Waste ground glass enhances the chemical resistance of concrete, providing robustness against corrosive substances such as sulfates and acids. This property is particularly valuable in environments where concrete is exposed to challenging conditions, ensuring longevity and structural integrity.

The CaO–Al_2O_3–SiO_2 ternary diagram in Figure 2 indicates the potential utilization of glass in cement-based products. SiO_2 is the primary reactive ingredient in the pozzolanic reaction, and the addition of glass enhances its concentration. Notably, the CaO content in cement significantly surpasses that in glass powder, playing a pivotal role in mortar strength. Presently, blends of Portland cement incorporating FA or granulated blast-furnace slag (GGBS) enjoy widespread popularity. The inclusion of waste glass in concrete could emerge as a viable option within contemporary cement formulations.

Figure 3 shows scanning electron microscope (SEM) micrographs of glass powder with two different particle sizes: (a) 75 µm and (b) 63 µm. Both images were captured at 900× magnification and reveal the morphology and size distribution of the glass particles. In image (a), the particles appear relatively larger and more angular, with some smooth edges, indicating minimal processing or breakage. In contrast, image (b) displays finer, more fragmented particles with sharper edges and more irregular shapes, suggesting a higher degree of mechanical grinding or milling. The 63 µm particles exhibit a denser distribution and seemed to pack more closely compared to the 75 µm particles, which are more loosely scattered. These morphological differences can significantly influence the physical properties of the glass powder in applications such as composite materials, sintering, or reactive fillers, where particle size and shape directly affect packing density, surface area, and reactivity.

Figure 4 represents a particle size distribution graph for four materials: glass powder, cement, sand, and coarse aggregate. The x-axis shows the particle size on a logarithmic scale ranging from 0.1 µm to 10 mm while the y-axis indicates the percentage of material passing through a sieve, from 0% to 100%. Glass powder and cement exhibit finer particle sizes, with most particles under 100 µm. Cement has a slightly coarser distribution than glass powder, which passes more material at smaller sizes. Sand shows a steeper curve beginning near 100 µm and reaching full passage around 2 mm, indicating a medium particle size distribution. Coarse aggregate has the largest

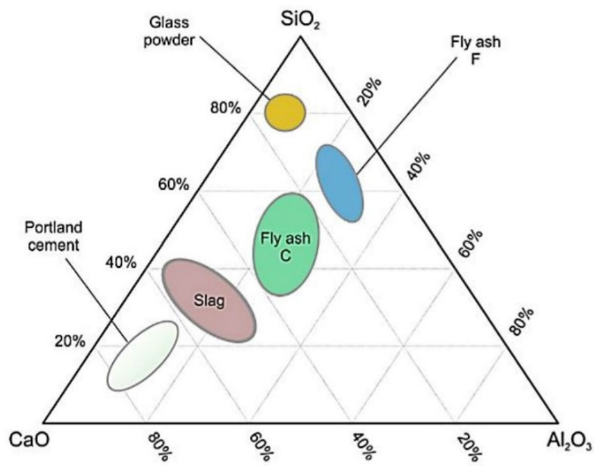


Figure 2. CaO-AL_2O_3–SiO_2 Ternary diagram of ground glass, FA and GGBS, and Portland cement [40].

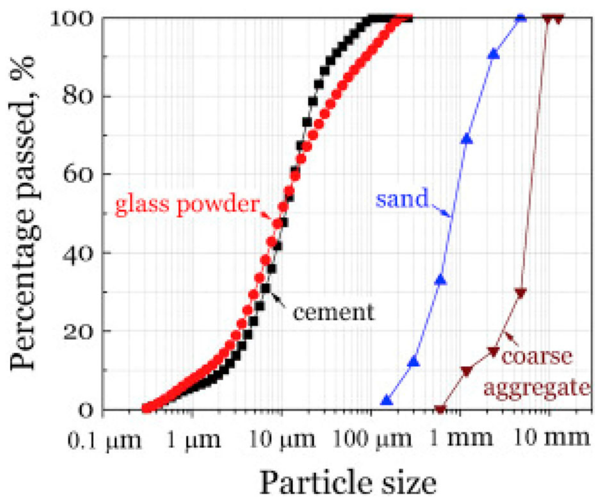
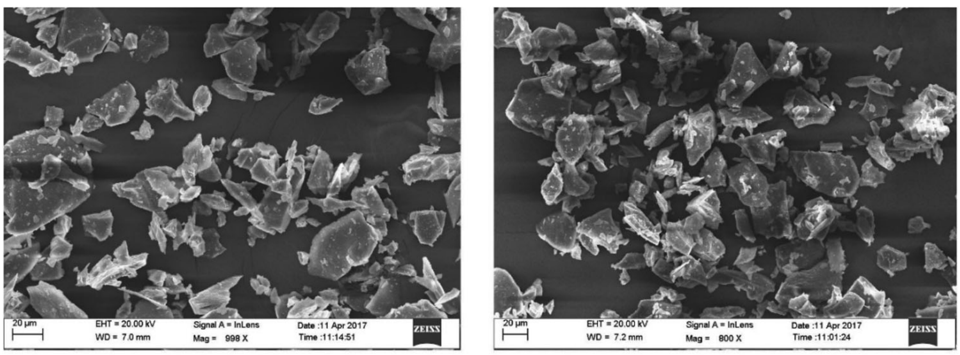


Figure 4. Particle size distribution for cement, glass powder, sand, and aggregate [42].



(a) SEM micrograph of 75µm glass powder

(b) SEM micrograph of 63µm glass powder

Figure 3. SEM micrograph of glass powder [41].

particle sizes, starting around 1 mm and peaking beyond 10 mm.

3.3. Setting time

The incorporation of glass powder in concrete significantly influences the setting time and early age properties. Glass powder, acting as an SCM, can accelerate or retard the setting time depending on its particle size and reactivity. Finely ground GWG powder may accelerate the early strength development due to pozzolanic reactions. However, higher glass powder contents might prolong the setting time. Proper understanding and control of these effects are crucial for optimizing concrete mix designs with glass powder for the desired performance. The size of the glass powder significantly impacts the hydration process and setting time of the binder. Smaller particles increase surface area, accelerating hydration, and reducing setting time. Conversely, larger particles slowed down hydration, extending setting time. Understanding this relationship helps optimize binder performance for specific construction or material requirements.

Glass powder acts as an SCM, influencing hydration kinetics and pozzolanic reactions. Finely ground glass powder, with increased surface area, accelerates hydration and promotes early strength development. Conversely, higher glass powder content or coarser particles may delay the setting time due to reduced reactivity. Understanding these effects is essential for optimizing concrete mix designs for specific performance needs. Glass sand, on the other hand, behaves differently due to its physical and chemical characteristics. Its hydrophobic nature increases the effective water demand in the mix [43,44], leading to prolonged setting times. The distinct properties of glass sand, compared to glass powder, require precise consideration to ensure clarity in the mix's impact on setting time and hydration.

Studies provide valuable insights into these effects. Aliabdo et al. [45] highlighted the influence of WGP on concrete's hydration and setting time, implicitly linking composition variations to performance changes. Jiang et al. [46] focused on the hydration and setting time of cement paste incorporating glass powder, examining curing conditions, including elevated temperatures, which alter hydration kinetics and affect setting time. Additionally, Çelik et al. [47] explored the role of WGP in geopolymer concrete, where setting time is a critical parameter. These findings underline the need for ongoing research to clarify specific correlations between glass powder or sand content and setting time under diverse conditions. Such studies will aid in developing optimized concrete mixes for various construction scenarios, ensuring clarity in the distinct roles of glass powder and sand in concrete performance.

4. Influence of GWG on concrete properties

GWG, when integrated into concrete as an SCM, significantly influences various properties. Its pozzolanic reactivity enhances long-term strength and durability. The controlled particle size distribution improves workability and packing density, reducing porosity. Functioning as a filler, GWG densifies the microstructure, decreasing permeability and enhancing overall durability. Alkaline activation further boosts its performance in cementitious systems. The incorporation of GWG also mitigates the heat of hydration, which is beneficial in large structures. Environmental advantages include waste reduction, resource conservation, and lower carbon footprint. Altogether, GWG profoundly shapes concrete properties, offering sustainable, high-performance solutions.

4.1. Workability and rheology

The incorporation of glass powder in concrete significantly influences its workability and rheology. Studies suggest that adding glass powder can enhance workability by acting as an SCM, improving particle packing and lubrication between particles. The fine nature of glass powder contributes to smoother concrete mixes, facilitating easier placement and finishing during construction. Additionally, the rheological properties of concrete, such as viscosity and flowability, are influenced by glass powder. Proper dosage and particle size distribution play crucial roles in optimizing these properties, impacting the overall performance of the concrete mix in terms of handling, pumping, and forming desired shapes.

The study by Niu et al. [48] investigated the rheological properties of mortar incorporating WGP. The findings (Figure 5 and Figure 6) reveal insights into yield stress and plastic viscosity, critical parameters influencing the flow behavior of mortar. The addition of WGP introduces changes in these rheological properties, impacting the mortar's workability and flow characteristics. Understanding these variations is crucial for optimizing mix designs and ensuring proper handling and placement during construction. The study's comprehensive examination sheds light on the intricate relationship between WGP content and the rheological performance of mortar, offering valuable information for sustainable concrete applications.

In the study by Tariq et al. [49], the focus was on self-compacting concrete, and the research investigates the impact of glass powder replacement on both rheological and mechanical properties. Self-compacting concrete is known for its ability to flow and fill formwork without the need for external compaction. The findings of this study contribute to understanding how glass powder influences the flow characteristics and strength of self-compacting concrete. Yin et al. [50] examined the utilization of WGP in cementitious grouts with superplasticizer and viscosity-modifying agent binary mixes. This study emphasizes the rheological and mechanical performances of the grouts, providing valuable insights into the potential of WGP in enhancing the properties of cementitious materials when combined with other additives.

Yin et al. [51] explored the mechanical and rheological properties of high-performance concrete (HPC) incorporating waste glass as a cementitious material and fine aggregate. HPC is known for its superior strength and

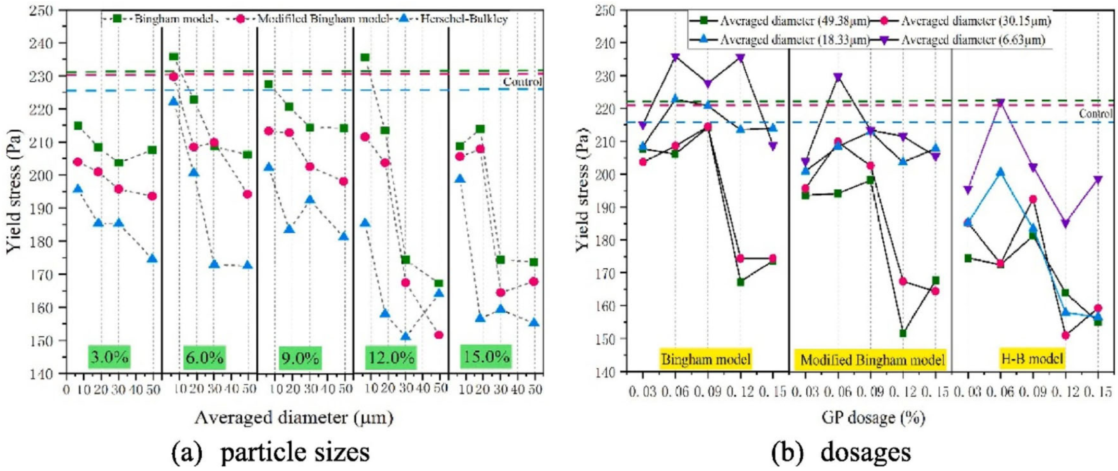


Figure 5. Effect of particle size and dosages of glass powder (by weight) on yield stress for fresh mortar [48].

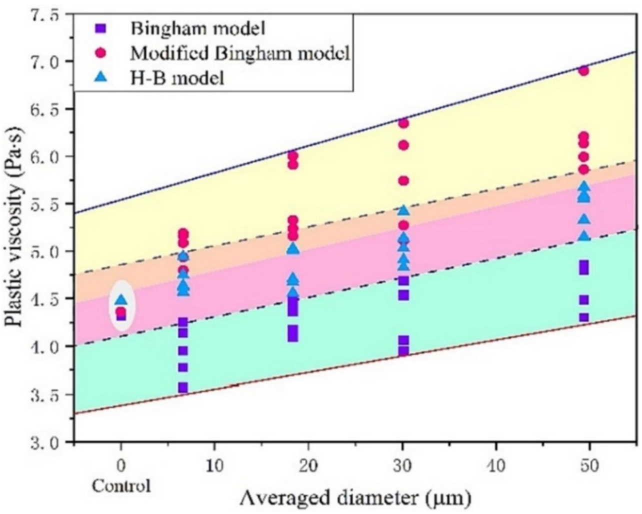


Figure 6. Plastic viscosity of fresh mortar incorporated with glass powder [48].

durability, and understanding how glass powder contributes to its properties is essential for developing sustainable HPC mixes. These studies collectively contribute to a comprehensive understanding of how glass powder influences the workability and rheology of concrete. The findings highlight the potential benefits of incorporating glass powder, not only in terms of sustainability but also in enhancing the mechanical and rheological properties of various types of concrete mixes. However, it is essential to note that the specific effects may vary based on the type of concrete, the proportion of glass powder used, and other admixtures included in the mix. Further research and standardization are needed to establish guidelines for the optimal use of glass powder in concrete production. Table 1 offers a concise overview of the studies, highlighting the context, findings, and the type of concrete explored, providing a quick reference to the effects of glass powder in different applications.

