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**Original Research Article**

# Utilization of Crushed and Powdered Waste Glass in Cementitious Composites: From Microstructure to Service Life

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## Abstract

The increasing demand for concrete, coupled with the environmental burden associated with ordinary Portland cement (OPC) production and natural aggregate depletion, has intensified the search for sustainable alternative materials. Waste glass, generated in large quantities worldwide and often landfilled due to recycling constraints, has emerged as a promising resource for cementitious composites when processed as powdered waste glass (PWG) or crushed waste glass. This review critically examines the utilization of waste glass as a sustainable binder and aggregate replacement, with particular emphasis on microstructural evolution, durability performance, and service-life implications. The pozzolanic reactivity of finely ground waste glass, driven by its high amorphous silica content, leads to secondary calcium silicate hydrate formation, portlandite consumption, and pore refinement. These microstructural modifications result in improved later-age mechanical strength, reduced permeability, enhanced resistance to chloride ingress and chemical attack, and effective mitigation of alkali–silica reaction when appropriate fineness and replacement levels are adopted. The review synthesizes quantitative data from recent studies to establish performance trends, identify optimal replacement ranges, and clarify durability mechanisms governing long-term behavior. Remaining challenges, including variability in glass composition, standardization of test methods, and limited long-term field data, are highlighted. Overall, the findings demonstrate that waste glass, when properly processed and proportioned, can contribute significantly to durable, low-carbon cementitious composites and support circular-economy-based infrastructure development.

**Keywords:** Powdered Waste Glass (PWG), Concrete, Ordinary Portland Cement (OPC), Recycling Constraints.



## 1. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and a major contributor to global carbon dioxide ($CO_2$) emissions. Ordinary Portland cement (OPC), the primary binding material in concrete, accounts for nearly 7–8% of global anthropogenic $CO_2$ emissions due to energy-intensive clinker production and limestone calcination (Andrew, 2018; Scrivener *et al*., 2018). Recent global assessments indicate that cement-related emissions remain high despite efficiency improvements, emphasizing the urgent need for sustainable alternatives (Figure 1). With rapid infrastructure growth worldwide, particularly in developing economies, the environmental burden associated with conventional concrete production has intensified.

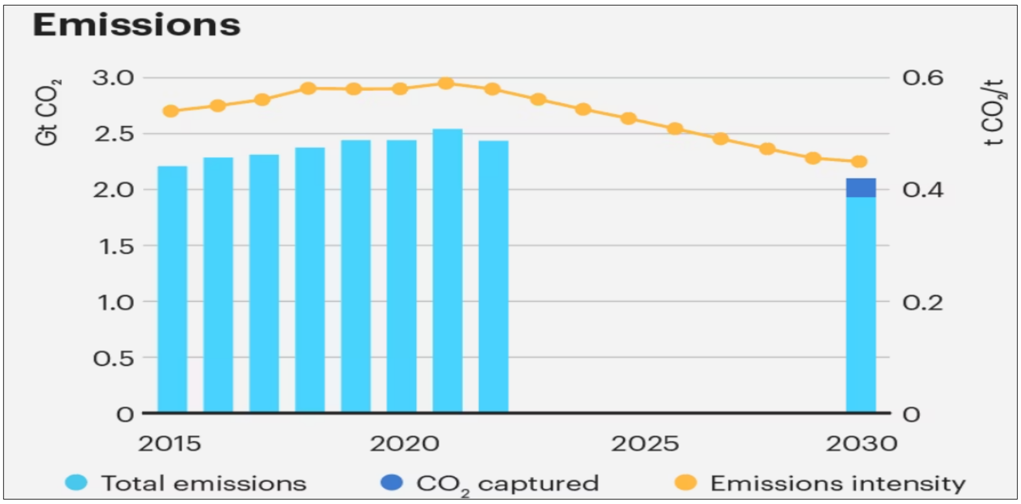


**Figure 1: Global $CO_2$ emissions associated with cement production and the increasing need for low-carbon and durable cementitious materials (adapted from Andrew, 2018; Scrivener *et al*., 2018; Habert *et al*., 2020).**

