



Ground Granulated Blast Furnace Slag as a Supplementary Cementitious Material in Concrete: A Comprehensive Review

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Abstract

The growth of the construction industry necessitates the development of sustainable and high-performance binders to reduce ordinary Portland cement (OPC) dependence. Among supplementary cementitious materials (SCMs), Ground granulated blast furnace slag (GGBFS) offers remarkable chemical reactivity, availability, and environmental benefits. This review synthesizes advances in GGBFS production, characteristics, and performance in concrete. At optimal replacement levels (30–50%), GGBFS enhances workability, strength, and durability against chloride ingress, sulfate attack, and alkali–silica reactivity through its pozzolanic and latent hydraulic reactivity. The formation of secondary C–S–H and C–A–S–H gels refines microstructure, lowers permeability, and improves long-term performance. Environmentally, GGBFS can reduce CO₂ emissions by up to 40% and supports circular-economy principles through industrial by-product valorization. Although early-age strength and compositional variability pose challenges, GGBFS remains a key material for low-carbon, durable concrete and future sustainable infrastructure.

Keywords: Ground granulated blast furnace slag (GGBFS); Supplementary cementitious materials (SCM); Sustainable concrete; Fresh properties; Mechanical properties; Durability.

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1. Introduction

Concrete is the most widely used manufactured material on the planet, serving as the structural backbone of infrastructure, housing, and industrial development. Yet, the material's environmental cost has become a matter of global concern. Ordinary Portland cement (OPC), the main binding constituent of concrete, is responsible for a significant portion of the construction sector's carbon footprint. Cement production alone contributes approximately 7–9% of global anthropogenic CO₂ emissions, consuming nearly 10.5 EJ of energy annually.^[1–5] The process involves the calcination of limestone and the burning of raw materials at temperatures reaching 1450 °C, leading to the release of large amounts of CO₂ not only from fossil fuel combustion but also from the chemical decomposition of calcium carbonate. With the increasing pace of urbanization and infrastructure expansion, especially in developing regions, the environmental burden of

cement manufacture continues to rise, posing a major challenge to achieving net-zero emission targets. Therefore, reducing the dependence on OPC through partial replacement with low-carbon alternatives has become a scientific, environmental, and industrial priority within the framework of sustainable development and the circular economy.

The search for sustainable construction materials has driven attention toward supplementary cementitious materials (SCMs), which include a wide range of natural pozzolans and industrial by-products such as Cellulose Nanofibers,^[6] ground granulated blast furnace slag (GGBFS),^[7] rice husk ash,^[8,9] fly ash,^[10] slag cement,^[8,11] silica fume, Cellulose Fiber,^[12] and metakaolin.^[13] These materials have proven capable of improving the performance of concrete while simultaneously mitigating its environmental impacts.

Numerous studies have investigated the incorporation of industrial by-products and alternative materials in concrete as partial replacements for conventional constituents, with the dual objective of improving performance and enhancing sustainability. In this context, slag cement (SC) and rice husk ash (RHA) have been shown to positively influence concrete properties when used as partial cement replacements, leading to improvements in both mechanical performance and environmental impact.^[8] In particular, it has been reported that increasing the RHA content from 0 to 200 kg/m³ can enhance

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compressive strength by up to 50%, highlighting the pozzolanic reactivity and filler effect of RHA.^[9]

Other studies have focused on the use of fibers to improve time-dependent and thermal behavior of concrete. The effects of cellulose fiber (CF), glass fiber (GF), and polypropylene fiber (PPF) on autogenous shrinkage and thermal behavior of high-strength concrete were investigated in.^[12] The results demonstrated that GF was the most effective in reducing shrinkage, achieving a reduction of 69.9% at a 1% fiber dosage. CF also exhibited significant shrinkage mitigation, with a 39.7% reduction at a 1% fiber content, while PPF reduced shrinkage by 24.4% when added at 0.5%.

In addition, the structural behavior of high-performance concrete incorporating cellulose nanofibers has been examined using finite element analysis.^[6] The findings indicated that cellulose nanofiber-reinforced concrete exhibits superior mechanical performance compared to conventional high-performance concrete, including enhanced equivalent stress distribution, reduced strain, and improved deformation resistance under applied loads.

Furthermore, the influence of silica fume and fly ash on the fresh and rheological properties of self-compacting concrete (SCC) has been extensively studied.^[10] The results showed that silica fume increases the viscosity and yield stress of cementitious matrices, thereby enhancing structural stability. Fly ash also increases viscosity and yield stress but exhibits more pronounced thixotropic behavior, which may lead to structural instability under low shear rate gradients.^[10]

SCMs contain significant amounts of reactive silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which react with calcium hydroxide ($\text{Ca}(\text{OH})_2$) generated during cement hydration to form additional calcium-silicate-hydrate (C–S–H) and calcium-alumino-silicate-hydrate (C–A–S–H) phases.^[7-10] These secondary gels refine the microstructure, fill capillary pores, and enhance both the density and durability of the cement matrix. Their inclusion reduces permeability and diffusion of aggressive ions, extending the service life of concrete structures. In addition to their technical merits, the valorization of industrial residues as SCMs contributes to waste reduction, resource conservation, and the development of low-carbon and circular-economy construction systems.

Among all SCMs, Ground Granulated Blast Furnace Slag (GGBFS) has emerged as one of the most effective and environmentally beneficial options due to its availability, consistent performance, and ability to significantly enhance long-term concrete properties.^[14-16] GGBFS is a non-metallic by-product obtained during the production of pig iron in blast furnaces operating at 1500–1600 °C. It is produced when molten slag, composed mainly of silicates and aluminosilicates of calcium and magnesium, is rapidly quenched with water, forming a glassy granular material with high amorphous content.^[17-19] This granulate is subsequently dried and finely ground to yield GGBFS powder suitable for cement and concrete applications. The material's chemical composition typically consists of 30–40% CaO , 28–38% SiO_2 ,

8–24% Al_2O_3 , and 1–18% MgO .^[14,18-19] Its reactivity is governed primarily by glass content and basicity ratio, $(\text{CaO} + \text{MgO})/(\text{SiO}_2 + \text{Al}_2\text{O}_3)$, which together determine its hydraulic potential. When blended with OPC, GGBFS reacts with calcium hydroxide liberated during cement hydration to form additional C–S–H gels, producing a denser microstructure and superior durability performance.

The incorporation of GGBFS in concrete confers multiple benefits across both the fresh and hardened states. In the fresh state, the spherical and finely ground particles improve workability, cohesion, and pumpability, while reducing water demand and bleeding.^[20] The lower heat of hydration makes GGBFS-based concretes particularly suitable for mass concrete applications and hot-weather environments. In hardened concrete, partial substitution of cement with GGBFS (typically 30–50% by mass) has been shown to enhance compressive, tensile, and flexural strengths at later ages through continued pozzolanic and latent hydraulic reactions.^[7,21-24] The material also markedly improves resistance to chloride ingress, sulfate expansion, and alkali-silica reactivity, thereby reducing steel corrosion risk and prolonging structural service life.^[18,24] Its beneficial effect on permeability and diffusivity can lower ion penetration by an order of magnitude compared with conventional OPC concretes. As a result, GGBFS is widely used in marine, bridge, and underground structures where durability is paramount.

From an environmental perspective, the use of GGBFS as a cement replacement offers a significant reduction in embodied carbon and energy. Each tonne of OPC substituted by GGBFS avoids up to 0.8 tonnes of CO_2 emissions and decreases the energy requirement by approximately 25–30%.^[16,20,24] Moreover, because GGBFS is an industrial by-product, its use in construction promotes waste valorization and reduces the burden on landfills. On a global scale, the potential for CO_2 mitigation through slag substitution is considerable, given that cement manufacturing alone accounts for around 8% of total global CO_2 emissions and that over 500 million tonnes of blast-furnace slag are generated annually.^[18]

The integration of GGBFS in blended and geopolymer systems can further improve sustainability by reducing clinker content, enhancing durability, and extending structural lifespan, thus lowering life-cycle costs. The environmental and economic advantages of GGBFS are closely aligned with international sustainability frameworks, including the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs), which emphasize resource efficiency, industrial symbiosis, and low-carbon infrastructure.

Despite these advantages, certain challenges limit the full-scale adoption of GGBFS in the concrete industry. The variability of slag properties depending on furnace type, raw materials, and cooling conditions leads to differences in reactivity and performance.^[14,25-26] Early-age strength development can be delayed, especially in cold climates, requiring extended curing or chemical activation to achieve adequate mechanical performance. Furthermore, standardized

mix-design methodologies and performance-based specifications for GGBFS concretes remain underdeveloped, leading to inconsistencies across regions and projects. Addressing these issues requires deeper understanding of slag hydration mechanisms, microstructural evolution, and long-term field performance through experimental studies and predictive modeling.

In this context, the present review provides a comprehensive synthesis of current research on ground granulated blast furnace slag as a sustainable supplementary cementitious material for concrete. It examines the origin, production, and physico-chemical properties of GGBFS, and discusses its influence on fresh, mechanical, and durability behavior of concrete. Furthermore, it evaluates its environmental contributions to CO₂ reduction, waste utilization, and circular-economy objectives, while identifying knowledge gaps related to material variability, carbonation behavior, and life-cycle performance.