The addition of glass powder to concrete significantly affects its workability and rheological properties, with the outcomes largely dependent on factors such as particle size, dosage, water-to-cement ratio, curing age, cement type, temperature, mixing time, and the use of chemical admixtures. When glass powder with a fine particle size is used, it improves the packing density of particles and enhances internal lubrication, leading to better flow characteristics. This refinement of the particle structure contributes to smoother and more cohesive concrete mixes, allowing for easier placement and finishing. However, higher dosages of glass powder can increase the mix's viscosity due to the greater surface area of fine particles, which in turn increases water demand or the need for superplasticizers.

The water-to-cement ratio plays a critical role in controlling the fresh properties of concrete with glass powder. Lower ratios, while beneficial for strength, can reduce flowability unless offset by suitable admixtures. The curing age also influences how glass powder interacts within the mix, particularly due to its pozzolanic behavior, which may not be immediately apparent at early stages but contributes to strength and durability over time. Additionally, the type of cement used can affect how effectively glass powder integrates into the binder phase, with some blends showing better compatibility than others.

Mixing time and ambient temperature further affect the dispersion and reactivity of the glass powder in the mix. Inadequate mixing may lead to poor distribution, while high temperatures can accelerate hydration, altering

Table 1. Summary of studies on the influence of glass powder on concrete workability and rheology.

Study	Focus	Key findings	Concrete type
Niu et al. [48]	Rheological properties of mortar incorporating WGP	Variations in yield stress and plastic viscosity due to WGP content and particle size; critical for optimizing mix designs.	Mortar
Tariq et al. [49]	Glass powder impact on rheological and mechanical properties of self-compacting concrete	Glass powder improves flow characteristics and strength of self-compacting concrete.	Self-compacting concrete
Yin et al. [50]	Rheological and mechanical performance of cementitious grouts with glass powder and additives	Glass powder enhances grouts' performance when combined with superplasticizers and viscosity modifiers.	Cementitious grouts
Yin et al. [51]	Mechanical and rheological properties of HPC with waste glass	Glass powder contributes to the sustainability and enhanced properties of HPC.	HPC
Topçu & Canbaz [52]	Waste glass as cement replacement, workability evaluation	Reduction in unit weight due to lower specific gravity of waste glass; reduced slump and air content due to poor geometry and smoother surface; enhanced flow table values; extended placing period with higher WG content.	General concrete
Elaqra & Rustom [53]	Effect of glass powder on rheological and mechanical properties of cement paste	Glass powder influences cement paste properties, crucial for predicting concrete performance.	Cement paste
Elaqra et al. [54]	Effect of immersion time on mechanical properties of concrete containing glass powder	Immersion time impacts the curing and mechanical performance of concrete with glass powder.	General concrete
Li et al. [55]	Rheology of alkali-activated slag/glass powder pastes	Glass powder is compatible with alkali-activated materials, influencing rheological properties positively.	Alkali-activated materials
Dadsetan et al. [56]	Rheology, strength, and microstructure of metakaolin-based geopolymer binders with glass powder	Incorporating glass powder enhances sustainability and modifies rheological and mechanical properties of geopolymer binders.	Geopolymer binders

workability. Overall, glass powder shows great potential in improving both the sustainability and performance of concrete, but its influence is not uniform. Each variable—whether dosage, fineness, or mix composition—plays a critical role in determining the final behavior of the concrete, and careful optimization is necessary to achieve the desired results.

4.2 Mechanical properties

4.2.1. Compressive strength

The incorporation of GWG as an SCM in concrete significantly influences compressive strength through multiple mechanisms. GWG undergoes pozzolanic reactions with calcium hydroxide, forming additional cementitious compounds that densify the concrete matrix over time. Acting as a filler, GWG reduces voids and optimizes particle packing, enhancing the material's load-bearing capacity. Its uniform dispersion refines the microstructure, creating a stronger crystalline network. The alkaline environment activates GWG's reactivity, producing supplementary binding materials that contribute to strength development. Additionally, GWG lowers the heat of hydration, mitigating thermal cracking but potentially affecting early strength gain. Optimizing factors such as particle size, replacement levels, and curing conditions ensures the balance between compressive strength and other performance characteristics. The intricate interplay of pozzolanic reactions, filler effects, microstructural refinement, and activation mechanisms underscores GWG's potential to enhance concrete strength while promoting sustainability and durability in construction.

Figure 7 illustrates the compressive strengths of mortars with recycled glass at different ages. Lower mean compressive strengths were observed at 7, 14, 28, and 56 days compared to the control mortar (0% glass replacement). However, except for the 25% glass addition, all other cement-replaced mortars surpassed the mean compressive strength of the control mortar at 90 days. These findings align with Nassar & Soroushian's [57] field investigation. Rashad's [58] review revealed a contradiction in reported strength changes. At 90 days, the study identified the greatest compressive strength at a 10% cement replacement level. A similar trend was observed at 180 days, with 15% cement replacement yielding the highest strength. Nevertheless, the increase in compressive strength with recycled glass at both 90 and 180 days was statistically insignificant. Notably, the 365-day test

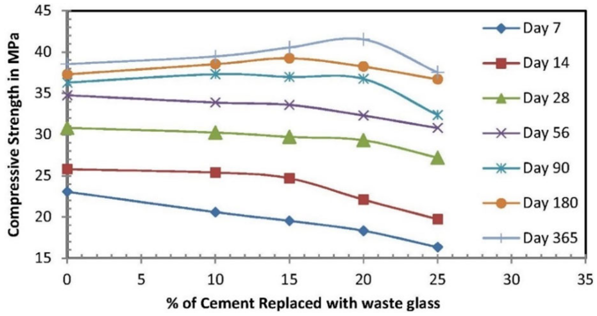


Figure 7. Compressive strength of mortar [13].

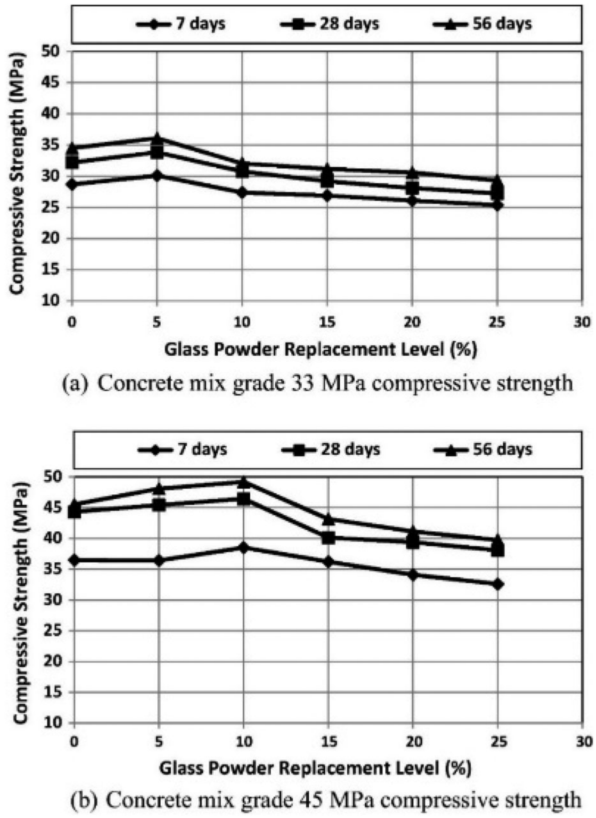


Figure 8. Compressive strength concrete with GWG replacing cement [45].

showed the highest compressive strength with a 20% waste glass addition, 8% higher than the glass-free control mortar. As suggested by Rahma and Naber et al. the improvement in strength could be due to high surface area and high tension that initially retains water, which generally delays cement hydration. Over time, as the water gradually becomes available, the glass powder contributes further to the hydration process, improving strength at later ages. This slow release of water supports the long-term development of strength properties.

Du & Tan [59] laid the foundational groundwork by pioneering an investigation into the viability of WGP as a substitute for traditional cement. Their study not only offered a foundational understanding of the intricate interactions within the concrete matrix but also placed a specific emphasis on the compressive strength, shedding light on the potential benefits of incorporating glass powder. Expanding on this work, Balasubramanian et al. [60] broadened the research landscape by introducing waste E-plastic alongside WGP. The objective was not merely confined to assessing compressive strength; rather, it aimed to unravel the combined effects of these materials on the holistic performance of concrete. This comprehensive approach provided a more nuanced and holistic perspective on the behavior of concrete beyond a singular strength parameter. Li et al. [61] directed their investigative lens toward pervious concrete, probing into the mechanical properties influenced by the incorporation of WGP. Their meticulous research underscored the significance of evaluating not only the compressive strength but also other critical performance aspects. This expanded perspective is crucial in understanding the broader implications of waste glass in diverse concrete formulations.

In the discourse led by Paul et al. [62], the trajectory shifted toward eco-friendly concrete formulations that embraced WGP. The emphasis evolved into sustainable and circular solutions in construction materials, aligning with the imperative for environmentally conscious building practices. This marks a paradigm shift toward holistic and environmentally friendly approaches to concrete construction. Muhedin & Ibrahim [63] delved into a specific investigation, meticulously exploring the nuanced effects of WGP as a partial replacement for both cement and sand in concrete. This in-depth study ventured into the intricate interactions within the concrete mix, deciphering how waste glass influenced various components to impact the overall performance of concrete. Ibrahim [64] contributed to the expanding exploration by incorporating recycled WGP in combination with silica fume and FA. This diversification extended the range of supplementary materials under consideration, offering insights into their collective impact on diverse concrete properties.

In Figure 8, the impact of substituting glass powder for cement on cube concrete compressive strength at 7, 28, and 56 days is illustrated. Notably, incorporating 5.0% glass powder as cement replacement yields a slight enhancement in concrete compressive strength for the 33 MPa grade, extending to 10% for the 45 MPa grade. This trend persists across different testing ages. However, employing glass powder as cement replacement beyond 10% adversely affects concrete compressive strength, potentially attributed to the reduced content of Portland cement at higher glass powder replacement levels. For instance, in 45 MPa grade concrete at 28 days, there is a reduction of 9.4%, 11.1%, and 12.5% in compressive strength for replacements of 15%, 20%, and 25% glass powder, respectively, compared to the control mix without glass powder. The mitigation of this reduction in concrete compressive strength can be achieved by lowering the concrete water/cement ratio.

In a comprehensive experimental study, Ramakrishnan et al. [31] conducted a thorough evaluation of the mechanical and durability properties of concrete incorporating WGP and ground GGBS as SCMs. Their meticulous research not only highlighted the individual contributions of waste glass but also uncovered synergies with other supplementary materials, providing valuable insights into concrete performance over the long term. Taking a holistic approach, Baikerikar et al. [65] embraced a multifaceted utilization of waste materials by incorporating WGP and waste glass sand in the production of eco-friendly concrete. This study underscored the importance of considering multiple waste materials simultaneously to enhance the overall sustainability profile of concrete, aligning with the principles of a circular economy. Zeybek et al. [66] specifically delved into the mechanical properties of concrete when cement was replaced with waste glass. Their detailed research offered a profound understanding of how waste glass influenced various strength characteristics of concrete. This granular exploration contributed significantly to the broader comprehension of material behavior and potential applications in concrete engineering. In essence, the collective body of past research outlined a rich tapestry of knowledge, unravelling the multifaceted influence of GWG, particularly WGP, on the compressive strength and overall performance of concrete. These studies collectively form a crucial foundation for future endeavors, guiding the trajectory of sustainable and innovative concrete construction practices. Table 2 summarizes key studies on the use of WGP in concrete, highlighting focus areas, materials studied, findings, and applications.

Incorporating glass fiber powder (GFP) in concrete enhances its compressive strength by improving the microstructure and reducing the propagation of cracks. The fine particles fill voids within the cement matrix, leading to denser and more cohesive concrete. Additionally, glass fibers inhibit the formation and growth of micro-cracks, effectively distributing stress and increasing load-bearing capacity. The high tensile strength of the fibers complements the inherent brittleness of concrete, boosting its overall durability. The interaction between the fibers and the cement matrix creates a composite material with enhanced mechanical properties, offering improved resistance to external pressures and longer structural performance in various applications.

Concrete performance with GWG is assessed through parameters such as particle size, which influences pozzolanic reactivity and filler efficiency; dosage, where optimal replacement levels (e.g. 10–20%) enhance long-term strength; and curing age, which reflects strength development over time. Water/cement ratio affects hydration and workability, while temperature and mixing time control reaction kinetics and uniform dispersion. The cement type determines compatibility with GWG. These factors interact complexly, making it difficult to isolate individual effects, as improved compressive strength often results from simultaneous pozzolanic, filler, and microstructural

Table 2. Comprehensive overview of studies on waste glass powder in concrete applications.