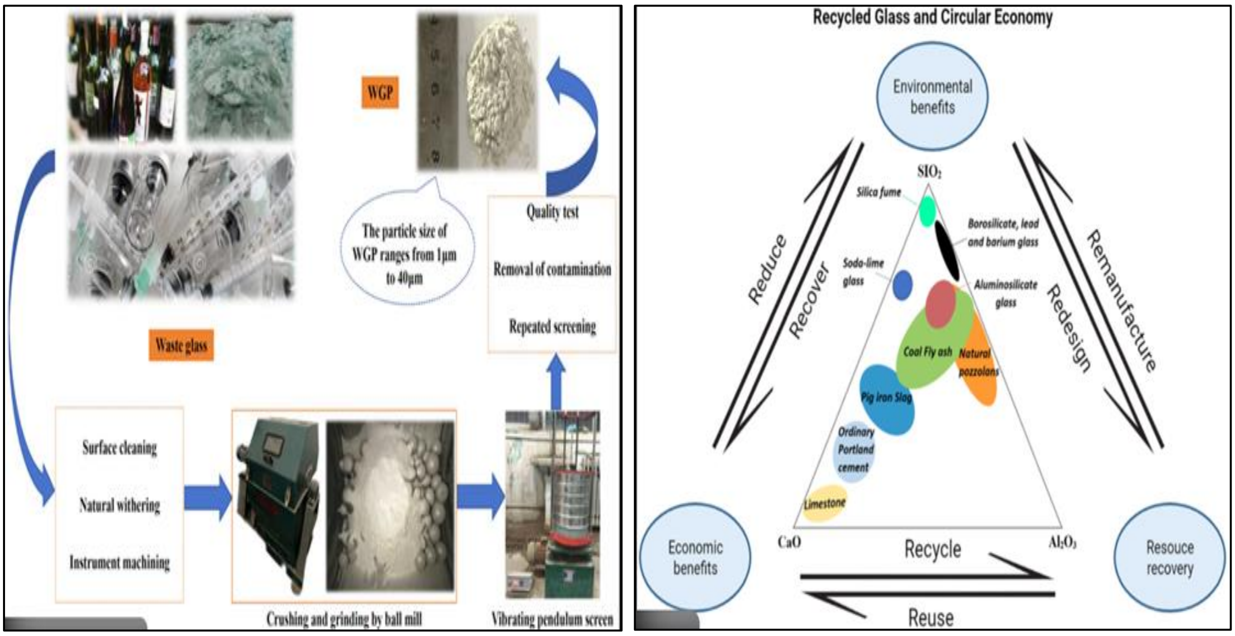


**Figure 2: Utilization pathways of waste glass in cementitious composites, illustrating powdered waste glass as a supplementary cementitious material and crushed waste glass as fine or coarse aggregate within a circular-economy framework**

Sustainable cementitious composites have emerged as a viable solution to reduce the environmental footprint of concrete while maintaining acceptable engineering performance. These composites commonly incorporate supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, limestone calcined clay cement ($LC^3$), agricultural ashes, waste glass, and alkali-activated or geopolymer binders (Mehta, 2001; Scrivener *et al.,* 2018; Provis, 2018). Waste glass is particularly attractive due to its high amorphous silica content and widespread availability, allowing its use either as finely ground powder acting as a pozzolanic binder or as crushed material replacing natural aggregates (Figure 2). Partial or full replacement of OPC using such materials can significantly lower $CO_2$ emissions, conserve natural resources, and promote circular-economy principles (Habert *et al*., 2020).

Although numerous studies have demonstrated that sustainable cementitious composites can achieve comparable or superior mechanical strength relative to OPC concrete, durability performance remains the most critical parameter governing their long-term applicability (Neville, 2011; Alexander *et al*., 2016). Durability directly influences service life, maintenance requirements, life-cycle cost, and overall environmental sustainability of concrete infrastructure. Structures exposed to aggressive environments such as marine, industrial, and urban conditions are particularly vulnerable to degradation mechanisms including chloride ingress, sulfate attack, carbonation, acid exposure, and moisture-driven transport processes (Bertolini *et al*., 2013).