Through this integrated perspective, the study aims to support the large-scale implementation of GGBFS as a key material for the next generation of low-carbon, durable, and eco-efficient concrete systems.

2. Objectives of the review

This review aims to provide a critical and integrated understanding of Ground Granulated Blast Furnace Slag (GGBFS) as a sustainable supplementary cementitious material in concrete. The main specific objectives are to:

1. Describe the production process and physicochemical properties of GGBFS that govern its reactivity and suitability for cementitious systems.
2. Evaluate the influence of GGBFS on the fresh, mechanical, and durability performance of concrete under varying replacement ratios and curing conditions.
3. Assess the sustainability advantages of GGBFS incorporation, including CO₂-emission reduction, waste valorization, and alignment with circular-economy principles.
4. Identify existing research gaps and practical challenges related to material variability, mix optimization, and long-term field performance.

These objectives, summarized schematically in Fig. 1, establish the conceptual framework of this comprehensive review and guide the analysis of how GGBFS contributes to sustainable and high-performance concrete systems.

3. Scope and structure

The scope of this review encompasses the origin, production processes, and chemical-mineralogical properties of GGBFS, followed by an in-depth evaluation of its influence on concrete behavior in both fresh and hardened states. Particular emphasis is placed on durability enhancement and environmental benefits in the context of sustainable construction. The paper is organized systematically (Fig. 2): Part 1 discusses the origin and properties of GGBFS; Part 2 examines its influence on fresh, mechanical, and durability characteristics; Part 3 evaluates its sustainability and environmental implications; and Part 4 presents key conclusions and directions for future research. Together, these parts provide a coherent understanding of GGBFS as a cornerstone material for next-generation, low-carbon concrete technology.

4. Origin, production, and properties of GGBFS

4.1 Production process of GGBFS

Ground-granulated blast furnace slag (GGBFS) is an industrial by-product formed during the production of pig iron in blast furnaces. The furnace operates continuously at temperatures of 1500–1600 °C, where a carefully proportioned mixture of iron ore, coke, and limestone (or dolomite) is smelted. Two molten phases are produced: molten iron and molten slag. The latter, which floats above the denser iron, consists mainly of silicates and aluminosilicates of calcium and magnesium.^[15,16,18,27]

To preserve its reactive properties, the molten slag is rapidly quenched with high-pressure water jets, converting it into a glassy, granular material. This process, known as granulation, prevents crystallization and produces a fine, amorphous product with latent hydraulic reactivity. The resulting granules are dewatered, dried, and finely ground to obtain GGBFS powder suitable for use in cement and concrete

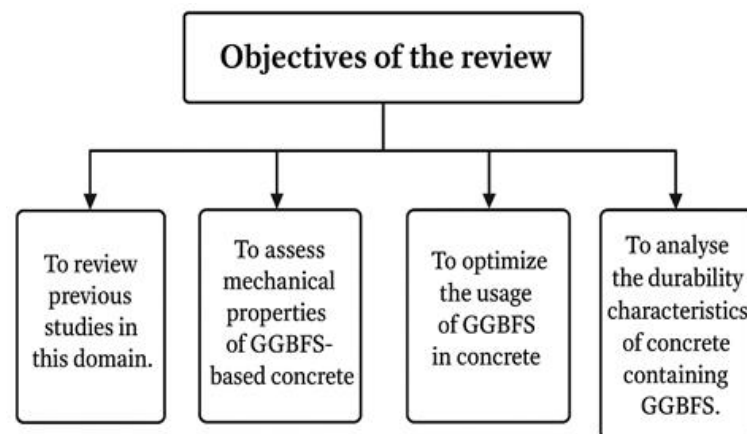


Fig. 1: The main objectives of the review.

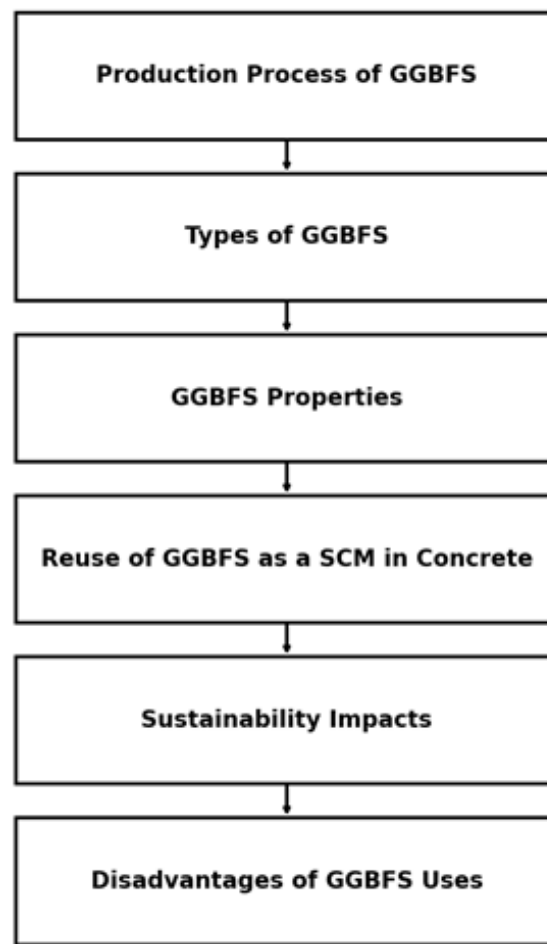


Fig. 2: Research structure.

production. Rapid cooling is essential; slowly cooled slags are largely crystalline and exhibit negligible cementitious activity.^[28]

Fig. 3 illustrates the GGBFS production process, showing the stages from raw material feeding, slag tapping, water quenching, and grinding.

Global production of granulated blast furnace slag exceeds 500 million tonnes annually, yet less than two-thirds is currently utilized in the construction sector.^[18,29] GGBFS contains high proportions of amorphous calcium, silica, and alumina, making it a valuable binder and strength enhancer for cementitious composites.^[29,30] Moreover, its production requires minimal additional energy beyond that used in iron-making, offering substantial reductions in CO₂ emissions, heat of hydration, and resource depletion when it replaces part of ordinary Portland cement (OPC).^[16]

4.2 Types of GGBFS

Depending on the cooling method, blast furnace slag can solidify as air-cooled slag, expanded (foamed) slag, or granulated slag. Only the granulated form, comprising glassy, sand-sized particles, possesses latent hydraulic and pozzolanic properties and is suitable for producing GGBFS.^[28] The main international classifications for blast furnace slag cements and GGBFS grades are summarized in Table 1.

Standards distinguish slag cements (factory-blended with clinker) from ground slags (stand-alone SCMs):

JIS R 5211 (Japan): Blast-furnace slag cements Type A, B, C by % GGBFS in the blend; the market mainstay Type B (BB) contains ~40–45 % GGBFS.^[15]

JIS R 6206 (Japan): GGBFS classified by specific surface (e.g., 3000, 4000, 6000, 8000 cm²/g classes). Finer (6000–8000) → higher early strength; coarser (3000) → low-heat mass work. GGBFS 4000 is the most prevalent balance grade.^[15]

ASTM C989 (USA): Grades 80, 100, 120 by strength activity index with a control OPC mortar.^[31]

EN 15167 (EU): Reactivity/fineness-based categories GGBS A & B for high-performance concretes.^[31]

CSA A23.5 (Canada): Performance-based Slag Class S for structural/marine concretes.^[28]

Standards distinguish between slag cements and ground slags. According to JIS R 5211, three types of blast furnace slag cement are defined; the most widely used, Type B (BB), typically contains 40–45 % GGBFS blended with clinker. Meanwhile, JIS R 6206 categorizes ground slag by specific surface area, which controls reactivity. Finer materials such as GGBFS 6000 or 8000 offer higher early-age strength, whereas coarser grades like GGBFS 3000 are used in mass concrete where low heat evolution is desirable. The most commercially



Fig. 3: Schematic representation of the GGBFS production process.

Table 1: Summarizes the main international classifications for blast furnace slag cements and GGBFS grades.