Reference	Focus area	Material studied	Key findings
Rahma & Naber [30]	Hydration and strength improvement mechanisms	Glass powder	Retention of water by high surface area delays hydration but improves long-term strength.
Ramakrishnan et al. [31]	Durability and mechanical properties with GGBFS	Glass powder and GGBFS	Synergistic effects of waste glass and GGBFS improve long-term durability and mechanical properties.
Aliabdo et al. [45]	Compressive strength with varying glass powder levels	Glass powder in high-grade concrete	5%–10% replacement enhances strength; >10% reduces strength unless water/cement ratio is adjusted.
Nassar & Soroushian [57]	Compressive strength of mortars with recycled glass	Recycled glass in mortar	Strength surpasses control at 90 days for most replacements.
Rashad [58]	Review of strength changes with glass powder	Glass powder in cement mortar	10% replacement highest at 90 days; 15% at 180 days; 20% replacement highest at 365 days (+8%).
Du & Tan [59]	Foundational study on glass powder in concrete	WGP	Established benefits of glass powder for compressive strength and concrete matrix interactions.
Balasubramanian et al. [60]	WGP and E-plastic in concrete	WGP and E-plastic	Combined effects enhance concrete performance, beyond compressive strength.
Li et al. [61]	Pervious concrete with WGP	WGP	Improved mechanical properties; emphasis on broader performance evaluation.
Paul et al. [62]	Eco-friendly concrete formulations	WGP	Promoted sustainable solutions using waste glass in construction materials.
Muhedin & Ibrahim [63]	Partial replacement of cement and sand with glass	Glass powder as cement and sand replacement	Nuanced effects of glass powder on concrete mix components and overall performance.
Ibrahim [64]	Supplementary materials in concrete	Glass powder, silica fume, and FA	Combined materials diversify concrete properties and enhance performance.
Baikerikar et al. [65]	Eco-friendly concrete with multiple waste materials	Glass powder and glass sand	Highlighted sustainability through simultaneous use of multiple waste materials.
Zeybek et al. [66]	Mechanical properties of concrete with glass	WGP	Detailed insights into strength characteristics when cement is replaced with WGP.

mechanisms, particularly visible at extended curing ages like 90 or 180 days.

4.2.2 Tensile strength

The exploration of GWG's influence on the tensile strength of concrete is a multifaceted endeavor, as evidenced by several insightful studies. Mohammed & Hama's [67] investigation into green concrete incorporating WGP and plastic aggregate sheds light on how these materials collectively impact not only tensile strength but also mechanical properties, impact resistance, and bond strength. Rajendran et al. [68] contribute valuable insights by experimenting with the replacement of binding material with WGP, providing a nuanced understanding of how this substitution affects tensile strength and other mechanical aspects. Jurczak et al. [69] delved into the low-strength concrete domain, assessing the effect of GWG addition on both strength and durability. This research likely offers specific insights into the nuanced relationship between GWG and the tensile strength of low-strength concrete mixes. Additionally, Jiang et al.'s [46] investigation into WGP as an SCM under high temperatures explores a unique aspect of tensile strength, considering the influence of elevated temperatures on the mechanical properties of glass-modified concrete. Prasetyo et al. [70] took a different approach by focusing on self-compacting concrete, aiming to enhance both tensile strength and porosity using glass waste powder. This study is likely to provide valuable insights into the optimization of self-compacting concrete properties, especially regarding tensile strength.

Figure 9 illustrates the splitting tensile strength performance of concrete incorporating GWG during 60- and 90-day curing periods. Notably, there is an observed increase in strength for replacement percentages up to 15%. Specimens cured at 7 and 28 days also exhibit a similar increase in splitting tensile strength, but it is capped at a 10% replacement level of cement with GWG. This behavior is attributed to the pozzolanic activity, where the strength contribution becomes more prominent in later ages. It is noteworthy that the highest recorded splitting tensile strength is observed at a 5% replacement level for all curing periods. The bar chart in Figure 9 illustrates the variation in tensile strength (in MPa) of concrete with different percentages of WGP replacement—0%, 5%, 10%, 15%, and 20%—measured over curing periods of 7, 28, 60, and 90 days. At all curing ages, concrete with 15% WGP exhibits the highest tensile strength, with a peak value of 6.3 MPa on day 90. The control mix (0% WGP) shows a steady strength gain, reaching 5.2 MPa at 90 days. Initially, the 20% WGP mix records the lowest strength, especially at 7 days (2.4 MPa), suggesting delayed pozzolanic activity. However, its strength improves over time, achieving 4.5 MPa at 90 days. Generally, tensile strength increases with curing time across all mixes. Moderate WGP additions (up to 15%) enhance tensile strength, likely due to the pozzolanic reaction and improved particle packing, whereas 20% replacement reduces strength, potentially due to dilution effects. Overall, 15% WGP appears optimal for tensile strength development.

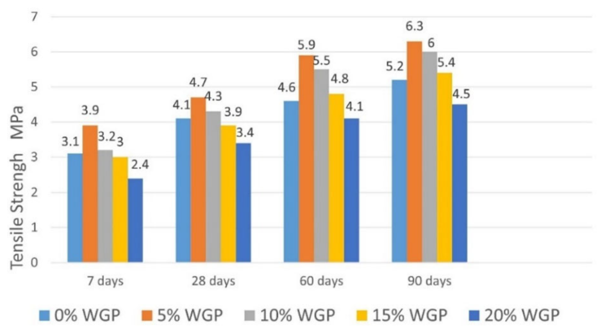


Figure 9. Splitting tensile strength of concrete containing different WGP as cement replacement [63].

Incorporating GFP significantly enhances the tensile strength of concrete by improving its ability to resist cracking and deformation under tension. The fibers act as a reinforcement, bridging micro-cracks and preventing their propagation, which is a primary cause of tensile failure in conventional concrete. GFP distributes tensile stresses more evenly throughout the concrete matrix, reducing localized stress concentrations. This improvement is due to the fibers' high tensile strength and strong bonding with the cementitious material. The resulting composite material exhibits better ductility and toughness, making it more resistant to dynamic loads and environmental stresses, improving structural longevity.

The experimental investigation by Mohammadyan-Yasouj & Ghaderi [71] involving WGP, basalt fiber, and carbon nanotubes is particularly intriguing as it examines the combined impact of multiple materials on the mechanical properties of concrete. Understanding the synergies between WGP and reinforcing materials contributes to a comprehensive comprehension of how these factors collectively influence tensile strength. Afshinnia & Rangaraju's [72] assessment of the combined use of GWG powder and crushed glass aggregate in Portland cement concrete likely elucidates the intricate relationships between different forms of glass and their impact on concrete's tensile strength. Ahmed et al.'s [73] exploration of the coupled effect of WGP and glass fibers on the mechanical properties of concrete represents a step toward a more holistic understanding. This study likely unveils how the synergy between waste glass components contributes to the overall enhancement of concrete properties, including tensile strength.

4.2.3. Flexural strength

The incorporation of GWG significantly enhances the flexural strength of concrete, a key indicator of its ability to resist bending forces. GWG, exhibiting pozzolanic activity, reacts with calcium hydroxide to form additional cementitious compounds, resulting in a denser, cohesive microstructure that strengthens the concrete matrix. The particle size distribution of GWG is critical; finer particles effectively fill voids, improving particle packing and promoting superior interlocking. This filler effect minimizes voids, optimizes material cohesion, and enhances load-bearing capacity. Furthermore, microstructural changes induced by GWG improve stress distribution and crystal arrangement, collectively elevating the concrete's flexural performance.

The influence of GWG on the flexural strength of concrete has been investigated through various studies, each providing unique insights into the material's behavior under different conditions. The investigations conducted by Jiang et al. revealed that addition of glass powder negatively affected flexural strength and ranged between 4 MPa and 8 MPa [8]. However, studies that accommodated glass powder with other materials prevented crack propagation and increased flexural strength, Orouji et al. [74] took an environmental approach, exploring the impact of glass powder and polypropylene fibers on the compressive and flexural strengths, toughness, and ductility of concrete. Hama et al. [75] specifically focused on the flexural behavior of reinforced concrete beams that incorporated WGP. By concentrating on flexural aspects, this research contributes to understanding how GWG influences the bending strength of concrete elements. Ramakrishnan et al. [31] conducted an experimental study on the mechanical and durability properties of concrete, incorporating WGP and ground granulated blast furnace slag as SCMs. This research likely sheds light on the combined impact of waste glass and other supplementary materials on flexural strength. Lu et al. [76] explored the combined use of WGP and cullet in architectural mortar, and although the focus might not be solely on flexural strength, architectural applications often demand materials with enhanced flexural performance.

Almesfer & Ingham [77] investigated the overall effect of waste glass on concrete properties. While the specific influence on flexural strength is not detailed, this study provides a broader context for understanding how GWG contributes to the material's characteristics. Liu et al. [78] examined 3D-printed concrete with recycled glass, considering the effect of glass gradation on flexural strength and fracture. This study is crucial for understanding the relationship between glass distribution and flexural properties in innovative construction methods. Tanwar et al. [79] conducted an experimental investigation of mechanical properties, acid resistance, and sulfate attack of concrete mixes with beverage glass waste as a fine aggregate. Although not explicitly focused on flexural strength, this research may offer insights into the overall performance of concrete with GWG in different applications. These studies collectively contribute to the understanding of how GWG, in various forms and applications, influences the flexural strength of concrete. The nuanced interplay of factors such as glass powder content, fiber reinforcement, supplementary materials, and glass gradation can significantly impact the flexural performance of concrete in diverse contexts. Incorporating GFP enhances the flexural strength of concrete by increasing its resistance to bending stresses. The glass fibers distribute tensile stresses across the concrete matrix, bridging cracks and reducing their propagation under flexural loads. This reinforcement mechanism improves the concrete's ductility and toughness, allowing it to withstand greater bending forces without failure. Additionally, the fibers contribute to a denser and more cohesive matrix, reducing internal voids and weak points. The result is a composite material with enhanced load-bearing capacity, reduced brittleness, and improved durability, making it ideal for applications where flexural performance is critical, such as slabs and beams.

4.3. Volume stability

4.3.1. Shrinkage

GWG can have a significant influence on the drying shrinkage of concrete. When used as a partial replacement for cement, it can enhance the concrete's microstructure due to its pozzolanic properties, which contribute to reduced porosity and improved durability. This results in less moisture loss during the drying process, thereby mitigating drying shrinkage. Additionally, the incorporation of finely ground glass particles helps in filling voids within the concrete matrix, further reducing shrinkage potential. Figure 10 illustrates the effect of glass powder dosage on the drying shrinkage of glass-fiber-reinforced cementitious (GFRC). GP-0 exhibited the highest drying shrinkage, measuring $-569.3\,\mu\varepsilon$ at 56 days. In contrast, GPIV-25 showed a drying shrinkage of $-342.3\,\mu\varepsilon$ at 56 days, a reduction of 39.9% compared to GP-0. As the glass powder content increased, the drying shrinkage of GFRC composites decreased, indicating that glass powder addition mitigates drying shrinkage in GFRC, which is advantageous for its applications. This reduction occurs because the small glass powder particles fill the pores of the GFRC, and the pozzolanic reaction between GP and CH enhances the pore structure of GFRC. Thus, incorporating GP reduces GFRC's drying shrinkage.

Studies [81–85] consistently demonstrate that GWG positively impacts drying shrinkage of concrete, primarily through microstructural improvements. It significantly reduces shrinkage by filling micropores and undergoing pozzolanic reactions, which refine the pore structure. The inclusion of GWG also enhances packing density and

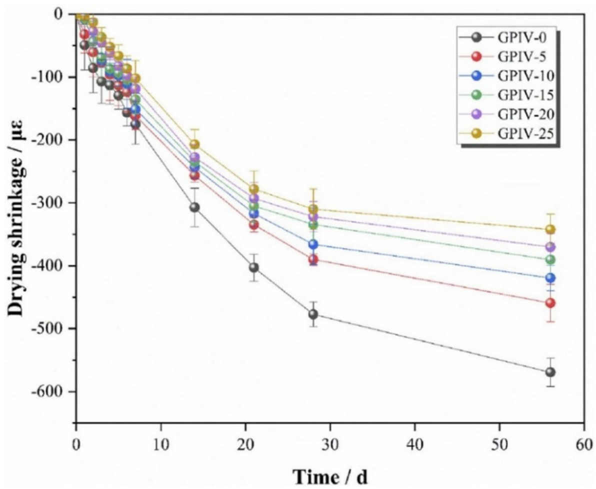


Figure 10. Drying shrinkage of the GFRC specimens with different glass powder dosages by weight [80].

modifies nanopore structures, leading to lower moisture loss and reduced capillary stress. These effects are observed across various cementitious composites, contributing to a denser and more stable matrix. However, further investigation is needed to fully understand the long-term durability and environmental implications of incorporating GWG into concrete. However, in some cases, the addition of glass powder can lead to an increase in drying shrinkage depending on the pozzolanic reaction between GP and calcium hydrate (CH) that leads to the formation of C-S-H. The increased reactivity can consume more water leading to increased shrinkage [86]. As noted by Omran & Tagnit-Hamou [11], another factor that may affect the drying shrinkage is the release of chemically bound water during the shrinkage process. Here, the fine particles of glass powder and its pozzolanic nature contribute to higher moisture retention, which when lost enhances shrinkage.