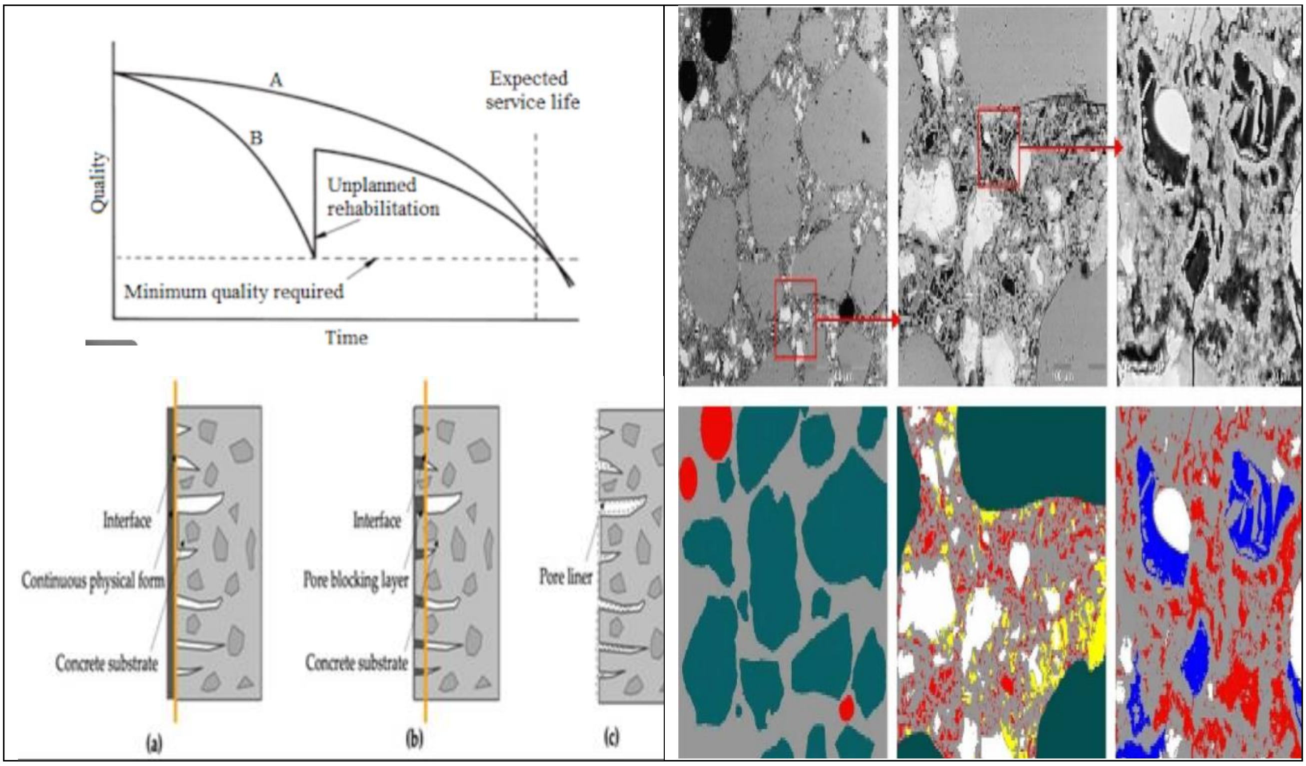


**Figure 3: Conceptual link between microstructural evolution, transport properties, durability mechanisms, and service life of cementitious composites incorporating waste glass (adapted from Alexander *et al*., 2016; Provis & van Deventer, 2014).**

The durability behavior of sustainable cementitious composites differs fundamentally from that of OPC concrete due to variations in binder chemistry, calcium content, hydration or polymerization products, and pore structure. SCM-rich systems often exhibit refined pore networks and reduced permeability, leading to enhanced resistance to chloride and sulfate ingress (Shi *et al*., 2011; Thomas, 2013). In contrast, low-calcium binders such as $LC^3$ and geopolymer systems may exhibit increased carbonation susceptibility because of reduced portlandite content and altered alkalinity, which can influence reinforcement corrosion risk (Avet & Scrivener, 2018; Bernal *et al*., 2014). These contrasting behaviors highlight the importance of linking microstructural characteristics with transport processes and durability performance, as conceptually illustrated in Figure 3.

Despite the growing volume of research on sustainable concretes and waste-glass-based cementitious composites, existing durability studies are often fragmented and limited to single exposure conditions or short-term laboratory testing. Variations in curing regimes, test methods, and exposure environments further complicate direct comparison of reported results (Alexander *et al*., 2016; Provis & van Deventer, 2014). Long-term field performance data and studies addressing coupled deterioration mechanisms remain scarce, restricting the development of durability-based design frameworks.

In this context, a comprehensive and mechanism-oriented review is essential. This review critically examines the utilization of crushed and powdered waste glass in cementitious composites, with emphasis on microstructural evolution, durability performance under aggressive environments, and service-life implications. By synthesizing recent experimental findings and identifying key research gaps, the review aims to support the rational design and wider adoption of durable, low-carbon cementitious composites for sustainable infrastructure.

## 2. Sources, Processing and Properties of Waste Glass

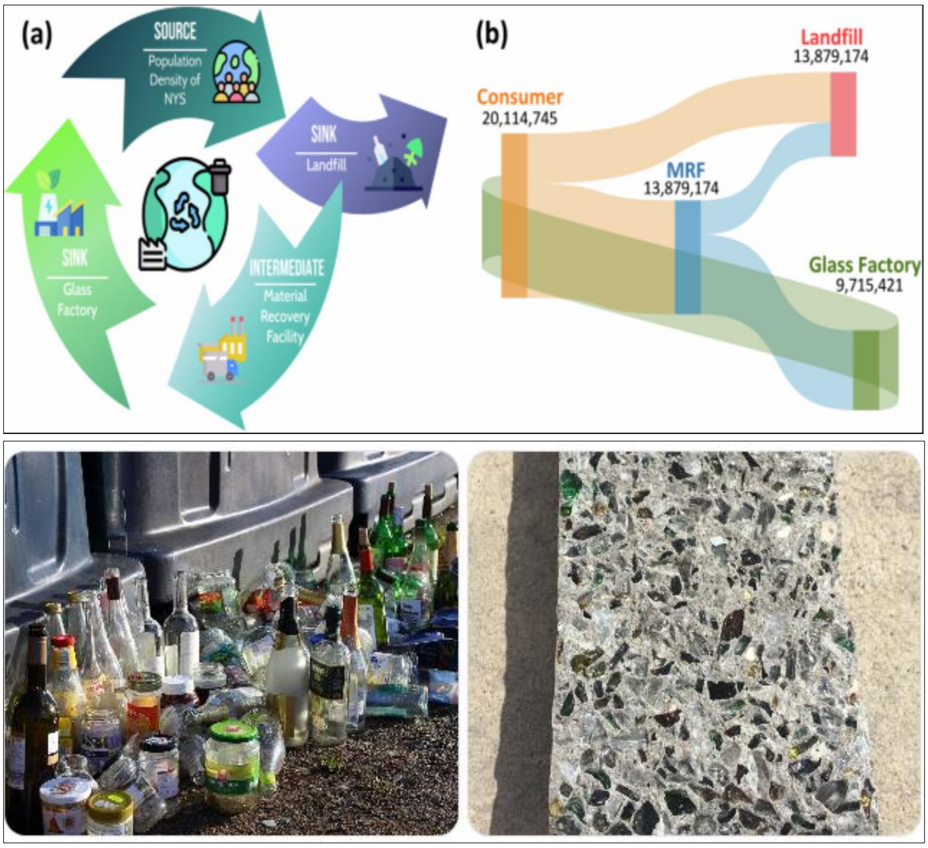


**Figure 4: Major sources of waste glass generated from municipal solid waste streams, including container glass, flat glass, and industrial glass, which can be utilized in cementitious composites.**

Waste glass is generated in large quantities from municipal, commercial, and industrial activities. Common sources include container glass (bottles and jars), flat glass (windows, automotive glass), and specialty glass from electronic and industrial applications. Among these, soda–lime glass constitutes the dominant fraction of waste glass worldwide and is most commonly investigated for concrete applications due to its high silica content and amorphous structure (Shi *et al*., 2011; Thomas, 2013). Despite high recyclability, a significant portion of waste glass is landfilled because of contamination, mixed colors, and economic constraints, making its utilization in construction materials an attractive sustainable alternative (Habert *et al*., 2020).