Standard / Specification	Designation	Basis of Classification	Typical Application
JIS R 5211 (Japan)	Type A, B, C	% GGBFS in blend	General-purpose cements ^[15]
JIS R 6206 (Japan)	GGBFS 3000–8000	Specific surface area	Mass and structural concrete ^[15]
ASTM C989 (USA)	Grade 80, 100, 120	Strength activity index	Blended cement and concrete ^[31]
EN 15167 (EU)	GGBS A & B	Fineness and reactivity	High-performance concretes ^[31]
CSA A23.5 (Canada)	Slag Class S	Performance-based	Marine and structural concretes ^[28]

prevalent grade, GGBFS 4000, balances workability, strength, and durability requirements.^[15]

4.3 Physical properties

The main typical physical and mineralogical characteristics of GGBFS, reported in literature, are presented in Table 2. GGBFS exhibits physical characteristics that directly affect its workability and performance in concrete. Its specific gravity typically ranges between 2.5 and 2.9, while the bulk density lies between 1200 and 1670 kg/m³, values comparable to OPC (~1440 kg/m³). The Blaine surface area generally varies from 4250 to 4700 cm²/g, exceeding that of Portland cement (~3310 cm²/g), indicating finer particle size and higher surface reactivity.^[18]

The grain size of raw granulate before grinding is usually 0.1–1.2 mm, with around 60 % retained within that range.^[32] Once ground, GGBFS achieves a cement-like fineness and displays an absorption capacity of about 1.2 %, influencing its flowability and paste demand. Properly proportioned mixtures improve cohesion, pumpability, and compaction, especially in self-compacting concrete (SCC) where slag enhances viscosity control and allows lower water/binder ratios.^[7,18]

In large structural pours, GGBFS contributes to lower peak hydration temperatures, reducing the risk of thermal cracking. Its fine particle morphology provides a filler effect, refining the pore structure and enhancing density and durability.^[16]

4.4 Chemical properties

The average chemical composition of GGBFS and the functional roles of its oxides are summarized in Table 3. The chemical

composition of GGBFS depends on the raw materials, ore, fluxes, fuel, and operational parameters of the blast furnace. Typical oxide compositions include CaO (30–40 %), SiO₂ (28–38 %), Al₂O₃ (8–24 %), and MgO (1–18 %).^[14,18]

Most of the CaO and SiO₂ are incorporated into a glassy matrix of calcium-silicate and calcium-aluminate networks, which hydrate under alkaline conditions. Reactivity depends primarily on the glass content and basicity ratio, expressed as (CaO + MgO)/(SiO₂ + Al₂O₃). Higher basicity enhances the hydraulic potential, enabling the formation of more C–S–H and C–A–S–H gels upon activation.^[33] Moderate MgO contents (≤ 10 %) are beneficial, while higher values can cause expansive hydration if not carefully controlled.

4.5 Practical considerations

The incorporation of GGBFS in cementitious systems offers both technical and environmental advantages. Technically, it improves long-term mechanical strength, lowers permeability, increases chemical stability, and reduces thermal cracking risk. Concrete made with GGBFS typically demonstrates superior resistance to chloride ingress, sulfate expansion, and ASR, resulting in a longer service life and lower maintenance costs.^[34,16] Environmentally, replacing a portion of Portland cement with GGBFS can reduce CO₂ emissions by 30–60 % per cubic meter of concrete.^[16] Since it is a waste valorization route, the use of GGBFS also supports circular-economy principles by diverting metallurgical residues from landfills and conserving natural resources. Some limitations remain: high replacement ratios (≥ 60–70 %) may delay early-age strength development, necessitating adequate curing and temperature control, particularly in cold climates.^[25,14]

Table 2: Summarizes the typical physical and mineralogical characteristics of GGBFS reported in literature.

Property	Typical Value / Range	Unit	Significance
Specific gravity	2.5–2.9	—	Indicates density and mix proportioning ^[18,38]
Bulk density	1200–1670	kg/m ³	Comparable to OPC (~1440 kg/m ³) ^[18]
Blaine fineness	4250–4700	cm ² /g	Controls reactivity and strength ^[18,32]
Absorption capacity	1.0–1.5	%	Affects workability ^[32]
Glass content	85–98	%	Determines hydraulic reactivity ^[28,33]

Table 3: The average chemical composition of GGBFS and the functional roles of its oxides.

Oxide Component	Symbol	Typical Range (% by mass)	Functional Role
Calcium oxide	CaO	30–40	Provides basicity and forms C–S–H gel ^[33]
Silicon dioxide	SiO ₂	28–38	Forms C–S–H phase with Ca ^[18]
Aluminum oxide	Al ₂ O ₃	8–24	Forms C–A–S–H, enhances durability ^[18]
Magnesium oxide	MgO	1–18	Network modifier, affects reactivity ^[33]
Iron oxide	Fe ₂ O ₃	0.3–1.5	Minor phase, influences color ^[31]
Sulfur trioxide	SO ₃	0.1–2.0	Controls setting and sulfate resistance ^[31]

Additionally, although global slag production is large, over 90 % is already utilized in cementitious or road-base applications, making regional supply management crucial for sustainable deployment.^[14,35,36] In high-performance concretes (HPC) and self-compacting concretes (SCC), GGBFS enhances paste fluidity, segregation resistance, and surface finish, while in alkali-activated systems, it promotes the formation of C–A–S–H and N–A–S–H gels, achieving compressive strengths above 60 MPa at moderate curing conditions.^[26,37] Its multifunctional role positions GGBFS as a cornerstone material for low-carbon and durable concrete technologies in the era of sustainable construction.

5. Use of ground granulated blast furnace slag (GGBFS) in concrete

5.1 The possibility of the reuse of GGBFS as a SCM in concrete

Industrial by-products such as fly ash (FA) and ground granulated blast furnace slag (GGBFS) have been increasingly used as supplementary cementitious materials (SCMs) to partially replace Portland cement or aggregates in concrete. Their inclusion improves both sustainability and performance of construction materials. Numerous investigations on FA,^[35,38–40] GGBFS,^[35,40–41] and their combined systems^[35,42–44] demonstrate that these admixtures, at suitable replacement ratios, enhance fresh and hardened properties of concrete, particularly durability under aggressive environments.

When introduced into the concrete mix, GGBFS exerts two synergistic actions: a physical filler effect, refining the microstructure and reducing porosity, and a chemical pozzolanic reaction, where Ca(OH)₂ produced during cement hydration reacts with the amorphous silica and alumina in GGBFS to form secondary calcium silicate hydrate (C–S–H). This dual mechanism leads to improved density, strength, and impermeability of concrete.^[40–41]

GGBFS is widely recognized as a sustainable binder for high-durability concrete structures. As stated by Sudharsan and Palanisamy,^[45] its adoption in Europe, the United States,

and Asia, especially in Japan and Singapore, has extended the expected service life of structures from fifty to one hundred years. Oner and Akyuz^[46] confirmed that while early-age strength is typically lower because of delayed pozzolanic activity, the strength of GGBFS concrete surpasses that of conventional concrete beyond 28 days.^[47]

The replacement level of GGBFS usually ranges between 20% and 80% of the total binder,^[13] depending on performance goals. Lower contents (20–30%) are recommended where early strength is critical, whereas higher levels (50–60%) are ideal for marine, sulfate-rich, or mass concrete works where heat reduction and durability are priorities.^[48,49] According to the Australian Standard AS 3582.25, GGBFS used as a supplementary cementitious material must meet chemical and physical criteria to ensure consistent reactivity.^[17,50–51]

5.2 Fresh properties of GGBFS concrete

5.2.1 Introduction

The fresh properties of concrete are vital for ensuring proper mixing, placing, compaction, and finishing, which in turn govern the quality and long-term performance of the hardened concrete. The incorporation of ground granulated blast furnace slag (GGBFS) as a supplementary cementitious material significantly influences these fresh-state behaviors due to its unique physical characteristics, such as smooth, glassy particles, fine fineness, and lower density, and its slower hydraulic reactivity compared to ordinary Portland cement (OPC).^[20,25]

When GGBFS is introduced into the concrete matrix, it affects the rheological performance through both physical and chemical mechanisms. Physically, the fine and rounded slag particles improve particle packing and cohesion, leading to enhanced workability and reduced segregation or bleeding.

Chemically, the delayed hydration kinetics of GGBFS contribute to extended setting times and reduced early heat evolution, making it particularly suitable for mass concrete applications and hot-weather concreting.^[7,17]

Several experimental studies.^[25,28,47,52,53] have reported that

Table 4: Effect of GGBFS on Fresh Properties of Concrete.

Property	Observed Effect	Optimum Replacement (%)	Key Remarks	Refs.
Workability (slump flow)	Increases up to ~30 %, then decreases	20–30	Improved lubrication; excess reduces flowability	[17,20,52]
Setting time	Slightly prolonged at high content or low T	20–60	Beneficial for hot climates	[8,25,53]
Bleeding / segregation	Reduced	20–50	Denser mix, improved cohesion	[20,28]
Water demand	Lower due to glassy texture	20–50	Needs longer curing >30 %	[47,54]
Heat of hydration	Significantly reduced	40–60	Ideal for mass concrete	[28]

moderate GGBFS replacement (20–40%) generally enhances water demand and temperature rise. However, excessive contents may prolong setting times and reduce early stiffness, necessitating careful adjustment of admixture dosage and curing practices.

Overall, the inclusion of GGBFS provides a balanced improvement in the fresh-state performance of concrete when properly optimized. Table 4 summarizes the main findings from the literature concerning the influence of GGBFS on the fresh properties of concrete, including workability, setting time, bleeding, water demand, and heat of hydration, along with the optimum replacement levels and corresponding references.

5.2.2 Workability and consistency

The influence of Ground Granulated Blast Furnace Slag (GGBFS) on the workability of concrete is mainly governed by its fineness and replacement percentage. At moderate incorporation levels, GGBFS generally enhances flowability due to its smooth, glassy surface texture, which reduces interparticle friction and allows the particles to act as micro-lubricants within the cementitious matrix.^[20] This effect improves particle mobility and packing efficiency, resulting in increased slump and better consistency of fresh concrete.