Figure 11 illustrates the autogenous shrinkage behavior of different concrete mixes over a 28-day period. The y-axis represents autogenous shrinkage in microstrain (με), while the x-axis denotes time in days. The control mix (CON) and various glass fiber-reinforced mixes (GF2.5 to GF15, indicating different dosages in percentage) are compared. Overall, all mixes experience a rapid initial shrinkage, which gradually stabilizes over time. The control sample (CON) shows moderate shrinkage compared to fiber-reinforced samples. GF7.5 exhibits the highest shrinkage, reaching nearly −700 με, indicating that increased fiber content beyond an optimal point may exacerbate shrinkage. Conversely, moderate fiber contents, especially GF5 and GFP10, demonstrate a balance between controlling shrinkage and maintaining material integrity. GFP5 shows the least shrinkage after the control, suggesting pozzolanic glass fibers may help mitigate autogenous shrinkage. The trend implies that fiber type and dosage critically influence shrinkage performance, highlighting the need for optimized mix designs.

GWG significantly affects the autogenous shrinkage of concrete. When incorporated as an SCM, ground glass enhances the concrete's microstructure due to its pozzolanic reaction with calcium hydroxide, producing additional C-S-H. This reaction reduces the porosity and refines the pore structure, mitigating autogenous shrinkage by limiting internal moisture movement. Moreover, the glass particles fill voids in the concrete matrix, reducing the extent of self-desiccation.

4.3.2. *Creep*

The inclusion of GWG in concrete positively influences its creep behavior. GWG reduces creep by enhancing the microstructure, thanks to its pozzolanic activity, which refines the pore structure and strengthens the interfacial transition zone. This results in a denser and more durable matrix. The fine particles of GWG fill voids and reduce the overall porosity, leading to improved load distribution and less deformation under sustained stress. Additionally, the chemical interactions between GWG and cement hydrates contribute to a more stable microstructure, further mitigating creep in concrete.

Figure 12 illustrates the variation in creep coefficient over a period of 180 days for different concrete mixes: plain concrete (C), and concrete blended with 10%, 20%, and 30% ground pozzolana (GP) labelled as C + 10GP, C + 20GP, and C + 30GP, respectively. The creep coefficient increases rapidly during the initial 40 days and then gradually levels off for all mixes. Plain concrete (C) exhibits the highest creep coefficient throughout the test duration, indicating greater long-term deformation under sustained load. The addition of GP significantly reduces the creep coefficient, with C + 20GP showing the lowest value, suggesting optimal improvement in creep resistance. Interestingly, at 30% GP, the creep coefficient increases slightly compared to 20% GP, indicating a diminishing return or possible compromise in mix performance at higher GP content. Overall, the data suggest that incorporating ground pozzolana improves the long-term deformation resistance of concrete, with 20% GP providing the most effective balance between performance and durability.

The influence of GWG on the creep of concrete has been investigated across several studies, highlighting both benefits and limitations. Jiang et al. [8] provided a

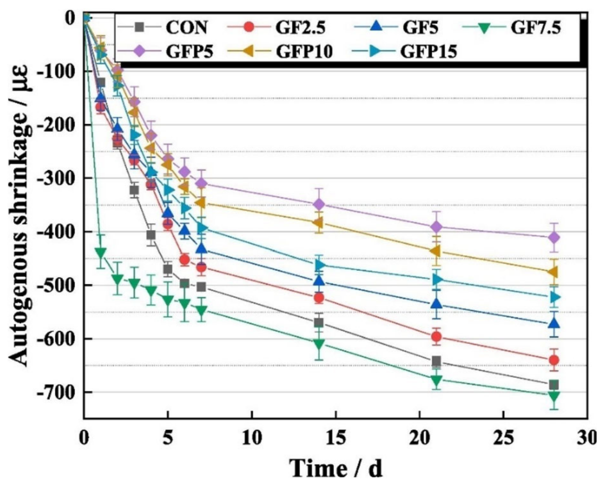


Figure 11. Autogenous shrinkage of mortars with different GF or GFP dosages by weight [87].

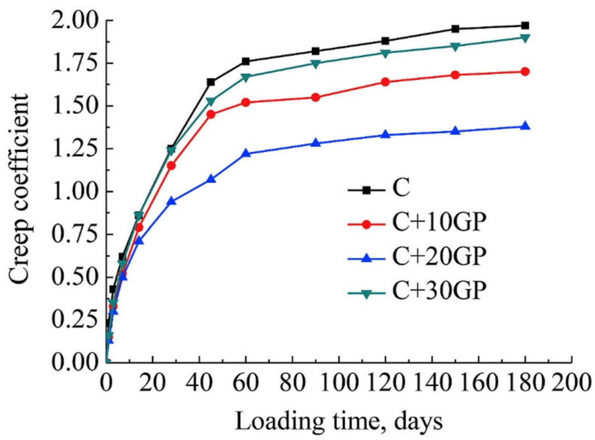


Figure 12. Effect of glass powder on creep strain of concrete [88].

comprehensive review of GWG's multiple roles in cement-based materials. They emphasize that GWG enhances the microstructure of concrete by participating in pozzolanic reactions that refine the pore structure. This improvement generally contributes to reduced creep by decreasing the porosity and enhancing the load-bearing capacity of the concrete matrix. However, the effectiveness of GWG in mitigating creep is influenced by its particle size and proportion relative to other components. Kumar et al. [89] explored the combined effects of GWG and recycled steel fibers on concrete's mechanical behavior. Their findings suggest that while GWG improves creep resistance by filling voids and contributing to a denser matrix, the inclusion of steel fibers further enhances this effect. Steel fibers help distribute stresses more evenly, reducing the potential for excessive deformation under sustained loads. The synergistic effect of GWG and steel fibers indicates that the reduction in creep strain is more pronounced when both are used together.

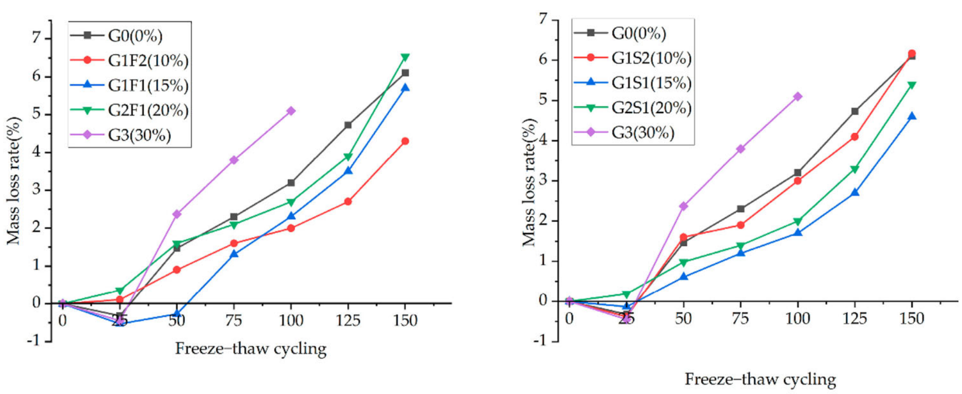
4.4. Durability

4.4.1. Freeze-thaw resistance

The incorporation of GWG into concrete significantly enhances its freeze-thaw resistance. Freeze-thaw cycles, common in cold climates, cause internal pressure and damage due to water ingress and freezing. GWG contributes to durability by improving concrete's microstructure. Its pozzolanic reactivity forms additional cementitious compounds, creating a denser, less permeable matrix that minimizes water penetration. Finer GWG particles effectively fill voids, reducing capillary porosity and pathways for ice formation. Additionally, GWG refines the pore structure, restricting water movement and internal ice formation. Studies confirm that GWG enhances freeze-thaw resistance through reduced permeability, refined pore structure, and its pozzolanic activity.

The influence of GWG on the freeze-thaw resistance of concrete has been investigated in several studies, providing valuable insights into the performance of concrete containing glass-based materials. Kim et al. [90] delved into the durability properties of concrete, specifically focusing on waste glass sludge under realistic environmental conditions. While their investigation contributes valuable insights, the exclusive concentration on a particular type of glass waste limits the scope of the study. A broader and comparative analysis involving various GWG sources is necessary to establish a more comprehensive understanding of the material's behavior in different contexts and compositions. Lee et al. [91] provided an assessment of concrete performance with glass powder and glass sludge as supplementary cementing material, showcasing potential benefits. However, a more thorough scrutiny reveals that a deeper exploration into the long-term effects and potential drawbacks associated with GWG usage is essential. Zhu et al. [92] conducted a crucial experimental study, investigating the influence of GWG on the freeze-thaw resistance of concrete (Figure 13). Focusing on long-term mechanical properties and durability, their research adds significant insights. By incorporating waste glass into Ordinary Portland Cement (OPC) concrete, the study explores the material's performance under freeze-thaw cycles. Such investigations are vital for sustainable construction practices, providing valuable data on the potential benefits and challenges associated with using GWG in concrete. Understanding the interplay between waste glass and freeze-thaw resistance contributes to enhancing the overall durability and performance of concrete structures.

In a study conducted by He et al. [93], the fine aggregate was replaced by WGP, waste rubber, and a mixture of both. After 100 freeze-thaw cycles, the samples containing glass powder increased brittleness and exhibited poor surface resistance due to its low tensile strength, leading to surface erosion. This was likely caused by the excessive surface tension exceeding the glass powder's strength during freezing. On the other hand, glass powder refined the internal microstructure by increasing gel and transition pores and reducing capillary pores, which enhanced the concrete's overall frost resistance and reduced internal damage. Smaller pores delayed freezing, further protecting the internal structure. Interestingly, concrete containing both rubber waste and glass powder in the ratio of 10% each showed much satisfactory results relative to plain concrete showing the lightest spalling and a low deterioration rate. It could be due to low stiffness of rubber crumbs that enhanced the deformation resistance of concrete.



(a) (b)

Figure 13. Mass loss due to freeze-thaw cycles [92].

Bisht & Ramana [86] conducted an experimental investigation into concrete mixes with beverage glass waste, introducing an unconventional source. Nevertheless, a more extensive exploration of the long-term durability and environmental implications of incorporating beverage glass waste is pivotal for a comprehensive assessment. Understanding the unique challenges and benefits associated with this unconventional glass source is crucial for informed decision-making. Nazir et al. [94] examined the durability properties of fiber-reinforced geopolymer mortar made with recycled concrete aggregate and glass powder, representing an innovative approach. From a critical perspective, there is a need for a more detailed examination of structural implications and the potential for scaling up such novel concrete formulations. Understanding the structural performance and scalability of these innovative materials is essential for their practical application in construction projects. The impact of GWG on the freeze-thaw resistance of concrete remains inconsistent, emphasizing the need for further research into particle size, activation methods, and mix designs. He et al. [93] observed brittleness and surface erosion after 100 freeze-thaw cycles, linked to excessive surface tension surpassing tensile strength. Finer GWG particles, however, reduced capillary pores and enhanced frost resistance. Adding 10% rubber waste improved performance by increasing deformation resistance and lowering stiffness. Zhu et al. [92] highlighted GWG's role in enhancing frost resistance, while Bisht & Ramana [86] explored unconventional sources. Standardized testing is essential to optimize GWG for sustainable concrete production.

The exploration of glass-based materials in concrete's freeze-thaw resistance is insightful. Studies highlight benefits, yet a broader understanding and scrutiny of long-term effects are essential. Emphasis on sustainability, as seen in recent research, prompts consideration of economic feasibility and scalability challenges. The introduction of a novel glass source adds complexity, requiring in-depth durability exploration. The innovative approach in geopolymer studies underscores the need for a nuanced understanding of structural implications. While these studies contribute significantly, gaps persist, demanding comprehensive research to practically integrate GWG across diverse concrete applications.

4.4.2. Chloride attack resistance

GWG, when used as an SCM in concrete, can significantly influence the chloride resistance of the final structure. The incorporation of finely powdered glass into the mix enhances the concrete's durability by mitigating chloride ion penetration. This is crucial in preventing corrosion of reinforcing steel, a common issue in concrete structures exposed to corrosive environment. The pozzolanic reaction between the glass particles and calcium hydroxide in the cement matrix forms additional cementitious compounds, creating a denser and less permeable microstructure. The release of sodium ions (Na^+) upon the addition of glass powder acts as depolymerization agents, breaking down polymerized silica into more reactive forms. During OPC hydration, the C-S-H gel and reactive silica from the glass powder react with CH, producing C-(N)-S-H gels with a low (Ca/Si) ratio. The formation of these pozzolanic products enhances the pore structure and densifies the microstructure of the concrete. This refined pore structure can inhibit moisture transport and oxygen diffusion [95], incorporation of glass powder increases alkalinity of the pore solution preventing steel corrosion induced by carbonation or chloride penetration due to the stable passivation effect [96]. As a result, the concrete becomes more resistant to chloride ingress, improving its long-term performance in chloride-laden environments such as coastal areas or de-icing salt exposure.