### 2.1 Processing of Waste Glass for Cementitious Applications

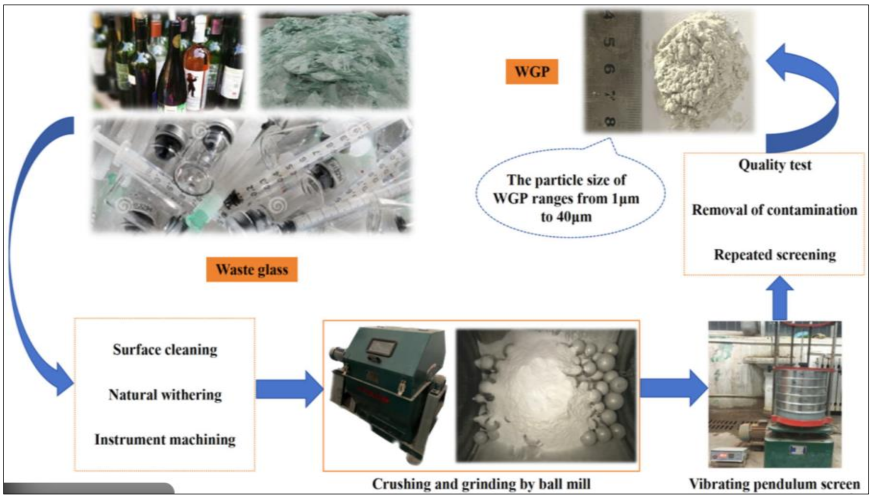

**Figure 5: Typical processing routes for waste glass used in cementitious composites, including crushing, grinding, sieving, and classification for aggregate or binder applications.**

The processing of waste glass strongly influences its performance in cementitious systems. Waste glass is typically cleaned, crushed, and milled to obtain the desired particle size distribution. When ground to fine particle sizes, usually below 75 µm, waste glass exhibits pozzolanic reactivity and can be used as powdered waste glass (PWG) replacing a portion of cement. Coarser fractions are used as crushed waste glass (CWG) for partial replacement of natural fine or coarse aggregates (Shi *et al*., 2011).

The degree of fineness is a critical parameter controlling reactivity. Finer glass powders provide higher specific surface area, accelerating dissolution of amorphous silica and enhancing secondary calcium silicate hydrate (C–S–H) formation. However, excessive grinding increases energy demand, and therefore optimization of particle size is necessary to balance performance and sustainability (Habert *et al*., 2020).

**2.2 Chemical and Mineralogical Characteristics**

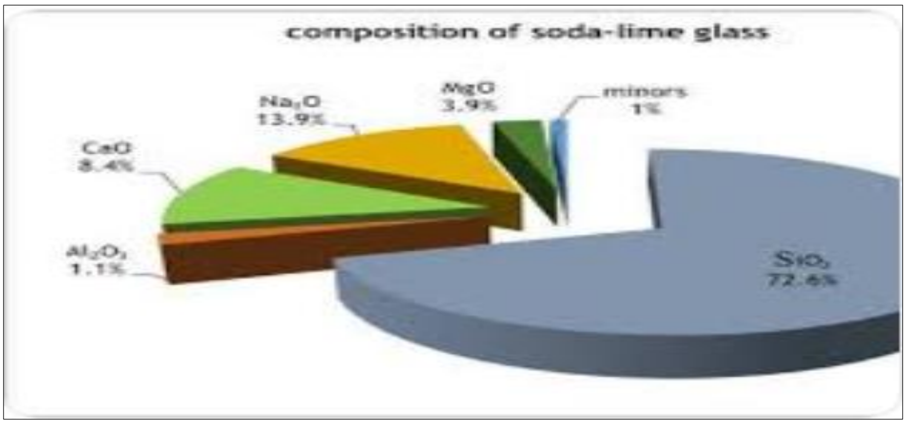


**Figure 6: Typical chemical composition and amorphous nature of soda–lime waste glass used in cementitious composites.**

Waste glass is primarily composed of silica ($SiO_2$), typically ranging from 65–75%, with smaller amounts of calcium oxide (CaO), sodium oxide ($Na_2O$), and minor oxides. The high amorphous silica content is responsible for the pozzolanic behavior of finely ground waste glass when incorporated into cementitious matrices (Shi *et al*., 2011; Provis, 2018). X-ray diffraction (XRD) patterns of waste glass typically exhibit a broad amorphous hump rather than sharp crystalline peaks, confirming its glassy nature.

The alkali content of waste glass, while beneficial for dissolution and reactivity, raises concerns regarding alkali–silica reaction (ASR) when glass is used in coarser aggregate form. This necessitates careful control of particle size, replacement levels, and synergistic use of SCMs to mitigate deleterious expansion (Thomas, 2013; Alexander *et al*., 2016).