However, when high replacement levels of GGBFS are used, a reduction in workability may occur. This behavior is attributed to the increase in water demand associated with finer slag particles and, in some cases, to the angular particle geometry produced during grinding. These factors can lead to higher paste viscosity and reduced flowability if water content or admixture dosage is not adequately adjusted.^[20]

In recycled aggregate concrete, the beneficial effect of GGBFS on workability is more pronounced. Recycled aggregates typically exhibit higher porosity and water absorption, which negatively affect fresh concrete performance. The incorporation of GGBFS helps mitigate these drawbacks by filling micro-voids within the cement paste and the interfacial transition zone, thereby reducing effective water demand and compensating for the porous nature of recycled aggregates.^[17] Consequently, improved workability and more stable fresh mixtures are commonly

reported.

Furthermore, GGBFS particles contribute to better cohesion and pumpability of concrete mixes due to their lower density and reduced bleeding tendency, which enhances the uniformity and stability of fresh concrete during handling and placement.^[25,28] These characteristics are particularly advantageous in concretes incorporating recycled aggregates or designed for applications requiring high flowability and segregation resistance.

5.2.3 Setting time and water demand

The inclusion of Ground Granulated Blast Furnace Slag (GGBFS) in concrete mixtures generally leads to a prolongation of both initial and final setting times, particularly at high replacement levels or when concrete is placed under low-temperature curing conditions. This behavior is primarily attributed to the latent hydraulic nature of GGBFS, whose hydration proceeds more slowly than that of ordinary Portland cement (OPC), resulting in delayed formation of early hydration products.^[8,25,53] The reduction in early heat evolution associated with GGBFS further contributes to slower setting kinetics, which can be advantageous in hot climates but may present challenges in cold environments or in applications requiring rapid strength gain.

Despite the delayed setting, GGBFS incorporation is often associated with a reduction in water demand compared with OPC-based concretes. This effect is linked to the smooth, glassy surface and low absorption capacity of slag particles, which improve particle dispersion and reduce the amount of mixing water required to achieve a given level of workability.^[47] Consequently, concrete mixtures containing moderate amounts of GGBFS can maintain satisfactory consistency even at lower water-to-binder ratios.

However, when the slag content exceeds approximately 30%, extended and well-controlled curing becomes essential to ensure adequate hydration and microstructural development. Prolonged moisture curing promotes the continued activation of GGBFS, leading to the formation of additional calcium–silicate–hydrate phases and improved long-term strength and durability.^[49] Inadequate curing at high replacement levels may result in incomplete slag hydration, delayed strength

development, and increased susceptibility to durability-related issues.

5.2.4 Influence of admixtures and curing

Polycarboxylate-based superplasticizers play a crucial role in optimizing the fresh performance of concretes incorporating Ground Granulated Blast Furnace Slag (GGBFS). These admixtures enhance the dispersion of slag particles within the cementitious matrix, reducing particle agglomeration and enabling improved flowability without the need for excess mixing water.^[55] As a result, GGBFS-containing concretes exhibit superior rheological stability, improved workability control, and enhanced consistency, even at low water-to-binder ratios.

In addition, concretes incorporating GGBFS demonstrate excellent slump retention, facilitating prolonged handling, transport, and placement operations. The improved cohesiveness and reduced bleeding tendency make these mixes easier to compact and finish, contributing to better surface quality and reduced risk of segregation. Beyond fresh-state benefits, the lower heat of hydration associated with GGBFS significantly reduces thermal gradients and internal stresses during early-age hydration, which is particularly advantageous in mass concrete applications, such as dams, raft foundations, and thick structural elements, where thermal cracking is a major concern.^[28]

5.3 Mechanical properties of GGBFS concrete

5.3.1 Introduction

The mechanical behavior of concrete incorporating ground granulated blast furnace slag (GGBFS) is a critical indicator of its structural performance, reflecting the combined effects of microstructural development, binder chemistry, and curing conditions. The substitution of ordinary Portland cement (OPC) with GGBFS alters the rate and products of hydration, influencing both early-age and long-term strength characteristics. In particular, the pozzolanic and latent hydraulic reactions of GGBFS contribute to the formation of additional calcium–silicate–hydrate (C–S–H) and calcium–alumino–silicate–hydrate (C–A–S–H) gels, which refine the pore structure and enhance the overall density of the cementitious matrix.^[16,18,24,28]

At early ages, concretes containing high GGBFS contents often exhibit reduced compressive and tensile strengths compared to control mixes due to the slower reaction kinetics of slag. However, long-term strength typically surpasses that of plain OPC concretes once hydration progresses and secondary C–S–H phases are formed. This delayed yet steady strength gain makes GGBFS concretes particularly advantageous for structural elements where long-term durability and load-bearing capacity are critical. Studies^[7,21,23,24,35] have consistently shown that replacement levels between 30% and 50% optimize the balance between early and later-age strength performance.

Beyond compressive strength, GGBFS improves tensile

and flexural capacities, modulus of elasticity, and load-deformation behavior. These enhancements are primarily attributed to the densification of the interfacial transition zone (ITZ) and the reduced micro-cracking tendency under stress. Additionally, the micro-filling ability of fine slag particles contributes to a more homogeneous stress distribution within the concrete matrix, thus improving fatigue and impact resistance.

The degree of improvement in mechanical performance depends on several factors, including slag fineness, replacement percentage, curing temperature, and the presence of chemical activators. Finer slags (specific surface area > 450 m²/kg) generally accelerate the hydration process and yield higher strength development at both early and later ages. Similarly, curing regimes involving moderate heat or steam activation have been found to further enhance mechanical properties by promoting the reactivity of GGBFS.^[23,28]

Overall, GGBFS serves not only as a cement substitute but also as a performance enhancer for concrete under various loading and environmental conditions. Table 5 provides a detailed summary of the experimental findings on the mechanical behavior of GGBFS concrete, highlighting its effects on compressive, tensile, and flexural strengths, as well as modulus of elasticity, optimum replacement levels, and associated reference sources.

5.3.2 Compressive strength development

Extensive research has consistently demonstrated that Ground Granulated Blast Furnace Slag (GGBFS) plays a significant role in enhancing the long-term mechanical performance of concrete, particularly compressive strength.^[1,8,18,28,34] At early ages (1–7 days), concretes incorporating GGBFS generally exhibit lower strength compared with ordinary Portland cement (OPC) systems. This behavior is mainly attributed to the slower hydration kinetics and delayed activation of the latent hydraulic phases of GGBFS, which result in limited early formation of strength-contributing hydration products.^[35,52,56–58]

However, as curing progresses, the continued reaction between calcium hydroxide released from OPC hydration and the amorphous silica and alumina phases in GGBFS leads to the progressive formation of secondary calcium–silicate–hydrate (C–S–H) and calcium–alumino–silicate–hydrate (C–A–S–H) gels. These secondary hydrates significantly refine the pore structure, densify the cement matrix, and strengthen the interfacial transition zone, thereby contributing to sustained strength development at later ages.^[16,18,20,24,28] As a result, GGBFS-based concretes often surpass the compressive strength of conventional OPC concretes at 28 days and beyond, with strength gains continuing well into long-term curing periods.

Numerous studies have identified an optimum GGBFS replacement range of approximately 30–50%, within which compressive strength performance is maximized.^[7,34] Within this range, improvements of up to 20–25% in compressive

Table 5: Effect of GGBFS on Mechanical Properties of Concrete.

Property	Trend	Optimum Range (%)	Remarks	Refs.
Compressive strength	↓ early, ↑ after 28–90 days	30–50	Up to +25 % at 90 days	[7,21,28,34,41]
Tensile strength	Moderate increase	20–40	+10–17 % vs control	[23,29,52]
Flexural strength	Increase then plateau	20–40	C–S–H improves bonding	[18,23]
Elastic modulus	Slight increase	30–50	Denser matrix	[23]
Density	Slightly reduced	-	Lower specific gravity	[18]

strength at 90 days relative to control OPC concrete have been reported, highlighting the effectiveness of GGBFS in promoting long-term hydration and microstructural densification.^[7,34] Replacement levels beyond this optimum may delay strength development excessively, particularly under inadequate curing conditions, whereas lower replacement levels may not fully exploit the latent hydraulic potential of GGBFS.

Overall, the strength development behavior of GGBFS-containing concrete reflects a shift from early-age strength dominance to long-term performance optimization, making GGBFS particularly suitable for structural applications where durability, service life, and long-term load-bearing capacity are prioritized over rapid early strength gain.