Du & Tan [42] undertook chloride diffusion and migration assessments on glass powder concrete to scrutinize its resistance against chloride penetration. After 56 days of immersion, Figure 14a illustrates the chloride content profiles across the diffusion distance. The reference concrete exhibited the highest chloride content at all depths, indicating its inferior resistance. Furthermore, Figure 14b presents the apparent diffusion coefficient, derived through regression analysis, revealing a value of 36.92×10^{-12} m^2/s for the reference concrete. This coefficient notably declines with glass powder incorporation in the binder, irrespective of the replacement level. The

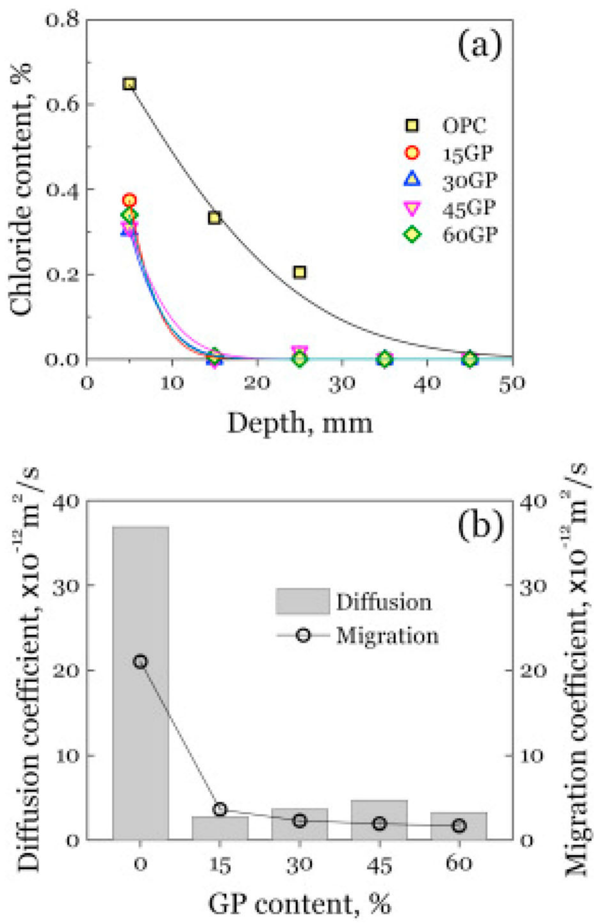


Figure 14. (a) Chloride content profiles and (b) chloride diffusion coefficient and migration coefficient for concrete-containing glass powder [42].

diminished chloride diffusivity is attributed to the denser microstructures of the paste at the interfacial transition zone (ITZ) and the reduced pore size and connectivity. Collectively, these studies suggest a consistent trend toward improved chloride resistance and durability in concrete with the incorporation of glass powder, affirming its potential as a sustainable and effective supplementary material in concrete production.

Figure 15 represents the outcomes of the rapid chloride permeability test as per ASTM C1202 [97]. This test gauges chloride permeability in concrete by measuring the charge passed across the specimen. Notably, except for the concrete modified with 5% GP2 after 28 days of curing, the introduction of glass powders GP1 and GP2 at 5%, 10%, 15%, and 20% replacement levels consistently lowered chloride permeability compared to the control concrete across all ages. The decline in chloride permeability values demonstrated an escalating trend with higher replacement levels of cement with glass powders, emphasizing the beneficial impact of glass powder incorporation on reducing chloride permeability in concrete. GP1 exhibits a greater reduction in chloride permeability than GP2 due to its finer particle size and higher reactivity. Smaller particles in GP1 provide a greater surface area for pozzolanic reactions, leading to the formation of more secondary C-S-H gel. This gel reduces porosity and enhances the concrete's resistance to chloride ion penetration. Additionally, the finer particles fill micro-voids more effectively, improving the material's overall density and durability. Conversely, GP2, with relatively coarser particles, has lower reactivity and a lesser ability to fill voids, resulting in comparatively higher chloride permeability as observed across all testing periods.

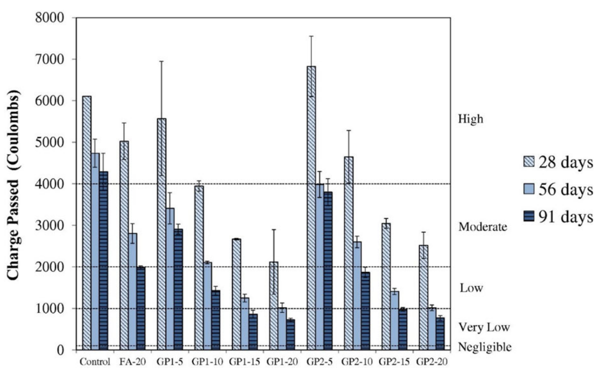


Figure 15. Rapid chloride permeability test results of concretes modified with glass powders (GP1 and GP2) and FA at various ages [98].

Table 3 highlights the benefits of incorporating glass powder into concrete, focusing on durability and sustainability. The pozzolanic reaction between glass particles and calcium hydroxide results in additional cementitious compounds, creating a denser and less permeable microstructure that enhances resistance to chloride ingress. When it comes to chloride permeability, glass powder acts both as a pore filler and a reactive agent, effectively reducing permeability at varying replacement levels. This leads to improved durability over time. The chloride diffusion coefficient also decreases due to a denser interfacial transition zone and lower pore connectivity, limiting chloride penetration. Increased alkalinity from glass powder contributes to the stabilization of the steel reinforcement's passivation layer, reducing the risk of corrosion in aggressive environments such as those exposed to de-icing salts or marine conditions. Finally, the use of waste glass promotes sustainability, improving concrete strength and durability while supporting eco-friendly construction and reducing landfill waste.

Table 3. Impact of ground waste glass on concrete durability and chloride resistance: mechanisms and benefits.

Aspect	Mechanism	Impact	Study/Findings	References
Pozzolanic reaction	Reaction between glass particles and calcium hydroxide forms additional cementitious compounds.	Creates a denser and less permeable microstructure.	Improves chloride resistance by reducing permeability.	[95]
Chloride permeability	Glass powder acts as a pore-filling and pozzolanic agent.	Lowers chloride permeability at 5%, 10%, 15%, and 20% replacement levels.	Enhanced durability compared to control concrete across all ages.	[98]
Chloride diffusion coefficient	Denser interfacial transition zone (ITZ) and reduced pore connectivity.	Reduces chloride diffusion coefficients significantly.	Reference concrete shows higher diffusion, while glass powder reduces chloride penetration depth.	[42]
Alkalinity and steel corrosion	Increased alkalinity of pore solution stabilizes the steel passivation layer.	Prevents steel corrosion induced by carbonation or chloride ingress.	Enhances long-term durability in corrosive environments such as coastal areas or exposure to de-icing salts.	[96]
Sustainability and practical use	Utilizes recycled waste glass as an SCM in concrete production.	Improves concrete durability and strength while contributing to sustainable construction practices.	Demonstrated viability in large-scale applications and reduction in environmental waste.	[99,100]

4.4.3 Sulfate attack

The incorporation of glass powder in concrete significantly influences its resistance to sulfate attack. Glass powder, an SCM, contributes to the formation of durable and sulfate-resistant concrete. When exposed to sulfate-rich environments, glass powder reacts with calcium hydroxide to form additional C-S-H gel, bolstering the concrete's structure. This enhanced C-S-H gel reduces the permeability of concrete, preventing sulfate ions from penetrating the matrix and causing deterioration. The study performed by Das et al. [101] suggests that with the increase in glass powder content in concrete, it leads to significant changes in the material's interaction with sulfate attack. Glass powder engages in a pozzolanic reaction with portlandite ($Ca(OH)_2$), a product of cement hydration, converting it into additional C-S-H gel. This process reduces the availability of portlandite for sulfate-induced ettringite formation, which is responsible for expansive damage in concrete exposed to sulfates. Furthermore, carbonation transforms portlandite into calcium carbonate, further depleting the calcium hydroxide required for ettringite development. Studies, including X-ray diffraction (XRD) analysis, have shown that as glass powder content increases, the intensity of ettringite peaks diminishes, even under prolonged sulfate exposure. At higher levels of replacement, the ettringite peaks almost disappear, indicating reduced susceptibility to sulfate-induced cracking. Therefore, increasing the glass powder content can enhance the concrete's sulfate resistance by limiting harmful ettringite formation and reducing porosity, leading to a more durable and stable matrix in sulfate-rich environments [101]. Consequently, the presence of glass powder improves the concrete's resistance to sulfate attack, resulting in a more durable and enduring construction material.

Rashidian-Dezfouli & Rangaraju [102] provided a comparative study on geopolymers produced with glass powder in sodium sulfate solution, indicating its durability benefits. Similarly, Tayeh et al. [17] explored the sulfate resistance of cement mortar containing glass powder, contributing to the understanding of its effectiveness in resisting sulfate attack. Kasaniya et al. [103] investigated the efficiency of GWGs in mitigating sulfate attack, expanding the discussion to include natural pozzolans and coal bottom ashes. Balasubramanian et al. [60] conducted an experimental investigation on concrete partially replaced with WGP and waste E-plastic, showcasing the potential of glass powder in sustainable concrete solutions. Shalan and El-Gohary [104] focused on the long-term sulfate resistance of blended cement concrete with WGP, emphasizing its durability over time. Collectively, these studies indicate that glass powder incorporation in concrete has a positive impact on mitigating sulfate attack, enhancing the material's durability and potential for sustainable construction practices.

The effect of glass powder on the resistance of concrete to sulfate attack has been a subject of interest in various studies. Chaïd et al. [105] focused on the microstructure and permeability of concrete with glass powder in a sulfatic environment. They observed that glass powder addition influenced the concrete's durability, highlighting its potential to mitigate sulfate attack. Matos and Sousa-Coutinho [106] conducted a macro and micro-scale study on WGP in cement, revealing insights into its impact on concrete properties. The study by Cao et al. [107] elucidates the mitigation effect of glass powder on external sulfate attack in concrete, focusing on its relationship with the alkalinity of pore solution. Glass powder, when incorporated into concrete, enhances resistance to sulfate attack as can be seen in Figure 16. The pozzolanic reaction of glass powder with calcium hydroxide produces additional C-S-H gel, reinforcing the concrete structure. This reaction, coupled with increased alkalinity, leads to the formation of sulfate-resistant compounds such as ettringite. The study emphasizes that glass powder improves concrete durability against sulfate attack, offering insights into the interplay between glass powder, pore solution alkalinity, and enhanced sulfate resistance.

The research collectively highlights the positive influence of glass powder on concrete's resistance to sulfate attack. Studies delve into microstructural changes, permeability, and macro-scale effects, consistently showcasing the potential of glass powder to enhance concrete durability in sulfatic environments. From WGP to geopolymers, the literature underscores its diverse applications and effectiveness in mitigating sulfate attack. The investigations into GWGs, natural pozzolans, and coal bottom ashes further emphasize the versatility of glass powder in countering sulfate aggression. Experimental studies, such as those involving waste E-plastic, demonstrate its potential in sustainable concrete solutions. Long-term assessments emphasize glass powder's enduring positive impact, positioning it as a potentially valuable component for durable and sustainable construction materials.