### 2.3 Physical Properties of Crushed and Powdered Waste Glass

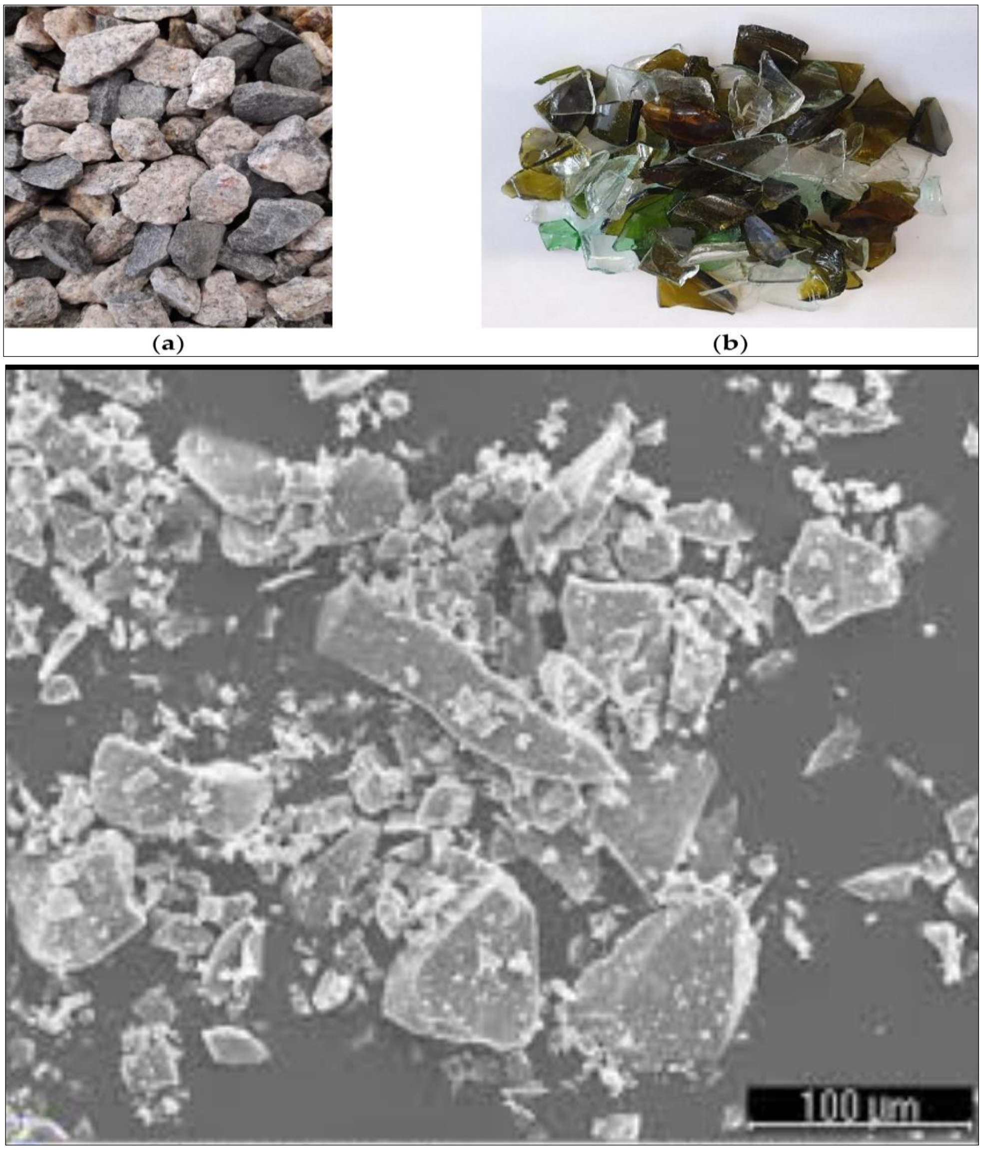


**Figure 7: Particle morphology of crushed and powdered waste glass, showing angular crushed glass aggregates and fine glass powder particles.**

Crushed waste glass aggregates are generally angular with smooth surfaces, which can influence workability and interfacial transition zone (ITZ) characteristics. The smooth surface texture may reduce mechanical interlocking with the cement paste, while angularity can increase internal friction, affecting fresh properties (Thomas, 2013). In contrast, powdered waste glass consists of fine particles that act as micro-fillers and reactive pozzolans, contributing to pore refinement and densification of the cementitious matrix.

The specific gravity of waste glass is comparable to that of natural aggregates, whereas water absorption is typically lower due to its non-porous nature. These characteristics can be advantageous in reducing water demand and improving durability-related properties such as permeability and sorptivity (Shi *et al*., 2011).

### 2.4 Implications for Microstructure and Durability

The combined chemical and physical characteristics of waste glass govern its interaction with cementitious systems and its influence on durability. Finely ground waste glass promotes secondary C–S–H formation, refines pore structure, and enhances resistance to transport of aggressive agents. Crushed waste glass, when used within optimized limits, can contribute to acceptable durability performance provided ASR mitigation strategies are employed.

A clear understanding of waste glass sources, processing routes, and intrinsic properties is therefore essential for interpreting the durability behavior and service-life performance of waste-glass-modified cementitious composites, which are discussed in subsequent sections.