5.3.3 Tensile and flexural strength

The development of tensile and flexural strengths in concrete incorporating Ground Granulated Blast Furnace Slag (GGBFS) generally follows trends similar to those observed for compressive strength, with performance strongly influenced by the replacement level. At moderate GGBFS contents, typically between 20% and 40%, notable improvements in both tensile and flexural strengths have been consistently reported. In this range, tensile strength increases of approximately 10–17% and flexural strength enhancements of up to 24% relative to conventional OPC concrete have been achieved.^[18,23,52]

These improvements are primarily attributed to the formation of additional calcium–silicate–hydrate (C–S–H) gel, which refines the pore structure and strengthens the paste–aggregate interface. The densification of the interfacial transition zone (ITZ) enhances stress transfer between the cement paste and aggregates, thereby improving resistance to crack initiation and propagation under tensile and flexural loading.^[18,23] Moreover, the micro-filler effect of finely ground GGBFS contributes to a more homogeneous stress distribution within the concrete matrix, further supporting enhanced tensile and bending performance.^[52]

However, when excessive amounts of GGBFS are incorporated, a reduction in splitting tensile strength has been observed in some studies.^[17] This decline is commonly linked to reduced workability and incomplete early-age hydration, which can lead to inadequate compaction, increased porosity,

and weaker bonding at the paste–aggregate interface. Without sufficient curing or appropriate mix optimization, high slag contents may therefore compromise tensile-related properties despite favorable long-term compressive strength development.^[17]

Overall, these findings indicate that moderate GGBFS replacement levels are optimal for enhancing tensile and flexural performance, while excessive substitution requires careful control of workability and curing conditions to avoid adverse effects on cracking resistance and structural integrity.

5.3.4 Elastic modulus and microstructure

The modulus of elasticity of concrete has been shown to increase with the incorporation of Ground Granulated Blast Furnace Slag (GGBFS), particularly at replacement levels between 30% and 50%, reflecting the development of a denser and stiffer cementitious matrix.^[23] This enhancement is primarily associated with the progressive formation of secondary hydration products, which reduce total porosity and improve the continuity of the solid phase, thereby increasing resistance to elastic deformation under applied loads.

Microstructural investigations provide strong support for this behavior. As the GGBFS content increases, a significant reduction in average pore size—up to 47% at 50% replacement—has been reported, indicating substantial refinement of the pore structure and improved matrix compactness.^[24] This pore refinement contributes directly to increased stiffness by limiting microcrack initiation and reducing stress concentrations within the cement paste.

The observed densification is consistently confirmed by mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) analyses, which reveal a more uniform and tightly packed calcium–silicate–hydrate (C–S–H) network along with a narrower pore size distribution compared with ordinary Portland cement systems.^[24] The improved microstructural homogeneity enhances load transfer efficiency between paste and aggregates, thereby contributing to the observed increase in elastic modulus.

Overall, these findings indicate that GGBFS incorporation not only improves strength and durability but also positively influences the elastic response of concrete, particularly at moderate replacement levels, making GGBFS-blended concretes well suited for structural applications

requiring enhanced stiffness and deformation control.

5.4 Durability characteristics

5.4.1 Introduction

Durability is one of the most decisive parameters governing the long-term performance and sustainability of concrete structures. It determines the material's capacity to withstand aggressive environmental conditions, such as chloride ingress, sulfate attack, carbonation, freeze–thaw cycles, and alkali–silica reactions, without significant deterioration in mechanical integrity or service life. The incorporation of ground granulated blast furnace slag (GGBFS) markedly enhances the durability of concrete through both chemical and physical mechanisms.

Chemically, the latent hydraulic and pozzolanic reactions of GGBFS consume calcium hydroxide ($\text{Ca}(\text{OH})_2$) released during the hydration of ordinary Portland cement (OPC), leading to the formation of additional calcium–silicate–hydrate (C–S–H) and calcium–alumino–silicate–hydrate (C–A–S–H) gels.^[18,24,28,48] These secondary hydrates refine the pore structure, reduce the connectivity of capillary pores, and lower the permeability of the hardened matrix. Physically, the fine and amorphous particles of GGBFS fill interstitial voids within the cement paste, creating a denser microstructure that resists fluid penetration and diffusion of aggressive ions.

Extensive experimental research has confirmed that concretes containing GGBFS exhibit superior resistance to chloride ingress, sulfate expansion, and alkali–silica reaction (ASR) compared with conventional OPC concretes.^[18,24,48] Chloride diffusion coefficients are often reduced by one order of magnitude when 40–60 % of OPC is replaced by GGBFS, substantially improving performance in marine and de-icing environments. Similarly, the reduced calcium hydroxide content mitigates sulfate attack by limiting the formation of expansive ettringite and gypsum phases. The pozzolanic activity of slag also contributes to lowering alkali concentrations in the pore solution, thus minimizing ASR-induced cracking.

In addition, GGBFS concretes show improved resistance to carbonation and freeze–thaw cycles when adequate curing is provided. Although the lower portlandite content can slightly accelerate carbonation under poor curing conditions, the resulting microstructural densification offsets this effect by limiting CO_2 penetration.^[24] The reduced permeability and refined pore system also enhance freeze–thaw durability, maintaining structural integrity even after repeated cycles of freezing and thawing.

Collectively, these effects demonstrate that GGBFS plays a pivotal role in enhancing the durability of modern concrete, thereby extending service life, reducing maintenance needs, and aligning with sustainability objectives in infrastructure development. Table 6 summarizes the main findings from the literature regarding the influence of GGBFS on the durability properties of concrete, including chloride penetration, sulfate resistance, alkali–silica reactivity, carbonation, and freeze–

thaw behavior, together with the optimum replacement levels and corresponding references.

5.4.2 Permeability and chloride penetration

Numerous studies have demonstrated that the incorporation of Ground Granulated Blast Furnace Slag (GGBFS) significantly reduces chloride penetration and permeability in concrete, thereby enhancing long-term durability. This improvement is primarily attributed to the refinement of pore structure and the reduction of pore connectivity resulting from the formation of secondary hydration products, which slow down ionic diffusion. However, the effectiveness of GGBFS depends strongly on the replacement level and curing conditions, with extended curing generally amplifying its beneficial effects.

Experimental investigations indicate that concretes incorporating 50–60% GGBFS exhibit very low chloride ion permeability and high electrical resistivity values exceeding $30 \text{ k}\Omega\cdot\text{cm}$, reflecting excellent protection of embedded steel reinforcement.^[24,59] Results from Rapid Chloride Permeability Tests (ASTM C1202) further confirm a progressive decrease in charge passed—from moderate to very low—as the GGBFS content increases.^[18,60,61] Consequently, based on the performance reported in these studies, GGBFS-based concretes satisfy the durability requirements for exposure to moderately aggressive water environments.^[62]

In addition, the beneficial role of GGBFS has been observed in fly ash (FA)-based alkali-activated concrete, where its inclusion substantially enhances resistance to chloride penetration by reducing permeability and effective porosity, two parameters closely linked to chloride transport mechanisms.^[63] However, the influence of GGBFS content is not always linear. It has been reported that chloride transport numbers decrease when concrete contains 20–30% GGBFS in combination with 5–10% silica fume (SF), whereas a higher replacement level of 40% GGBFS may increase chloride transport due to changes in pore structure and binder composition.^[64]

Further studies reveal that water absorption and chloride permeability decrease consistently with increasing cement replacement by GGBFS, confirming its role in densifying the cementitious matrix.^[65] Investigations into chloride ion diffusion coefficients also highlight the importance of curing conditions. Specifically, air-cured specimens exhibit higher diffusion coefficients than underwater-cured ones, while increasing GGBFS content systematically reduces chloride diffusion.^[66,67] This behavior is attributed to the high fineness and latent hydraulic activity of GGBFS, which promote continued hydration and pore refinement when adequate moisture is available.

Overall, the collective findings indicate that GGBFS significantly enhances resistance to chloride ion penetration through combined microstructural densification and reduced ion transport pathways, provided that optimal replacement levels and appropriate curing regimes are applied.^[68] These characteristics confirm the suitability of GGBFS as a key

Table 6: Effect of GGBFS on Durability.

Durability Parameter	Observed Behavior	Optimum Replacement (%)	Mechanism / Benefit	Refs.
Permeability / Sorptivity	Decreases significantly	40–60	Secondary C–S–H fills pores	[48,24,18]
Chloride penetration (RCPT)	Moderate → Very low	50–60	Dense structure, >30 kΩ·cm resistivity	[24,18]
Sulfate attack resistance	Improved	≥60	Less CH, less ettringite	[48,28]
ASR mitigation	Reduced expansion	40–50	Alkali binding by C–S–H	[52,28]
Carbonation	Slightly higher; mitigated by curing	30–50	Lower CH but denser paste	[24]
Freeze–thaw durability	Maintained	20–50	Adequate air voids	[28]
Porosity / Pore size	↓ up to 47 %	30–50	Micro-filling and hydration	[24]

supplementary cementitious material for improving the durability of concrete exposed to chloride-rich environments.

5.4.3 Sulfate and acid attack resistance

Sulfate attack in concrete primarily arises from the interaction between sulfate ions and the hydration products of Portland cement, particularly calcium hydroxide (CH) and aluminate phases, leading to the formation of expansive compounds such as ettringite and gypsum. These reactions induce internal stresses, cracking, mass loss, and progressive deterioration of mechanical properties. The incorporation of Ground Granulated Blast Furnace Slag (GGBFS) has been widely demonstrated as an effective strategy to mitigate these degradation mechanisms through several complementary physicochemical effects.

First, GGBFS significantly reduces the effective tricalcium aluminate (C₃A) content of the binder system, thereby limiting the availability of reactive aluminates susceptible to sulfate-induced expansion. Second, the latent hydraulic reaction of GGBFS consumes calcium hydroxide and generates additional calcium silicate hydrate (C–S–H) gel, resulting in pore refinement, reduced connectivity of capillary pores, and lower permeability. This densified microstructure restricts sulfate ion ingress and slows the kinetics of deleterious chemical reactions within the cement matrix.^[69,70] Consequently, GGBFS-blended concretes exhibit enhanced resistance to sulfate penetration and expansion compared to ordinary Portland cement (OPC) systems.