4.4.4. Carbonation

GWG, when used as a partial replacement for cement in concrete, can influence carbonation. Due to its amorphous structure, glass particles enhance the pozzolanic reaction, increasing calcium hydroxide consumption. This accelerates carbonation, as carbon dioxide reacts with calcium hydroxide to form calcium carbonate. The presence of glass can enhance the density and strength of the concrete matrix, potentially slowing down carbonation over time due to reduced permeability. However, factors such as glass particle size, content, and curing conditions also play vital roles in determining the extent of carbonation. The study by Das et al. [101] meticulously examined carbonation in concrete with varying ratios of glass powder replacement and identified three key factors influencing concrete as the replacement ratio exceeds the optimal value. First, the inclusion of glass powder as a cement replacement increases the amount of free water in the mix due to the material's low absorption capacity and smooth surface texture. As the glass powder content rises, the free water also increases, resulting in more interconnected voids and higher porosity in the cement paste, which accelerates the penetration of CO_2. Second, glass powder, being relatively inert, slows the hydration process, thereby

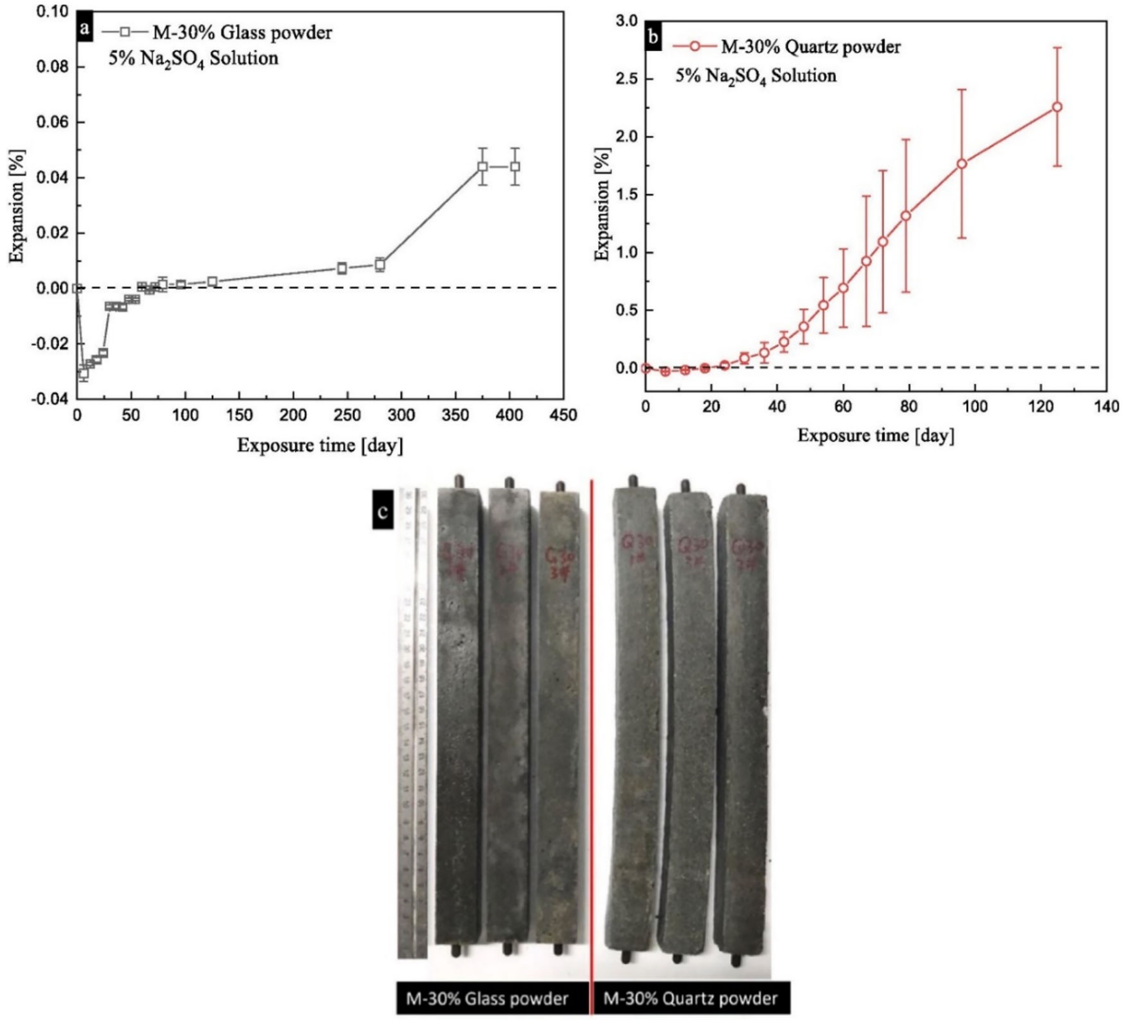


Figure 16. Expansion of mortar bars blended with (a) 30% glass powder; (b) 30% quartz powder and, (c) pictures of samples immersed in 5% Na_2SO_4 solution for 100 days [107].

raising the degree of carbonation. Lastly, the presence of glass powder aids in dispersing cement particles, providing more access for CO_2 to react and serving as nucleation sites for the precipitation of calcium carbonates. These factors together can lead to an increased susceptibility of concrete to carbonation when the replacement ratio of glass powder exceeds the optimal level.

Liu et al. [108] studied the role of recycled waste glass incorporation on the carbonation behavior of sodium carbonate-activated slag mortar. The study findings suggest that a high dosage of sodium carbonate or water glass as an activator enhances resistance to carbonation (Figure 17). As depicted in Figure 5(a), mortars activated with 3% Na_2O attained complete carbonation prior to the 28-day test, reaching a depth of 20 mm. Conversely, Figure 5(b) illustrates that mortars activated with a higher dosage of activator (5% Na_2O) exhibited improved resistance to carbonation. Additionally, incorporating 30% RGP in GGBS binder systems significantly improves carbonation resistance in mortars, reducing shrinkage and increasing strength. RGP in sodium carbonate-activated GGBS blends does not alter reaction product species but promotes nahcolite formation post-carbonation, with less bound water loss and calcium carbonate formation. RGP-containing samples exhibit a higher volume of gel pores (<10 nm), enhancing carbonation resistance. Overall, RGP incorporation in sodium carbonate-activated GGBS mortars improves resistance to carbonation, offering potential benefits in concrete durability.

The influence of GWG (WGG) on concrete carbonation is scrutinized across several studies. Matos and Sousa-Coutinho [106] delved into WGG's impact at macro and micro scales, hinting at its potential to bolster concrete durability. Limbachiya et al. [109] investigated granulated foam-glass concrete, suggesting promising performance in resisting carbonation. De Castro & de Brito [110] evaluated concrete's durability with crushed glass aggregates, finding encouraging results. Matos et al. [111] showcased durability improvements in self-compacting concrete incorporating WGG. Sales et al. [112] and Ali-Boucetta et al. [113] examined mortar durability with fine glass particles, both reporting favorable outcomes. Additionally, Liu et al. [114] explored WGG as a binder in alkali-activated mortars, indicating its potential utility in mitigating carbonation. Collectively, WGG incorporation in concrete formulations holds promise for enhancing resistance to carbonation, where glass powder is added in an optimal amount (up to 30%). However,

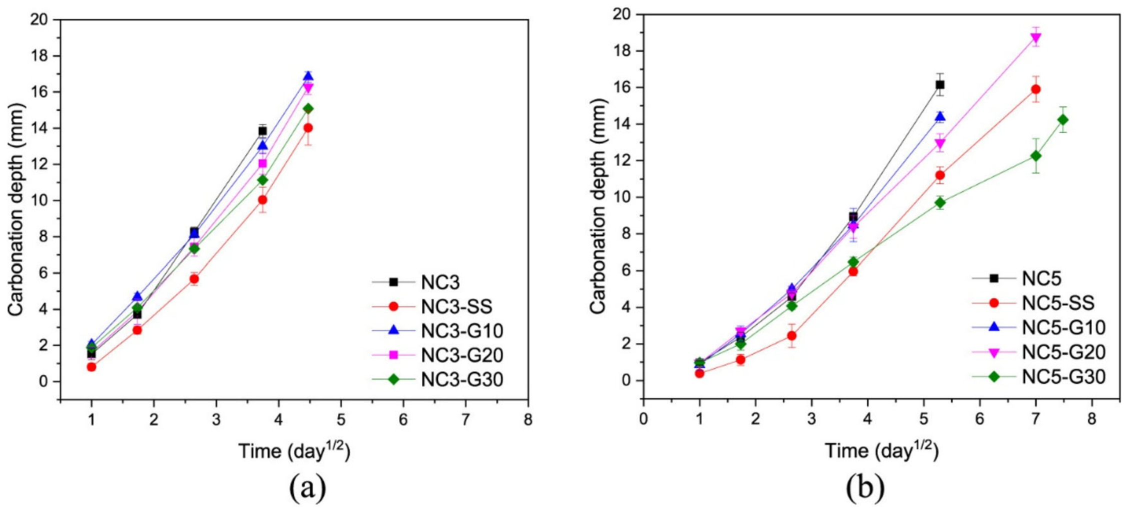


Figure 17. Carbonation depth of different mixtures (a) 3% Na_2O% series mortars and (b) 5% Na_2O% series mortars (No data after spot means a full carbonation) [108].

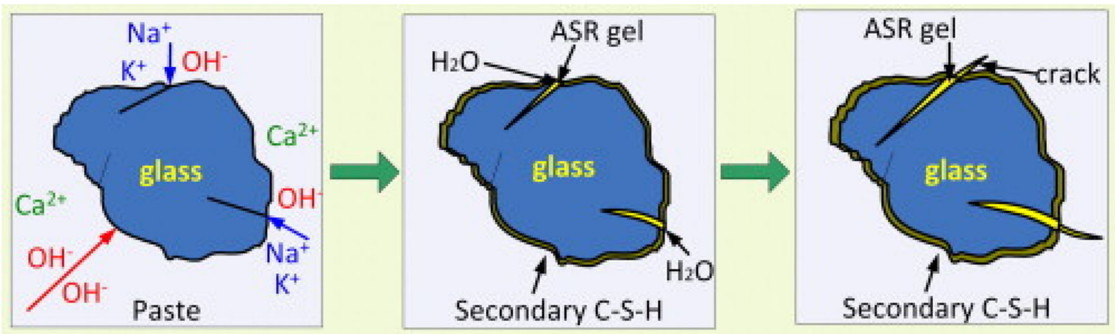


Figure 18. ASR gels formation in the cracks inside of the glass particles [59].

further research is necessary to comprehensively understand its mechanisms and optimize its effectiveness. Factors such as WGG particle size, content, and curing conditions should be explored to unlock the full potential of WGG in improving concrete's durability against carbonation, thereby contributing to sustainable construction practices.

4.4.5. Alkali-silica reaction

GWG in concrete can mitigate alkali-silica reaction (ASR) due to its pozzolanic properties. ASR occurs when alkalis in concrete react with certain types of reactive silica in aggregates, leading to gel formation and expansion, causing cracking and deterioration. Incorporating GWG reduces the availability of alkalis by consuming them during pozzolanic reactions, thereby suppressing ASR. Additionally, the amorphous silica present in glass can react with alkalis to form stable compounds, further inhibiting ASR. Properly sized and distributed glass particles can effectively mitigate ASR, improving the durability and longevity of concrete structures.

Figure 18 visually represents the ASR development in cement mortar incorporating large waste glass aggregate [59]. It reveals a crucial aspect: the size of the glass particles significantly influences ASR progression. Larger glass particles, when subjected to the milling process, are more susceptible to cracking compared to smaller ones. As these cracks form, they become sites for the formation of ASR gel within the glass particles themselves. This internal gel exacerbates the deterioration of the composite material, further amplifying ASR expansion. This insight underscores the importance of understanding the role of aggregate size in ASR mechanisms for effective concrete design and durability management. The mitigation of ASR, as illustrated in Figure 18, involves the interaction of alkali ions, silica from GWG, and moisture. In this study, the coarse aggregate had a maximum particle size of 20 mm. For GWG, the optimum particle size range for reducing ASR was found to be 75 to 150 μm. This particle size promotes pozzolanic reactions while minimizing the formation of ASR gel, contributing to effective mitigation. Including these details highlights the critical role of aggregate and GWG particle sizes in managing ASR, enhancing the clarity and practical applicability of the findings.

Contrary to the conventional expectation of higher ASR with larger surface area glass, empirical findings demonstrate reduced expansion with decreased glass particle size. Rajabipour et al. [115] suggested ASR expansion primarily occurs within microcracks induced by glass rather than on its surface. Smaller glass particles induce fewer cracks and pores in cementitious materials, thereby mitigating ASR expansion. Additionally, fine glass exhibits high pozzolanic reactivity, forming nonexpansive C-S-H and consuming calcium in composites. This accumulation of C-S-H and decreased calcium concentration further inhibits ASR gel formation and expansion. Furthermore, Maraghechi et al. [116] observed that cracks within crushed glass particles act as sites for ASR gel generation. A multitude of research endeavors have delved into examining the effectiveness of high-alkali waste glass in counteracting ASR. Researchers [117–126] have contributed significantly in this domain. Collectively, their findings indicate that GWG holds promise in mitigating ASR-induced expansion. Moreover, finer particle sizes have been consistently associated with enhanced efficacy in this regard, as highlighted by studies conducted by Zheng [127].

4.4.6. Acid attack resistance

GWG plays a pivotal role in bolstering the acid attack resistance of concrete. When incorporated into concrete mixtures, finely ground glass particles react with the cementitious matrix, forming secondary cementitious compounds that enhance the concrete's durability. This reaction reduces the permeability of the concrete, fortifying it against the ingress of acidic substances. Additionally, the incorporation of GWG helps fill pores within the concrete, reducing its susceptibility to acid penetration and subsequent deterioration. By mitigating acid attack, the utilization of GWG not only enhances the longevity and performance of concrete structures but also fosters sustainable practices by repurposing waste materials.

Research into the acid resistance of cementitious materials incorporating waste glass has produced mixed findings. Lu et al. [128] conducted experiments involving mortar samples submerged in a 3% sulfuric acid solution, revealing diverse weight changes. They observed substantial mass loss in plain mortar, while mortar modified with fine glass exhibited a slight weight increase. This phenomenon suggests that finer waste glass particles contribute to enhanced performance against acid attack. This improvement is attributed to several factors, including increased consumption of portlandite, augmented generation of C-S-H, and the unique vitreous structure of glass, which collectively bolster the mortar's resilience. Siad et al. [129] found that mortars containing a combination of glass and limestone powder displayed the highest resistance to acid, followed by those with FA and slag. Furthermore, they noted that the acid resistance increased proportionally with the inclusion of glass powder, reaching its peak at 45%.