### 3. Waste Glass as Binder (Powdered Waste Glass – PWG)

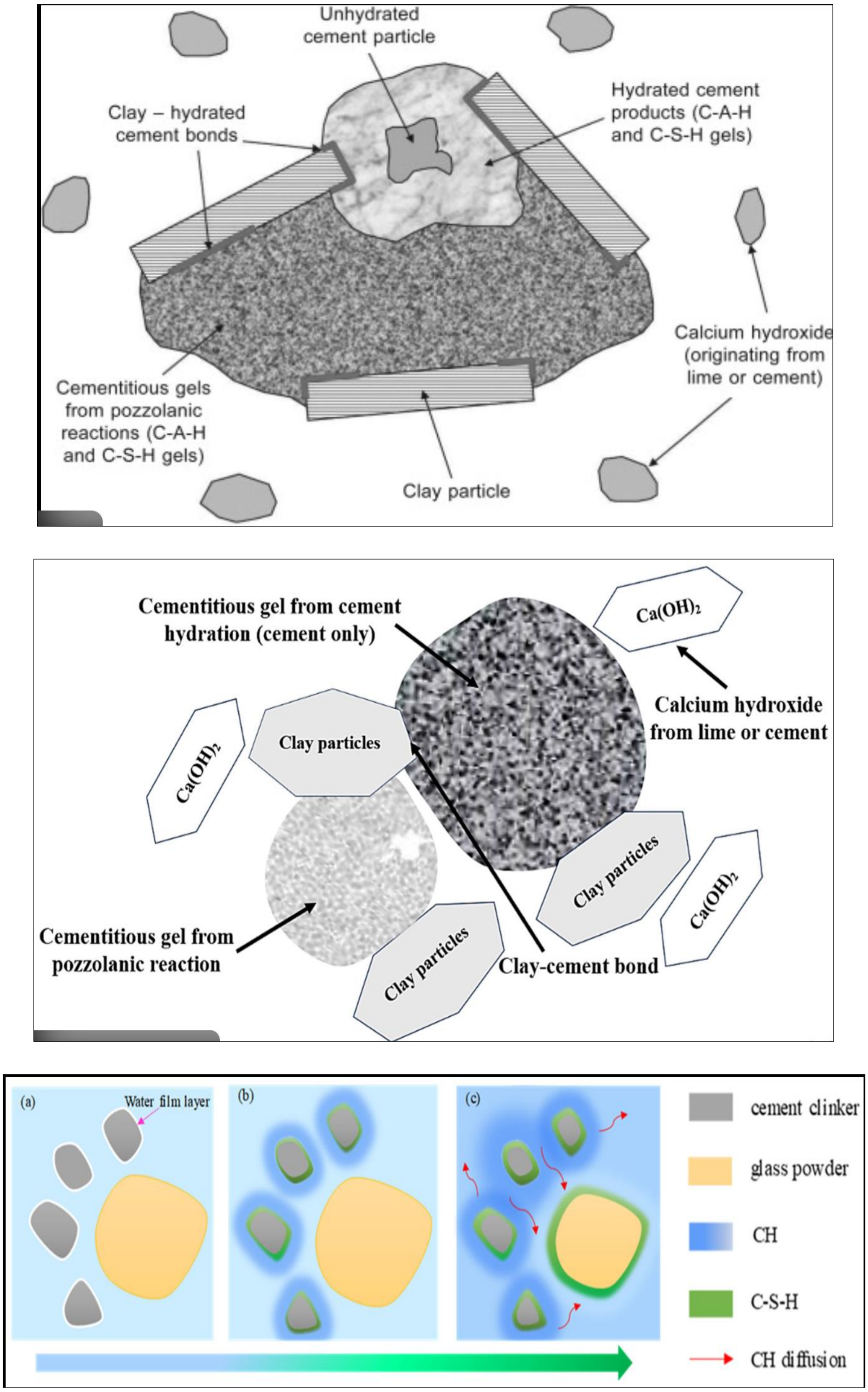


**Figure 8: Schematic illustration of the pozzolanic reaction mechanism of powdered waste glass (PWG) in cementitious composites, showing dissolution of amorphous silica, consumption of calcium hydroxide, and formation of secondary C–S–H gel.**

**3.1 Characteristics and Pozzolanic Reactivity of PWG**

Powdered waste glass (PWG) is obtained by grinding post-consumer or industrial glass to fine particle sizes, typically ≤75 µm. PWG consists predominantly of amorphous silica ($SiO_2$ ≈ 65–75%), which enables it to behave as a pozzolanic material when incorporated into Portland cement systems (Shi *et al.,* 2005). In the highly alkaline pore solution of hydrating cement, silica from PWG dissolves and reacts with calcium hydroxide (CH) to form additional calcium silicate hydrate (C–S–H), the primary strength-giving phase in concrete.

Quantitative evaluation of pozzolanicity using strength activity index (SAI) and thermogravimetric analysis (TGA) shows that PWG exhibits delayed but significant reactivity. For cement replacement levels of 20–30%, reported SAI values range from 75–85% at 7 days, increasing to 95–110% at 28–90 days, indicating strong later-age pozzolanic contribution (Shi *et al*., 2005; Du & Tan, 2014). Correspondingly, CH content reductions of 25–40% relative to OPC paste have been reported at 28–90 days, confirming active pozzolanic reaction (Schwarz & Neithalath, 2008).