Numerous studies confirm that concretes containing moderate to high levels of GGBFS show lower expansion, reduced mass loss, and improved long-term mechanical stability when exposed to sulfate-rich environments. The reduced calcium hydroxide content and denser matrix limit the formation of expansive ettringite and gypsum, which are the primary causes of sulfate-induced damage.^[25,27] In this context, the Australasian Slag Association, as reported by Frearson,^[71] indicated that slag replacement levels of at least 60% provide strong protection against sulfate attack, making such binders particularly suitable for marine structures and industrial foundations exposed to aggressive ionic environments.

The beneficial role of GGBFS is also evident in alkali-

activated and geopolymer systems. Studies have shown that the proportion of fly ash (FA) to GGBFS has a major influence on sulfate resistance, with higher GGBFS contents enhancing durability due to the formation of more chemically stable binding phases such as calcium–aluminum–silicate–hydrate (C–A–S–H) and sodium–aluminum–silicate–hydrate (N–A–S–H) gels.^[72] These phases exhibit greater resistance to sulfate attack than conventional C–S–H formed in OPC systems.

Further evidence indicates that high-alumina slag-blended cements can achieve significant long-term sulfate resistance even at relatively low replacement levels, provided sufficient cement hydration and appropriate calcite availability are ensured.^[73] In addition, it has been reported that the incorporation of calcium carbonate and calcium sulfate can exert a consistent beneficial effect on the resistance of GGBFS concretes to conventional sulfate attack, reducing both expansion and surface disintegration, through modifications of hydration pathways and phase assemblages.^[74]

Comparative studies also reveal that blended cements incorporating GGBFS exhibit significantly higher resistance to both sodium sulfate and magnesium sulfate attacks compared to reference OPC concretes.^[75] While magnesium sulfate is typically more aggressive due to decalcification of C–S–H, the reduced calcium hydroxide content and refined pore structure of GGBFS concretes delay the onset and progression of damage.

In relation to combined sulfate and acid exposure, promising results have been reported in terms of mass change and compressive strength retention, although increased void content may adversely affect water absorption behavior.^[76] Moreover, investigations into sulfuric acid environments indicate that although GGBFS significantly reduces sulfate-induced expansion compared to CEM I and CEM II binders, extremely harsh acidic conditions can still lead to premature deterioration of all cementitious systems, highlighting the limitations of cement-based materials under strong acid attack.^[77]

Additional insights from geopolymer concrete systems show that sorptivity decreases with increasing sodium silicate-to-sodium hydroxide ratios in 100% GGBFS binders, while blended systems containing 50% GGBFS and 50% fly ash

exhibit the lowest sorptivity values across curing ages, indicating improved resistance to fluid ingress.^[78] Furthermore, GGBFS-based geopolymer concretes can be produced using conventional concrete equipment and achieve high structural strength through self-curing mechanisms, exceeding the minimum requirements for “extreme” exposure conditions as defined by IS 456-2000.^[79]

Overall, the collective findings demonstrate that GGBFS significantly enhances sulfate resistance through chemical stabilization, pore refinement, and reduced permeability, while also offering improved performance in blended and alkali-activated systems. Although resistance to strong acid environments remains limited, GGBFS-containing binders provide a robust and sustainable solution for concrete structures exposed to sulfate-rich and moderately aggressive conditions.

5.4.4 Alkali–silica reactivity (ASR) mitigation

Alkali–silica reactivity (ASR) is a deleterious chemical process resulting from the reaction between alkalis in the cement pore solution and reactive forms of silica present in certain aggregates. This reaction leads to the formation of an expansive hygroscopic gel that absorbs moisture, generating internal stresses that cause cracking, loss of stiffness, and long-term durability degradation in concrete structures.^[80] The incorporation of Ground Granulated Blast Furnace Slag (GGBFS) has been widely recognized as an effective mitigation strategy for ASR due to its combined chemical, microstructural, and transport-modifying effects.^[28,48]

Experimental investigations consistently indicate that moderate to high replacement levels of GGBFS significantly suppress ASR-induced expansion, with increasing slag content generally enhancing mitigation efficiency. In particular, replacement levels in the range of 40–50% have been shown to effectively prevent excessive ASR expansion, establishing GGBFS as a reliable preventive agent when reactive aggregates are used.^[49] This beneficial effect is attributed not only to alkali dilution but also to changes in hydration chemistry and pore solution composition.

At the microstructural and chemical level, quantitative elemental analyses have demonstrated that the incorporation of GGBFS can slow silica dissolution at the aggregate surface by promoting the formation of an aluminum-rich layer. This layer inhibits the interaction between alkalis and reactive silica, prevents the calcification of ASR gel, and limits the development of harmful crystalline ASR products.^[81] Such mechanisms play a critical role in stabilizing the aggregate–paste interface and reducing the severity of ASR-related damage.

Further studies have shown that combining GGBFS with other supplementary materials can yield additional benefits. Mortar specimens in which 30% of cement was replaced by a mixture of alum sludge and GGBFS exhibited both considerable compressive strength and significantly enhanced ASR resistance compared with reference samples.^[82] This

highlights the synergistic potential of GGBFS when used in blended binder systems tailored for durability performance.

However, it has also been reported that GGBFS may be less effective than fly ash (FA) in certain ASR mitigation scenarios. For example, when GGBFS was added at replacement levels of 20%, 40%, and 70% to concrete already containing 30% FA, ASR expansion was reduced by only 3%, 9%, and 12%, respectively, indicating a comparatively lower mitigation efficiency than FA under those specific conditions.^[83] These findings emphasize that the effectiveness of GGBFS in controlling ASR depends strongly on binder composition, alkali content, and aggregate reactivity.

Additional enhancement of ASR resistance can be achieved through combined material strategies. Test results have shown that the incorporation of GGBFS in conjunction with steel fibers leads to a significant reduction in ASR expansion.^[84] In such systems, GGBFS reduces the chemical driving forces of ASR, while steel fibers contribute to crack-bridging and stress redistribution, limiting the propagation of ASR-induced microcracks.

Overall, the reviewed studies confirm that GGBFS is an effective and versatile material for mitigating ASR, primarily through alkali dilution, chemical stabilization of reactive silica, pore refinement, and moisture transport control. While its efficiency may vary relative to other supplementary cementitious materials depending on mix design and exposure conditions, GGBFS remains a robust and sustainable solution for improving the durability of concrete in ASR-prone environments.

5.4.5 Carbonation behavior

Carbonation is a physicochemical process in which atmospheric CO₂ penetrates the concrete matrix and reacts primarily with calcium hydroxide (Ca(OH)₂), leading to the formation of calcium carbonate (CaCO₃). This reaction progressively reduces the alkalinity of concrete, which may compromise the passive oxide layer protecting embedded reinforcing steel and thereby increase the risk of corrosion, ultimately affecting long-term durability.^[85] The incorporation of Ground Granulated Blast Furnace Slag (GGBFS) has a complex and sometimes contrasting influence on carbonation behavior, governed by interactions between binder chemistry, microstructural refinement, and curing conditions.

One of the dominant effects of GGBFS addition is the reduction of calcium hydroxide content in the hardened cementitious matrix. Through its latent hydraulic and pozzolanic reactions, GGBFS consumes portlandite and produces additional calcium silicate hydrate (C–S–H) gel. While this reaction enhances matrix densification, it simultaneously reduces the alkaline buffering capacity available to neutralize incoming CO₂. As a result, GGBFS-blended concretes may exhibit higher carbonation rates than ordinary Portland cement (OPC) concretes, particularly at early ages or under insufficient curing conditions.^[24] The lower availability of Ca(OH)₂ accelerates the drop in pore solution

pH once carbonation begins.

Experimental studies have confirmed that concrete containing GGBFS generally shows lower carbonation resistance than OPC concrete, primarily due to the consumption of portlandite during slag hydration. However, it has been reported that a blended binder composed of 70% OPC and 30% GGBFS performs comparably to 100% OPC concrete under accelerated carbonation exposure, with similar carbonation depths. Furthermore, the results indicate that carbonation rate is more sensitive to the percentage of GGBFS replacement than to curing duration, while specimens exposed to natural indoor carbonation exhibit lower carbonation rates than those subjected to accelerated carbonation conditions.^[86]

Additional investigations have shown that the incorporation of GGBFS does not necessarily lead to a significant increase in carbonation depth in all cases. For instance, studies reported that the use of GGBFS or ettringite-based expansive agents did not noticeably increase carbonation depth, regardless of material fineness, suggesting that microstructural effects and binder interactions can partially offset reduced alkalinity.^[87] Nevertheless, other findings indicate that carbonation depth and rate tend to increase with higher GGBFS content in mortars, while extended curing periods significantly reduce carbonation progression by promoting further hydration and pore refinement.^[88]

In general terms, the combination of GGBFS with Portland cement—within the compositional ranges defined by standards such as BS EN 197-1^[89] is associated with an increased susceptibility to carbonation compared to pure OPC systems. However, the magnitude of this increase strongly depends on parameters such as GGBFS and cement fineness, mix design, water-to-binder ratio, curing quality, and concrete maturity at the time of exposure.^[90] Adequate curing is therefore essential to ensure sufficient slag hydration and microstructural densification, which can mitigate CO₂ ingress and reduce carbonation rates.