Wang & Huang [44] observed a gradual enhancement in acid resistance in self-compacting concrete as the content of waste LCD glass increased. However, Wang [130] reported contradictory results, indicating increased weight loss in mortars with higher levels of glass powder. This discrepancy was attributed to a reduced pozzolanic reaction and cement hydration due to higher substitution rates of cement with glass powder. XRD study conducted by Das et al. [101], reveals the presence of primary hydration products such as belite, ettringite, portlandite, and C-S-H. These products undergo chemical changes when exposed to an acidic environment over time, with portlandite dissociating and the transformation of C-S-H and calcium aluminosilicates into secondary phases such as ettringite. The formation of ettringite increases as acid exposure continues, indicating the degradation of the matrix. This behavior is typical of water-cured samples, where the ongoing acid attack progressively breaks down hydration products, increasing porosity and making the concrete more susceptible to further deterioration. As a result, prolonged acid exposure weakens the integrity of water-cured concrete, leading to potential structural vulnerabilities. Thus, while the incorporation of waste glass generally improves acid resistance in cementitious materials, the effectiveness may vary depending on factors such as particle size and substitution rates.

5. Compatibility of GWG with cementitious systems

5.1. Interaction with Portland cement

The interaction of glass powder with Portland cement plays a pivotal role in the development of sustainable and HPC mixes. When utilized as a supplementary SCM, glass powder engages with Portland cement through various mechanisms. Primarily, glass powder demonstrates pozzolanic reactivity, undergoing a reaction with the calcium hydroxide generated during Portland cement hydration. This reaction results in the formation of additional C-S-H gel, contributing to the densification of the concrete matrix and thereby enhancing both strength and durability. Additionally, the amorphous nature of glass powder serves as nucleation sites for the early stages of cement hydration. This facilitates the formation of hydration products and accelerates the setting time of the concrete. This interaction is critical for achieving the desired early-age properties and overall performance of the concrete. Moreover, the incorporation of glass powder alongside Portland cement offers the potential to reduce the overall clinker content, thereby mitigating the environmental impact associated with cement production. This sustainable approach aligns with ongoing efforts to reduce carbon emissions in the construction industry. However, it is imperative to exercise careful consideration in optimizing the glass powder content to prevent potential issues such as excessive retardation of setting time or undesirable changes in workability. Proper understanding and control of the interaction between glass powder and Portland cement are indispensable for harnessing the beneficial effects of this supplementary material in the production of high-quality, sustainable concrete. This nuanced approach ensures that the incorporation of glass powder contributes not only to improved concrete properties but also aligns with broader environmental goals in the pursuit of a more sustainable construction industry.

5.2. Influence on cement hydration

The interaction of glass powder with cement hydration processes significantly influences the properties of concrete, offering both performance enhancements and sustainable advantages. One of the key mechanisms through which glass powder exerts its influence is the pozzolanic reactivity. During cement hydration, the production of calcium hydroxide occurs. Glass powder, as an SCM, reacts with this calcium hydroxide, resulting in the formation of additional C-S-H gel [131]. This reaction is pozzolanic in nature and contributes to the densification of the cement matrix. The increased formation of C-S-H gel enhances the strength and durability of the concrete, leading to improved mechanical properties. In addition to its pozzolanic reactivity, the amorphous nature of glass powder provides nucleation sites for the early stages of cement hydration [132,133]. These sites facilitate the rapid formation of hydration products, including C-S-H gel, accelerating the setting time of the concrete. The early strength development and accelerated setting time are crucial factors in achieving the desired properties and ensuring the practicality of concrete applications.

The influence of glass powder on cement hydration extends to environmental considerations, offering a sustainable approach to concrete production. By incorporating glass powder into cement mixes, there is potential to reduce the overall clinker content [134–136]. This reduction is significant in mitigating the environmental impact associated with traditional cement production, aligning with global efforts to reduce carbon emissions in the construction industry. The progression of the glass powder reaction degree, as depicted in Figure 19, indicates a faster reaction in the 10GP mix compared to the 20GP mix within the initial 7 days. Subsequently, the reaction rates in both mixes become comparable. Despite this, the absolute quantity of reacted glass powder at early stages appears relatively similar in both systems. This similarity suggests that the reaction is not constrained by the availability of glass powder but rather influenced by ionic concentrations in the pore solution and the overall evolution of the OPC-GP system.

While the benefits are substantial, careful optimization of the glass powder content is essential. Excessive amounts may lead to challenges such as prolonged setting times or undesirable changes in workability. Therefore, achieving a balanced and well-controlled incorporation of glass powder in cement mixes is crucial to ensuring the positive influence on cement hydration is maximized without compromising the practical aspects of concrete construction. Understanding the multifaceted interplay between glass powder and cement hydration is essential for harnessing the full potential of this supplementary material. This understanding not only contributes to the development of HPC with improved properties but also aligns with sustainability goals in the construction industry, making strides toward a more environmentally friendly and resilient built environment.

5.3. *Effects on pozzolanic activity*

The effects of adding GWG on pozzolanic reactivity are extensively explored in the cited references. Shi et al. [120] delved into the characteristics and reactivity of glass powders, emphasizing the importance of particle fineness. Khmiri et al. [138] studied the chemical behavior of GWG in mortars, indicating potential improvements in mechanical properties. Christiansen & Dymond [139] examined the impact of composition on GWG pozzolan performance, highlighting the need for careful material selection. Omran et al. [140] provided a comprehensive review, emphasizing the promising performance of ground-glass pozzolan in various applications. Carsana et al. [141] compared GWG with other SCMs, offering valuable insights into its viability. Kasaniya et al. [142] investigated pozzolanic reactivity of natural pozzolans, GWGs, and coal bottom ashes, addressing their influence on chloride permeability. Idir et al. [143] explored the pozzolanic properties of color-mixed glass cullet, contributing to the understanding of the potential variations in reactivity.

Figure 20 presents scanning electron microscope (SEM) images illustrating the microstructure of concrete incorporating WGP. Image (a) shows the interconnection of cement, glass powder, and other components, indicating a well-bonded matrix. Image (d) highlights the interaction between hydrated cement and WGP, suggesting partial reaction and integration of WGP. In image (e), the interface of WGP is visible, illustrating the boundary between glass particles and the cement matrix. Image (f) reveals the presence of voids and gaps, implying incomplete mixing or insufficient hydration. Image (g) captures

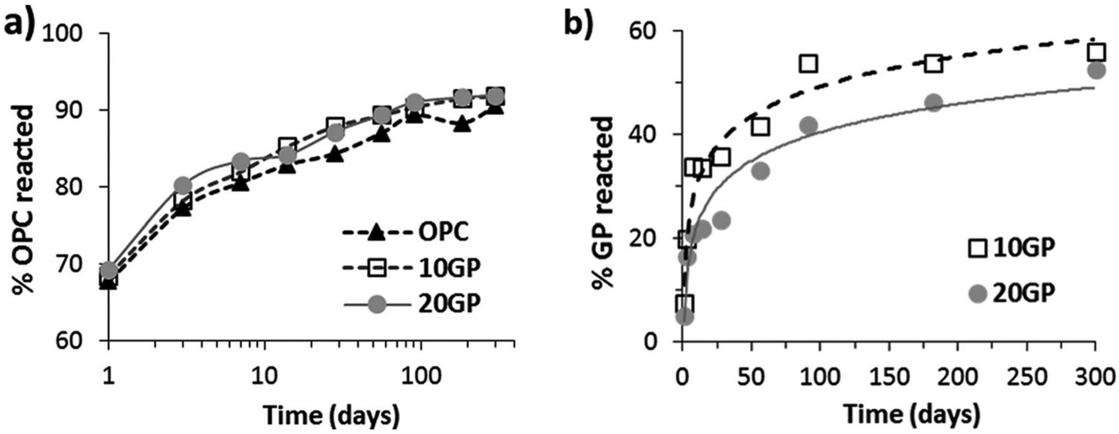


Figure 19. Degree of reaction of (a) OPC and (b) GP as a function of time [137].

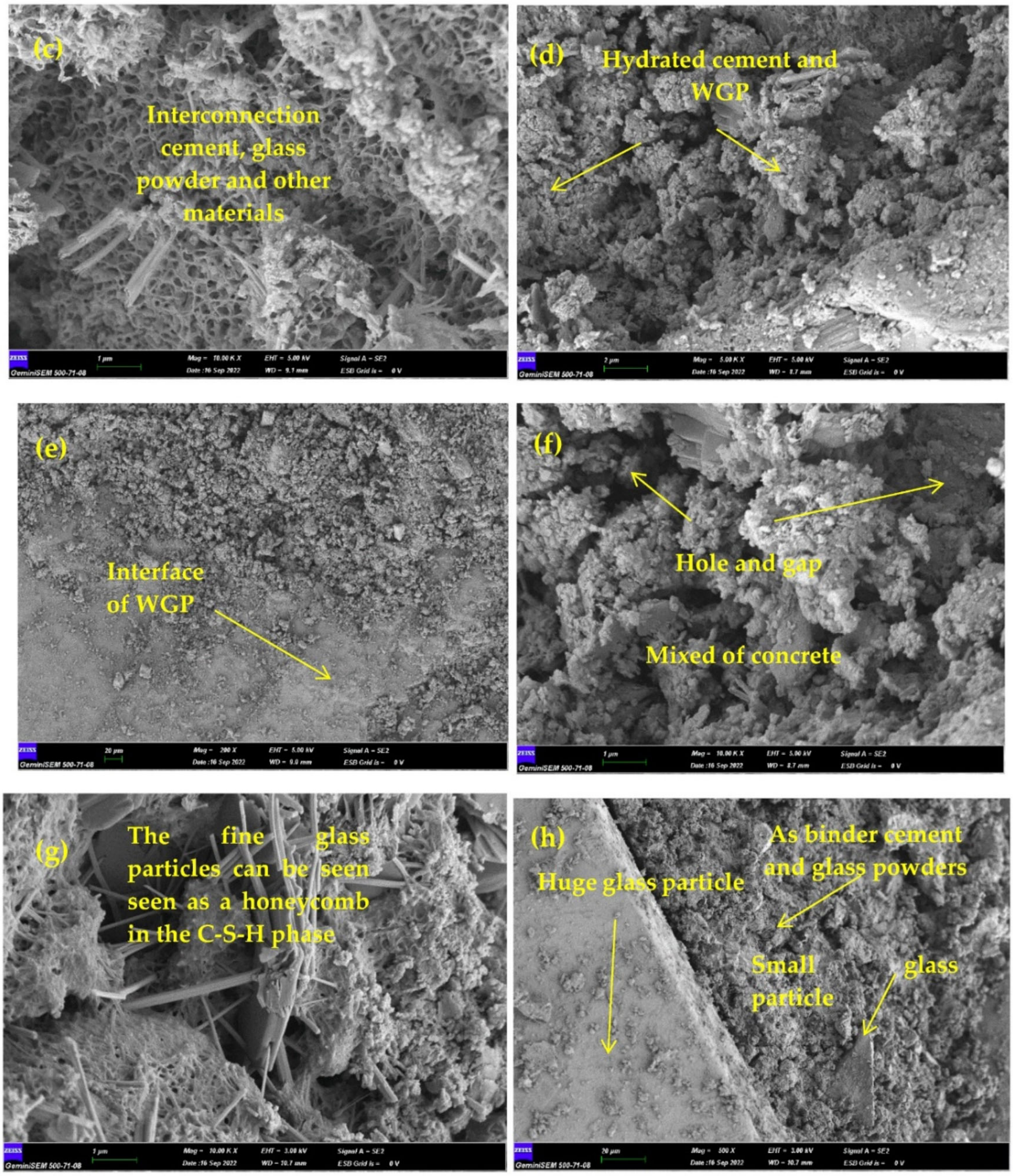


Figure 20. Microstructural analysis of concrete incorporating waste glass powder as cement replacement [66].

fine glass particles embedded in the calcium silicate hydrate (C-S-H) phase, forming a honeycomb-like structure, which may enhance mechanical properties. Finally, image (h) differentiates between large and small glass particles, showing how they act as fillers and binders within the cement matrix. Overall, the images demonstrate the physical interaction and dispersion of WGP in cementitious composites, influencing porosity and potential strength development.

The literature suggests that GWG can positively impact pozzolanic reactivity, offering environmental benefits and potential improvements in concrete properties. However, it is essential to consider factors such as particle size, composition, and long-term durability to harness its full potential effectively. Further research and standardization efforts are crucial for enhancing our understanding and promoting the sustainable use of GWG in concrete applications.

5.4. *Selection of an appropriate grade of concrete*

The selection of an appropriate grade of concrete for incorporating waste ground glass as an SCM is a crucial step in optimizing its performance and sustainability benefits. Waste ground glass, due to its high silica content, can act as a pozzolan, contributing to the strength and durability of concrete when properly processed and utilized. When selecting the grade of concrete, the intended application and performance requirements should guide the decision. For structural applications requiring high compressive strength, higher grades such as M30 or above are preferred, as these allow for lower water-cement ratios and higher cement content, maximizing the reactivity of the ground glass. The fineness of the glass and its pozzolanic activity also play a critical role in determining its effectiveness in higher grades. For nonstructural or lightweight applications, lower grades such as M15 or M20 can effectively incorporate ground glass as SCM, focusing on cost efficiency and sustainability. In these cases, higher proportions of glass may replace cement without compromising performance. The proportion of waste glass used must be carefully optimized to avoid issues such as alkali-silica reaction (ASR). Rigorous testing, including strength development and durability assessments, is essential to ensure that the selected concrete grade achieves the desired performance and environmental benefits.