**3.2 Influence on Hydration and Microstructural Evolution**

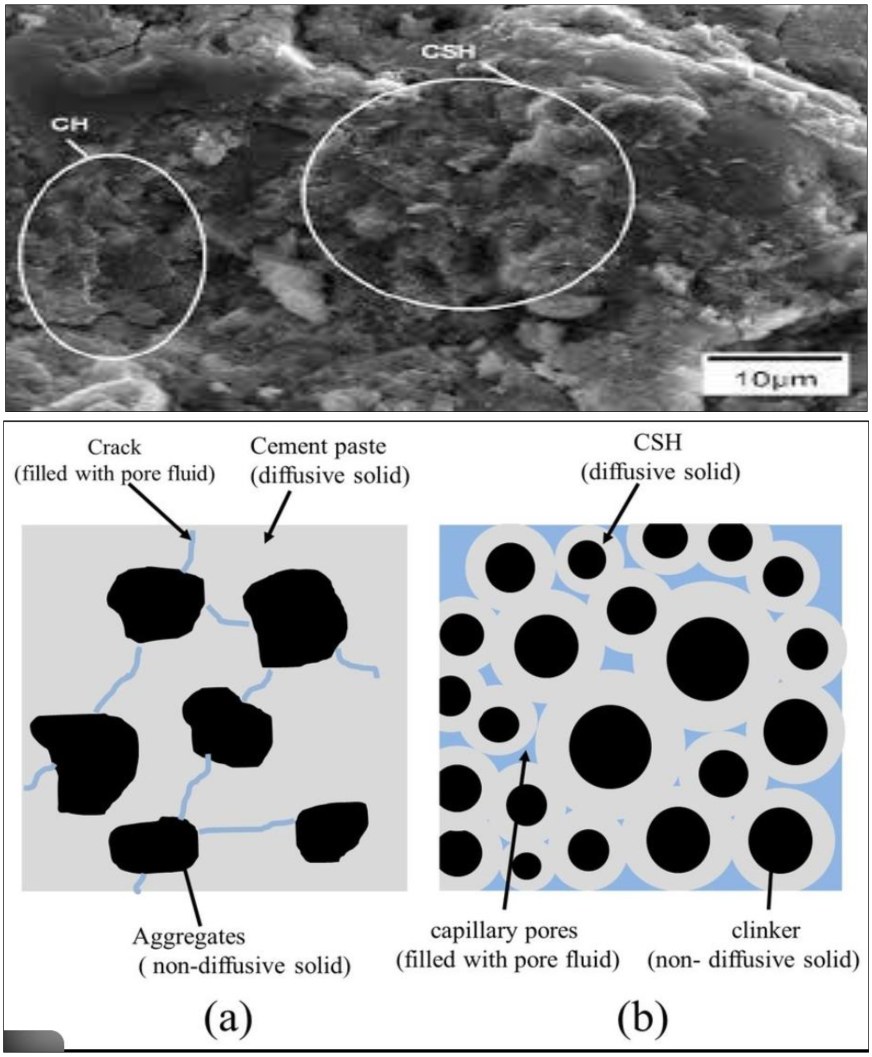


**Figure 9: Conceptual representation of microstructural refinement in PWG-modified cementitious composites, illustrating dense C–S–H formation and reduced capillary pore connectivity.**

Microstructural investigations using scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and X-ray diffraction (XRD) consistently demonstrate that PWG modifies hydration products and pore structure. The combined pozzolanic reaction and micro-filler effect of fine glass powder leads to a denser cement matrix with refined pore size distribution.

Reported pore structure data indicate a 15–30% reduction in total porosity at 90 days for PWG-modified systems compared to OPC, along with a shift in dominant pore size from >100 nm (OPC) to <50 nm in PWG blends

(Federico & Chidiac, 2009; Du & Tan, 2014). SEM images reveal compact C–S–H gel with reduced microcracking and fewer large capillary voids, which directly influences transport-controlled durability properties (Schwarz & Neithalath, 2008).

### 3.3 Mechanical Performance of PWG-Based Composites

The mechanical performance of PWG-modified concrete is governed by replacement level and curing duration. At moderate replacement levels, PWG concretes exhibit mechanical properties comparable to or exceeding those of OPC at later ages.

Experimental studies report that:

- 10–20% PWG replacement yields 95–105% of OPC compressive strength at 28 days and 105–120% at 90 days (Shao *et al*., 2000; Du & Tan, 2014).
- Higher replacement levels (≥30%) may reduce early-age strength by 15–25% due to dilution effects, though partial strength recovery occurs at later ages (Afshinnia & Rangaraju, 2015).
- These trends highlight an optimum PWG content of approximately 15–25% for balanced strength and durability.