Overall, the carbonation behavior of GGBFS-blended concrete reflects a balance between reduced alkaline buffering capacity and enhanced microstructural compactness. While higher slag contents may increase carbonation susceptibility under unfavorable curing or exposure conditions, optimized mix design and proper curing can effectively control carbonation depth, allowing GGBFS concretes to achieve satisfactory durability performance while benefiting from improved sustainability and reduced clinker consumption.

5.4.6 Freeze–thaw behavior

Freeze–thaw deterioration is a critical durability issue for concrete structures exposed to cyclic freezing and thawing in the presence of moisture. Damage originates from the freezing of pore water, which expands and generates hydraulic and osmotic pressures, leading to microcracking, surface scaling, and gradual loss of mechanical integrity. The incorporation of Ground Granulated Blast Furnace Slag (GGBFS) influences

freeze–thaw performance primarily through its effects on pore structure refinement, hydration kinetics, and air-void characteristics.

Several studies indicate that the freeze–thaw resistance of GGBFS-blended concretes can remain comparable to that of ordinary Portland cement (OPC) concretes, provided that adequate air entrainment and proper curing are ensured before exposure.^[28] The refinement of pore structure induced by slag hydration reduces permeability and limits the amount of freezable water, which is beneficial for freeze–thaw durability. However, because slag hydration proceeds more slowly than OPC hydration, insufficient early-age curing may leave the matrix vulnerable to freeze–thaw damage.

The interaction between freeze–thaw cycles and other aggressive mechanisms further complicates durability behavior. The synergistic effects of freezing–thawing (FRTH) cycles and chloride ion (Cl⁻) penetration have been shown to amplify damage and accelerate degradation. In this context, concretes incorporating both GGBFS and air-entraining agents (AEA) demonstrated improved resistance to chloride ingress and reinforcement corrosion even after FRTH exposure, highlighting the importance of combined durability strategies.^[91]

Quantitative durability indicators also support the influence of slag content on frost resistance. It has been reported that the k-value, used to assess frost durability, decreases as GGBFS content increases. For slag contents up to 40%, k-values range from 0.6 to 1.0, while higher slag contents (>40%) result in lower k-values of approximately 0.5–0.6. These findings confirm that increasing slag replacement may reduce frost resistance unless compensated by mix design adjustments, and they validate the k-value approach as a simple and effective method for evaluating frost durability.^[92]

Conversely, some experimental results indicate that increasing GGBFS replacement can negatively affect frost resistance, particularly in self-compacting concrete (SCC). Studies have shown that higher slag contents lead to reduced compressive strength and lower freeze–thaw resistance in SCC mixtures, emphasizing the sensitivity of such systems to binder composition and air-void structure.^[93] These findings underline that the benefits of GGBFS are not universal and depend strongly on concrete type and mix design.

Other investigations have demonstrated improved freeze–thaw performance under specific conditions. In mortar and concrete incorporating blast-furnace slag sand, calcium hydroxide precipitated around aggregate particles reacts with both cement paste and slag sand, modifying the interfacial transition zone. This microstructural improvement resulted in high freeze–thaw resistance even in salt-water environments, indicating the potential of slag-based aggregates to enhance durability in severe exposure conditions.^[94]

Overall trends suggest that frost resistance generally decreases with increasing GGBFS content; however, it has been clearly shown that frost-resistant concrete can still be

produced with up to 50% GGBFS, provided that key mix parameters—such as air content, air-void spacing, and curing regime—are properly controlled.^[95] This highlights the critical role of air-entrainment and mix optimization in slag-rich concretes.

Further evidence confirms that durability performance depends on the combined use of GGBFS and aggregate characteristics. For instance, mixtures containing 15% slag powder and high proportions of artificial aggregates exhibited reduced durability after 300 freeze–thaw cycles, whereas lowering the artificial aggregate content significantly improved freeze–thaw resistance. The best performance was observed in mixtures with 15% slag powder and 20% artificial aggregates, outperforming conventional concrete blends.^[96]

In summary, the freeze–thaw resistance of GGBFS-blended concrete is governed by a balance between pore refinement and reduced early-age strength, as well as the quality of the air-void system. While high slag contents may reduce frost resistance if not properly designed, optimized mixtures incorporating adequate air entrainment, suitable aggregate selection, and sufficient curing can achieve equal or superior freeze–thaw durability compared to OPC concretes. These findings confirm that GGBFS can be effectively used in freeze–thaw-exposed environments when supported by appropriate mix design strategies. Shrinkage, Thermal Cracking, and Long-Term Performance

Drying shrinkage is a critical time-dependent phenomenon in concrete, primarily governed by moisture loss from the cementitious matrix and the associated capillary stresses that develop within the pore network. Concretes incorporating Ground Granulated Blast Furnace Slag (GGBFS) generally exhibit lower drying shrinkage than ordinary Portland cement (OPC) concretes, a behavior that can be attributed to several interrelated microstructural and physicochemical factors. The finer particle size and glassy nature of GGBFS enhance particle packing efficiency, leading to a refined pore structure with reduced capillary porosity and lower pore connectivity. This refinement limits moisture migration and reduces shrinkage strains associated with water evaporation from the hardened matrix.^[48]

In addition, the hydration products formed in GGBFS-blended systems contribute to improved dimensional stability. The secondary hydration of slag produces additional C–S–H gel that progressively fills voids and strengthens the internal skeleton of the paste, thereby increasing resistance to shrinkage-induced deformation. As a result, GGBFS concretes often show reduced cracking potential under restrained drying conditions, which is particularly beneficial for slabs, pavements, and structural elements where shrinkage cracking can compromise serviceability and durability.

Beyond drying shrinkage, GGBFS concretes are well known for their lower heat of hydration and slower temperature rise during early-age hydration. Unlike OPC systems, which can generate high peak temperatures shortly after casting, slag-blended concretes release heat more

gradually due to the delayed activation of GGBFS. This behavior is especially advantageous in mass concrete applications, where excessive heat generation and steep thermal gradients can induce tensile stresses and lead to early-age thermal cracking. By reducing peak temperatures and moderating thermal gradients, GGBFS significantly lowers the risk of thermally induced cracking in large structural elements such as foundations, bridge piers, retaining walls, and dams.^[28]

The long-term performance of GGBFS concretes further reinforces their suitability for durable construction. While early-age strength development may be slower than that of OPC concrete, GGBFS concretes exhibit continuous hydration and strength gain over extended periods. Long-term studies have shown that compressive strength can increase substantially beyond the conventional 28-day reference age, with values reported to double after 10–12 years due to ongoing slag hydration and microstructural densification.^[20] This sustained strength development is accompanied by progressive reductions in permeability and improvements in resistance to chemical ingress, contributing to superior long-term durability.

From an engineering perspective, the combined effects of reduced drying shrinkage, controlled heat evolution, and prolonged strength development make GGBFS a highly effective supplementary cementitious material for minimizing cracking risk and enhancing the service life of concrete structures. These characteristics are particularly valuable in large-scale infrastructure and long-life applications, where dimensional stability, crack control, and durability are critical design requirements. Consequently, the incorporation of GGBFS represents a robust strategy for producing concrete with improved early-age performance and superior long-term structural integrity.

5.5 Microstructural evolution

Microstructural analyses provide strong evidence that Ground Granulated Blast Furnace Slag (GGBFS) plays a crucial role in the microstructural refinement and chemical stabilization of cementitious systems. The incorporation of GGBFS promotes the formation of fine calcium–silicate–hydrate (C–S–H) gels that progressively fill the interfacial transition zone (ITZ), thereby reducing porosity and enhancing the bond between paste and aggregate. Mercury intrusion porosimetry results indicate a reduction in average pore diameter by 15–47% as the GGBFS content increases from 10% to 50%.^[24] The slag's amorphous, glassy surface accelerates secondary hydration reactions, leading to a denser matrix and improved water impermeability.^[24,56]

Complementary X-ray diffraction (XRD) and scanning electron microscopy (SEM) observations confirm that the hydration products in GGBFS concretes resemble those in ordinary Portland cement (OPC) systems, mainly C–S–H and ettringite, but they develop more gradually and persist over longer curing durations.^[48] This prolonged hydration reduces

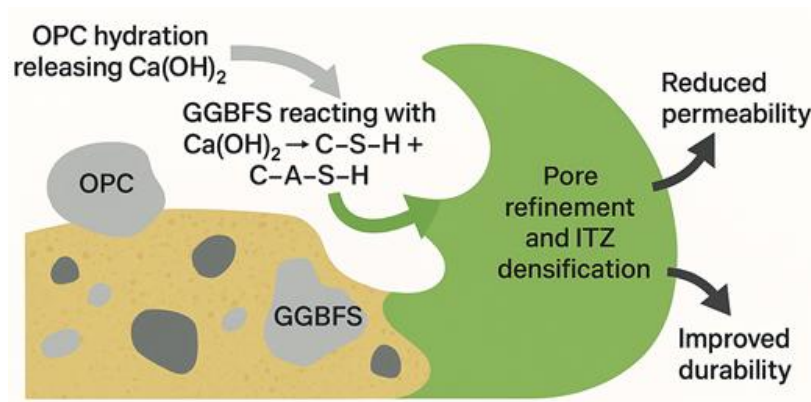


Fig. 4: Microstructural Mechanism of GGBFS Reactivity.