6. Availability, standardization and environmental considerations

6.1. Availability of waste glass for use in concrete

Determining the availability of recycled waste glass for use in concrete would require comprehending the dynamics surrounding glass recycling and reuse in a wider context. First, the global production of glass, reported as 130 million tons [144], is significantly smaller than that of cement, which is reported as 3.7 billion tons [145]. This suggests that even if much of the recycled portion of waste glass would be made available for use as SCM in concrete, it would not be enough to decarbonize cement globally and is most likely suitable as a complementary localized solution for cement replacement in concrete. Further to this, glass can in fact a 100% recyclable material. It can in principle be recycled endlessly to produce new glass, with relatively lower carbon footprint. However, nowhere in the world glass is fully recycled with varying degrees of glass recycling in different countries, with nonrecycled glass mostly sent to landfill. The availability of recycled glass therefore plays an important role on the possibility of utilizing recycled glass in concrete as an SCM. As an example, In North America at the moment there is limited container glass recycling but it is apparently growing, and even more limited recycling of flat glass, even off-cuts from processing. However, it has been previously reported that 1–2 million tons, 400,000–500,000 tons and 180,000 tons of recycled containers, plate and E-glass could be made available for use as an SCM in concrete in North America [146].

As glass can be fully recycled to produce new glass and through this process reduce the carbon footprint of new glass manufacturing, it will be expected that preference for glass recycling will go into new glass production. Once the glass is returned as cullet for glass making, it can keep going around that cycle. Also, this displaces consumption of glassmaking sand, limestone and dolomite, with the sand supply becoming problematic. There generally is good response toward recovering glass from buildings to recycle into float glass, therefore, it might be expected for the market to move that way rather than look for opportunities to down-cycle. The form of using glass as a cement replacement would be seen to be the lowest form of downcycling, i.e. glass cannot be usefully recovered after that point and reuse as cullet is then returned at equal value. Therefore, from utilization perspective accounting for market dynamics, the supply of glass for grinding up for SCM for use in concrete might be restricted.

Going forward, there will be quantities of fritted architectural glass to be disposed of in a few years, which cannot be recycled, albeit these will be on small volumes by cement terms. Fritted architectural glass, which has a partial layer of lower melting point glass containing pigments, is unsuitable for glass recycling. Body tinted solar control glass in bronze, gray and green are unwanted for recycling as they are not so frequently used in construction. Therefore, it appears that there is an element of dependency on type of glass cullet grade, with closed-loop recycling of flat glass, e.g. for facades, requiring Grade A cullet and container and mineral wool accommodating Grade B/C cullet. While the glass industry might want to keep the higher-grade recycled glass in close circulation as there might be a higher embodied carbon saving in such a way, there definitely is a potential for using lower grades for other applications, such as concrete. Therefore, it seems that only in specific locations recycled glass will be available for potential use in concrete. The European region has a relatively high glass recycling rate, currently at approximately 76%, while there are ambitions for increasing it to 90% in the next decade. This probably leaves less room for using recycled glass in concrete. Conversely, countries in Asia and North America appear to send most of recycled glass to landfills and as such, there is a higher potential for using recycled glass in concrete in these regions, provided that it will not be used for remaking of glass elements.

The performance of GWG in concrete is highly influenced by its source, as regional differences in manufacturing processes, raw materials, and recycling methods lead to variations in its chemical composition, particle fineness, and presence of impurities. These factors directly affect the pozzolanic activity of GWG, which is critical for its ability to enhance the mechanical and durability properties of concrete. For example, GWG with a high silica content and finely ground particles tends to exhibit better pozzolanic reactivity, contributing significantly to strength and durability. Conversely, GWG with lower silica content or coarser particles may deliver suboptimal results. Additionally, impurities such as organics, metals, or other contaminants present in GWG can interfere with hydration reactions, alter mix consistency, or reduce compatibility with other concrete ingredients, potentially compromising the desired performance.

To address these challenges, a detailed characterization of GWG is essential before its use in concrete applications. This includes analyzing its chemical properties, such as silica and alkali content, as well as its physical properties, such as particle size distribution and surface area. Such assessments ensure that the material meets the required standards and delivers consistent and reliable performance. In the revised manuscript, we emphasize the importance of understanding these regional variations and advocate for thorough testing and quality control measures to optimize the use of GP in concrete production, thereby ensuring both structural integrity and environmental sustainability.

6.2. Environmental considerations of using ground glass as an SCM

The primary contributor to embodied carbon emissions of concrete is Portland cement. This is associated with the manufacturing process of Portland cement, which involves calcination and chemical decomposition of limestone predominately and the fact that Portland cement is commonly used as the primary binder to produce concrete. Currently, one of the most popular and efficient ways to reduce the embodied carbon of concrete is to partially replace Portland cement in concrete with a SCM of proven performance and suitability, such as ground granulated blast furnace slag, FA, silica fume, or other pozzolanic materials.

Recycled glass cullet, if regarded as a waste product, can be used to also lower the embodied carbon of concrete through replacing a quantity of Portland cement in the mix, which can be in the region of up to 20 to 30% depending on performance. However, understanding the exact carbon footprint reduction from using recycled glass in concrete depends on several factors. It is relatively well understood that the management of waste glass can be a worldwide issue [147–149] due to the nonbiodegradable nature of the material, which occupies landfill space and induces additional costs due to landfilling operations. Therefore, its reuse in concrete would suggest that a certain quantity of the waste material will no longer be landfilled, saving associated energy and costs from landfilling the waste glass and producing Portland cement for use in concrete [150,151].

Yet, a holistic perspective is required to understand the potential embodied carbon savings when recycled glass is used in concrete. Previous analyses have shown that the carbon footprint of recycled glass when used in concrete can be relatively low, indicating that recycled glass is a viable lower carbon cement alternative [152–154]. Results from previous studies summarized in Bueno et al. [27] indicated if glass is recycled as an SCM, (−)0.48 $kgCO_2eq$. could be averted per kilogram of recycled glass together with (−)3.23 MJ of energy. In the same studies it was reported that traditional glass recycling (−)0.31 $kgCO_2eq$. and (−)2.48 MJ of energy could be saved, while landfilling was estimated to result in net positive emissions (0.044 $kgCO_2eq$.) and energy consumption (0.31 MJ). Therefore, consideration needs to be given to which kind of recycling/repurposing is of higher value. It should also be noted that recycling glass cullet to produce new glass offers savings in raw materials, specifically, 1 ton of recycled glass cullet saves approximately 590 kg of sand, 185 kg of soda ash, and 172 kg of limestone [155]. As there is currently a global sand crisis with natural sand being extensively used for construction purposes, particularly for producing glass and concrete [156,157] the sustainability case for using ground glass as a pozzolan in concrete has to be extended to whether this deprives a valuable natural resource for manufacturing of glass.

It is somewhat clear that much of the recycled glass is going to landfill globally, particularly in certain locations. Under the locations where most of glass is recycled in making new glass, there should be limited scope for use in concrete as a pozzolan. However, in regions where most of recycled glass is landfilled there is merit for the landfilled glass to be used as a pozzolan in concrete. This would prerequisites that the landfilled or recycled glass would not be suitable or intended for recycling into glass remaking, as glass remaking from recycled glass cullet can be regarded as higher value repurposing for recycled glass compared to using the cullet as SCM in concrete.

Reusing waste glass pellets in the production of new glass contributes to significant environmental benefits by reducing the fusion temperature during manufacturing, which directly translates to lower energy consumption and decreased CO_2 emissions. This application benefits the glass production sector by improving energy efficiency and reducing the environmental impact of creating new glass products. On the other hand, using finely ground waste glass powder as a partial replacement for cement addresses sustainability in the construction sector. Cement manufacturing is a major contributor to CO_2 emissions, primarily due to clinker production. Incorporating glass powder in concrete reduces the demand for clinker, directly lowering emissions and contributing to sustainable construction practices. While both uses of waste glass promote sustainability, their impacts vary by industry. Glass pellet reuse focuses on energy efficiency in manufacturing, while glass powder addresses emissions reduction in construction, each fulfilling distinct environmental objectives.

6.3. Current state of standardization

The standardization of incorporating glass into concrete globally is not regarded as a progressed matter reflecting the limited popularity of considering ground glass for use as pozzolan in concrete. Currently, the only internationally recognized standard specific to the use of ground glass as SCM in concrete is that of ASTM C1866/C1866M-20 [158]. This standard applies to ground glass from sources that consist of container glass, plate glass, or E-glass and contains requirements for conformance of the glass pozzolan based on its chemical composition, e.g. limits for SiO_2, Al_2O_3, CaO, NaO_{eq}, LOI and others, as well as physical characteristics, e.g. fineness and strength activity index. Recommendations for measuring ASR expansion potential are also inherent in the standard.

An indirect approach toward the standardized use of GWG in concrete could be through establishing performance-based standards for concrete. In such a way, performance testing for a concrete with GWG could be conducted, and demonstrated that if its durability and mechanical performance are equivalent to that of standard concrete, then that would enable its adoption as an SCM.

This method, which is agnostic to the type of SCM used, is somewhat standardized in Europe in a method known as Equivalent Concrete Performance Concept (ECPC) inherent in EN 206 [159] and in the USA through ASTM C1157/C1157M-20a [160]. Going forward and to potentially encourage wider consideration of GWG as pozzolan in concrete, further standardization efforts are recommended that would focus on processing methods, influence of glass intermixing and achieving consistent behavior of concrete depending on the type of ground glass cullet.

7. Concluding remarks

Based on the review, the following conclusions can be made:

The incorporation of GWG in concrete demonstrates promising results in enhancing its mechanical properties and overall durability. By leveraging waste glass, concrete formulations can achieve both environmental and functional benefits, contributing to greener, more efficient building materials. Based on the review, the following conclusions can be made:

- The integration of WGP as an SCM enhances mechanical properties of concrete due to its pozzolanic activity. This results in an improved compressive strength, particularly after extended curing periods by forming additional C-S-H and densifying the microstructure. The filler effect optimizes particle packing, reduces porosity, and enhances tensile and flexural strengths by promoting better interlocking of particles and microstructural uniformity. Optimal performance is achieved with replacement levels between 10 to 20%, while incorporating other materials such as fiber can further prevent crack propagation and improve ductility.
- Incorporation of WGP reduces shrinkage and long-term creep strain by densifying the concrete matrix, especially at optimal replacement levels lying between 10% and 25%. This ensures better load distribution and moisture retention, minimizing deformation and cracking.
- Resistance to freeze-thaw cycles, chloride penetration, sulfate attack, and acid exposure is improved by the pozzolanic reaction of WGP, which reduces permeability, enhances durability, and strengthens concrete in aggressive environments.
- Workability and lubrication were reported to improve with the addition of WGP, also refining the concrete's pore structure. Although it accelerates carbonation initially, it ultimately increases density, slowing further carbonation.
- GWG can effectively replace up to 20% of cement in concrete mixes, contributing to improvements in performance. When used as a filler, the quantity varies based on desired properties and specific application needs. Typically, the amount ranges from 10% to 30% by weight of the total cementitious materials. While some performance improvements can be attained in replacement levels of 20% to 30%, most of the existing works indicate that concrete's properties are negatively impacted for additions of GWG exceeding 30%.
- Based on its pozzolanic properties and compatibility with concrete, the suitable type of GWG is finely ground glass with a particle size of less than 75 microns. Its high silica content enhances pozzolanic reactivity, forming additional cementitious compounds. This improves concrete's strength, durability, and sustainability, supporting eco-friendly construction practices.
- The incorporation of GWG in concrete can offer sustainability benefits. This, however, depends on whether GWG is sent to landfill with no intention of being recycled in the future for the production of new glass. If regarded as a waste, then GWG can have a near-negligible carbon footprint compared to Portland cement but its higher value repurposing is toward the production of a new glass, which can perpetuate its recycling rather than being used as an SCM in concrete and become nonretrievable. Thus, this leaves the possibility of using GWG as SCM open only in certain parts of the world and under certain conditions.

The use of GWG as an SCM and filler in concrete presents a sustainable option but comes with significant challenges. A key issue is the chemical incompatibility of glass, which introduces alkali elements that can cause alkali-silica reactions, leading to concrete deterioration over time. This risks compromising the long-term structural integrity of concrete incorporating waste glass. Additionally, achieving uniform particle size distribution is difficult, potentially affecting the concrete's workability and mechanical properties.

Ground glass can also reduce early strength development, which is problematic in projects requiring rapid construction or early strength gains. Esthetic concerns arise from the variability in glass color, posing challenges for projects where visual uniformity is important, though this can also be an advantage in some architectural designs. The environmental benefits of using recycled glass may be negated by the energy-intensive process of grinding it into a fine powder. Moreover, consistent supply and quality control of recycled glass are critical, as contaminants can negatively affect concrete properties. The lack of standardized regulations and potential high processing costs further complicate its adoption. While promising, overcoming these challenges is essential for the effective and sustainable use of GWG in concrete.

Disclosure statement

No potential conflict of interest was reported by the authors.

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