### 3.5 Alkali–Silica Reaction (ASR) Mitigation

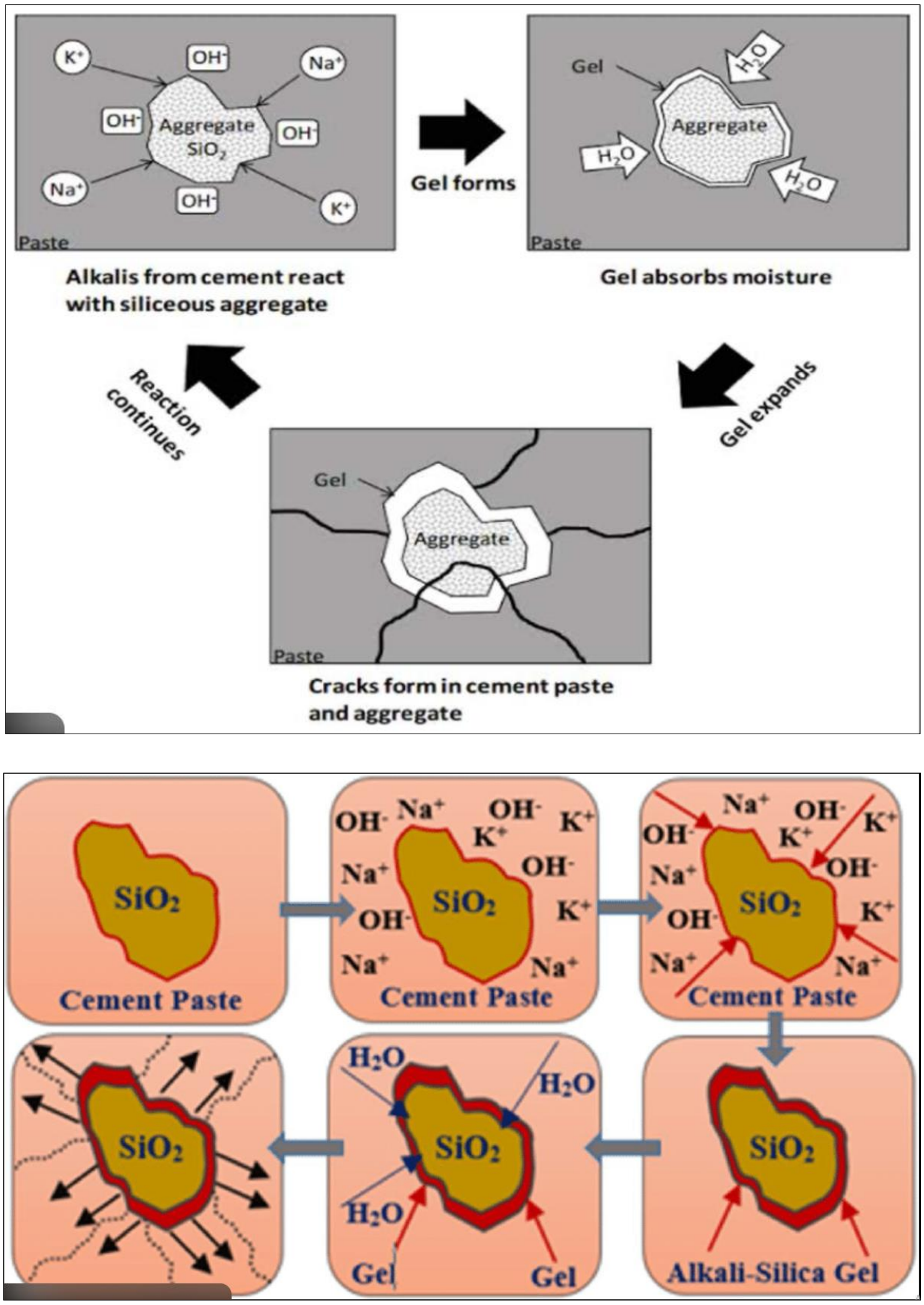


**Figure 10: Mechanism of alkali–silica reaction mitigation in PWG-modified cementitious composites.**

Although glass is a silica-rich material, finely ground PWG has been shown to mitigate ASR rather than exacerbate it. ASTM C1260 expansion tests demonstrate that PWG reduces expansion by consuming alkalis and binding them within secondary C–S–H gel. Reported expansion values decrease from >0.20% (deleterious) in unmitigated glass systems to <0.10% when 15–25% PWG (<45 µm) is incorporated (Afshinnia & Rangaraju, 2015; Zhang *et al.*, 2021).

## CONCLUSIONS

This review has critically assessed the role of crushed and powdered waste glass in cementitious composites, linking material characteristics and microstructural mechanisms to durability performance and service life. Based on the synthesis of available experimental evidence, the following conclusions can be drawn:

1. **Pozzolanic Potential of Powdered Waste Glass**: Finely ground waste glass (≤75 µm) exhibits clear pozzolanic behavior due to its high amorphous silica content. The reaction with calcium hydroxide results in secondary C–S–H formation, leading to significant microstructural densification and reduction in portlandite content.
2. **Microstructural Refinement Governs Durability**: The combined pozzolanic and filler effects of powdered waste glass refine pore structure, reduce total porosity, and shift pore size distribution toward finer pores. These microstructural changes directly control transport properties and are central to durability enhancement.
3. **Mechanical Performance is Replacement-Level Dependent**: Moderate replacement levels of powdered waste glass (typically 15–25%) yield comparable or superior later-age compressive strength relative to OPC concrete, while excessive replacement may adversely affect early-age strength due to dilution effects.
4. **Improved Transport and Durability Properties**: Waste-glass-modified concretes exhibit substantially lower chloride permeability, reduced water absorption, and decreased sorptivity, indicating enhanced resistance to moisture and aggressive ion ingress and improved long-term performance.
5. **Effective Mitigation of Alkali–Silica Reaction**: When used in finely ground form, waste glass can suppress alkali–silica reaction by consuming alkalis and binding them within secondary hydration products, provided that appropriate fineness and replacement levels are maintained.
6. **Sustainability and Service-Life Benefits**: The incorporation of waste glass contributes to reduced cement consumption, conservation of natural aggregates, diversion of waste from landfills, and potential extension of service life, thereby improving the overall environmental and economic sustainability of concrete infrastructure.

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