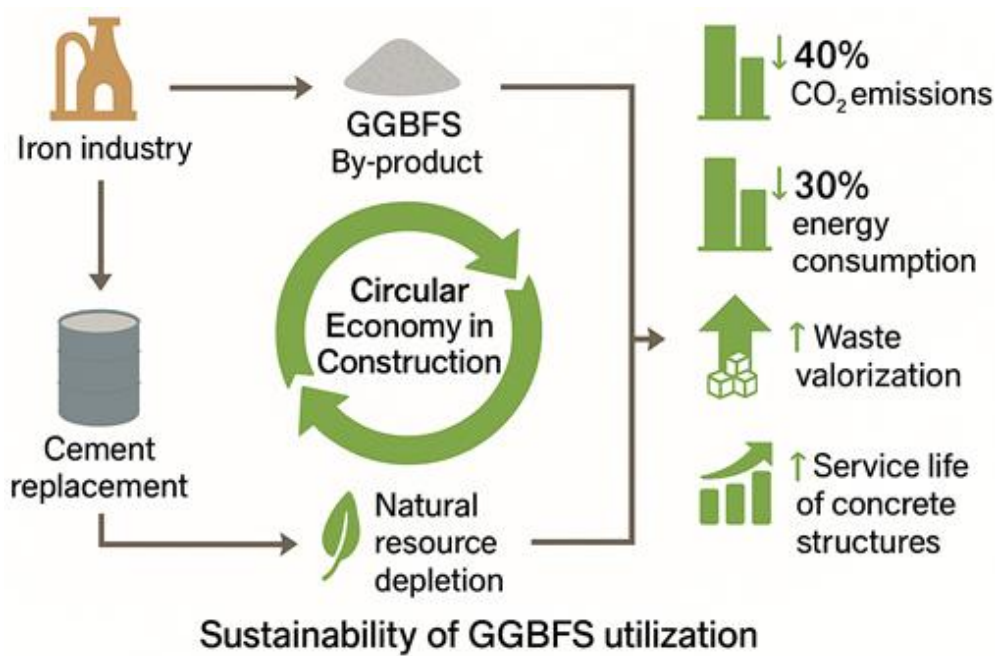


Fig. 5: Sustainability framework of Ground Granulated Blast Furnace Slag (GGBFS) utilization in concrete.

portlandite content while increasing the proportion of secondary C-S-H and C-A-S-H phases, resulting in improved mechanical strength, chemical stability, and resistance to aggressive agents.

These microstructural interactions are illustrated in Fig. 4, which depicts the reactive mechanism of GGBFS in concrete. The diagram shows how calcium hydroxide, Ca(OH)₂, produced during OPC hydration reacts with the silica and alumina present in GGBFS to form additional C-S-H and C-A-S-H gels. This reaction sequence refines the pore structure, densifies the matrix, and strengthens the ITZ, thereby reducing permeability and enhancing long-term durability.^[24,48,97]

5.6 Sustainability impacts

The utilization of Ground Granulated Blast Furnace Slag (GGBFS) in concrete contributes substantially to sustainable construction by promoting circular economy principles and reducing environmental impacts. As a by-product of the iron industry, GGBFS transforms what was once considered industrial waste into a high-value supplementary cementitious

material, effectively linking the steel and construction sectors within a closed-loop system. This industrial symbiosis minimizes waste generation and fosters resource efficiency across the material lifecycle.^[18,24]

Replacing ordinary Portland cement (OPC) with GGBFS significantly mitigates greenhouse gas emissions and energy consumption. Studies have shown that substituting up to 50% of OPC with GGBFS can reduce CO₂ emissions by approximately 40% and overall energy consumption by about 30%, while simultaneously decreasing natural resource depletion associated with clinker production.^[18,24] In addition, the incorporation of GGBFS enhances durability, reducing permeability, corrosion risk, and the need for maintenance—factors that directly extend the service life of concrete structures and improve their life-cycle performance.

These sustainability pathways are illustrated in Fig. 5, which depicts the circular economy framework of GGBFS utilization. The diagram highlights the transformation of iron industry by-products into cement replacements, leading to measurable environmental benefits such as lower carbon

emissions, reduced energy use, increased waste valorization, and improved structural longevity. The holistic integration of GGBFS into construction aligns with Leadership in Energy and Environmental Design (LEED) standards, qualifying for credits that advance green building certification and reinforce the global transition toward low-carbon and resilient infrastructure systems.^[18]

6. Limitations and disadvantages of GGBFS use in concrete and mortar

Despite its recognized environmental and durability benefits, the use of Ground Granulated Blast Furnace Slag (GGBFS) in concrete presents several limitations that may affect practical implementation. One of the main drawbacks is delayed early-age strength development, particularly at replacement levels above 40%. This behavior is attributed to the slower hydration kinetics and latent hydraulic nature of GGBFS, which can restrict rapid construction schedules and early demolding, especially under low-temperature curing conditions.

GGBFS-blended concretes are also highly sensitive to curing quality. Insufficient moisture curing can hinder slag hydration, resulting in incomplete microstructural development, increased permeability, and reduced durability. Compared with ordinary Portland cement (OPC) systems, GGBFS concretes require longer and more controlled curing to achieve their full performance potential.

Another limitation is the increased susceptibility to carbonation at high slag contents. The consumption of calcium hydroxide during slag hydration lowers the alkaline buffering capacity of the matrix, which may accelerate carbonation depth and increase reinforcement corrosion risk if cover thickness and curing are inadequate.

Performance variability is further influenced by differences in slag composition and fineness, which depend on blast furnace operation and processing conditions. Such variability can lead to inconsistent setting behavior and strength development, emphasizing the need for performance-based specifications and quality control.

Finally, reduced freeze–thaw resistance may occur at high GGBFS replacement levels if air-void systems and curing are not properly optimized, particularly in cold climates.

Conclusion and Perspectives This review comprehensively examined the role of Ground Granulated Blast Furnace Slag (GGBFS) as a supplementary cementitious material (SCM) in sustainable concrete. The findings confirm that GGBFS is not merely a substitute for ordinary Portland cement (OPC), but a multifunctional constituent that enhances fresh and hardened properties while significantly reducing environmental impacts. Its combined pozzolanic and latent hydraulic reactivity promotes the formation of secondary C–S–H and C–A–S–H gels, leading to pore refinement, densification of the interfacial transition zone (ITZ), and improved long-term strength and durability.

Overall, GGBFS incorporation improves workability and rheological stability, reduces heat of hydration and thermal

cracking risk, and enhances long-term mechanical performance through sustained hydration and microstructural densification. From a durability perspective, GGBFS concretes exhibit superior resistance to chloride ingress, sulfate attack, and alkali–silica reactivity, contributing to lower permeability, delayed degradation processes, and extended service life in aggressive environments. Environmentally, the valorization of GGBFS as an industrial by-product reduces clinker consumption and can lower CO₂ emissions by up to 40%, aligning concrete production with circular economy principles and global decarbonization strategies.

Despite these well-established benefits, several challenges continue to limit the broader and more consistent adoption of GGBFS in practice. Variability in slag chemical composition and fineness can lead to inconsistent early-age performance and setting behavior, particularly in cold climates or at high replacement levels. In addition, reduced early strength development, increased carbonation susceptibility under certain conditions, and the lack of harmonized performance-based standards remain critical concerns for designers and practitioners.

To address these challenges, several perspectives and potential solutions are identified. First, the development of unified, performance-based mix design guidelines and predictive models that explicitly link GGBFS characteristics (composition, fineness, and replacement ratio) to mechanical and durability outcomes is essential. Second, advanced multi-scale experimental techniques combined with kinetic and microstructural modeling can improve the understanding of hydration mechanisms and long-term evolution of C–S–H and C–A–S–H gels. Third, long-term field studies under diverse climatic exposures are required to better quantify carbonation behavior, durability, and service-life performance of GGBFS concretes. Fourth, hybrid systems combining GGBFS with other SCMs or alkali-activated binders offer promising pathways to overcome early-age limitations while maximizing strength development and CO₂ reduction. Finally, integrating comprehensive life-cycle assessment and techno-economic analyses will enable a more robust evaluation of GGBFS within circular construction frameworks and support evidence-based decision-making.

In conclusion, GGBFS represents a key material for advancing high-performance, durable, and low-carbon concrete. Addressing the identified challenges through targeted research, standardization, and holistic sustainability assessment will be crucial to unlocking its full potential and ensuring its widespread implementation in future green and resilient infrastructure.

7. Conclusion

This review comprehensively examined the role of Ground Granulated Blast Furnace Slag (GGBFS) as a supplementary cementitious material (SCM) in sustainable concrete. The findings confirm that GGBFS is not merely a substitute for

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not Applicable.

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