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A Comprehensive Review of High-Performance Concrete Using Ground Granulated Blast Furnace Slag (GGBS)

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ABSTRACT

The construction industry is confronted with the dual challenge of satisfying rapidly growing infrastructure demands while simultaneously reducing its significant environmental impact. High-performance concrete (HPC) incorporating Ground Granulated Blast Furnace Slag (GGBS) has emerged as an effective solution that addresses both enhanced performance requirements and sustainability objectives. This review paper presents a systematic synthesis of recent research published between 2023 and 2025 on GGBS-based HPC. The influence of GGBS on fresh concrete properties, including workability and rheological behavior, mechanical performance such as compressive, tensile, and flexural strength, and durability characteristics encompassing resistance to chloride ingress, sulfate attack, and reinforcement corrosion is critically examined. The review identifies optimal GGBS replacement levels of 30–50% for achieving balanced overall performance, while higher replacement ratios in the range of 40–60% demonstrate superior durability under aggressive exposure conditions. Emerging developments, including nano-GGBS applications and geopolymer-based systems, are discussed in the context of next- generation sustainable concrete technologies. In addition, sustainability assessments reveal notable reductions in CO emissions and life-cycle costs associated with GGBS utilization. Finally, the paper highlights existing research gaps and provides recommendations to guide future investigations and facilitate effective practical implementation of GGBS-based HPC.

Keywords: - GGBS; High-performance concrete; Durability; Sustainability; Mechanical properties;

1. INTRODUCTION

High-performance concrete (HPC) is an advanced category of cementitious material specifically engineered to achieve superior mechanical performance and enhanced durability characteristics beyond those attainable with conventional concrete. Unlike traditional concrete, which is generally designed with primary emphasis on compressive strength, HPC is proportioned to satisfy multiple performance requirements simultaneously, including high workability, excellent long-term mechanical properties, low permeability, and strong resistance to aggressive environmental conditions [1]. Owing to these attributes, HPC has become increasingly important in infrastructure applications subjected to severe exposure conditions, such as marine structures, bridges, high-rise buildings, and industrial facilities [2].

Alongside advancements in concrete performance, the construction industry is under increasing pressure to mitigate its environmental impact. The production of Ordinary Portland Cement (OPC) is a significant contributor to global carbon dioxide emissions, accounting for approximately 5–8% of total anthropogenic greenhouse gas emissions worldwide [3], [4]. This substantial environmental burden arises primarily from the high energy demand of cement manufacturing processes, which require kiln temperatures exceeding 1400 °C, as well as from the calcination of limestone, during which CO is released as an inherent chemical byproduct. Considering that global concrete consumption has reached nearly 30 billion tonnes annually, the magnitude of this sustainability challenge is considerable [6].

Ground Granulated Blast Furnace Slag (GGBS) has emerged as one of the most effective supplementary cementitious materials (SCMs) for simultaneously enhancing concrete performance and reducing environmental impact. GGBS is an industrial byproduct generated during iron production, obtained by rapid quenching of molten blast furnace slag followed by grinding into a fine powder. The material exhibits latent hydraulic behavior, enabling it to develop cementitious properties when activated in the presence of Portland cement or alkaline activators. Its chemical composition, primarily comprising calcium oxide, silicon dioxide, aluminium oxide, and magnesium oxide, contributes to both its pozzolanic and hydraulic reactivity [7].

The incorporation of GGBS in concrete offers significant environmental and technical advantages. From a sustainability perspective, GGBS utilization reduces the demand for virgin OPC, diverts industrial waste from landfills, and lowers the overall carbon footprint of concrete construction. From a performance standpoint, GGBS has been shown to improve both fresh and hardened concrete properties, including enhanced workability, reduced heat of hydration, improved long-term strength development, and increased resistance to chloride ingress and sulfate attack [8].

The primary objective of this review paper is to present a comprehensive synthesis of recent research on GGBS-based high- performance concrete. Specifically, the review aims to: (1) examine the effects of GGBS on the fresh, mechanical, and durability properties of HPC; (2) identify optimal GGBS replacement levels for various performance objectives; (3) evaluate the sustainability implications associated with GGBS utilization; (4) discuss emerging developments such as nano-GGBS and geopolymer-based technologies; and (5) highlight existing knowledge gaps and directions for future research. The review predominantly focuses on studies published between 2023 and 2025, thereby capturing the most recent advancements in this rapidly evolving research domain [10].

2. GGBS: PRODUCTION, PROPERTIES AND MECHANISMS

2.1 Production Process

Ground Granulated Blast Furnace Slag (GGBS) is obtained as a byproduct during the production of pig iron in blast furnaces. In this process, iron ore, coke, and limestone are charged into the furnace, where combustion at temperatures approaching 1500 °C results in the formation of molten iron, which collects at the bottom of the furnace. The slag, consisting of non-metallic impurities derived from the iron ore and fluxing agents, separates from the molten iron and floats on the surface. This molten slag is primarily composed of silica, alumina, and oxides of calcium and magnesium. To preserve its latent hydraulic properties, the slag is rapidly quenched, most commonly using high-pressure water jets. Rapid cooling inhibits crystallization and produces a granular, glassy material. These granules are subsequently dried and ground to a fine powder, typically achieving a specific surface area in the range of 400–600 m^2/kg, thereby yielding GGBS suitable for use as a supplementary cementitious material [11].

2.2 Physical and Chemical Characteristics

The physical characteristics of GGBS play a critical role in determining its performance in concrete. The material generally exhibits a specific gravity between 2.85 and 2.95, which is marginally lower than that of Ordinary Portland Cement (OPC). GGBS is typically finer than OPC, with a higher Blaine specific surface area, which enhances its reactivity and contributes to improved particle packing and pore refinement within the cementitious matrix. The particles are predominantly angular and irregular in shape, influencing both water demand and packing density in concrete mixtures [9].

From a chemical perspective, GGBS is characterized by a high proportion of amorphous, glassy phases that impart latent hydraulic reactivity. Its chemical composition is mainly governed by the relative contents of calcium oxide, silicon dioxide, aluminum oxide, and magnesium oxide. The typical compositional ranges reported in recent studies are summarized in Table 1, based on data available in the literature [14].

Table 1: Typical Chemical Composition of GGBS

Component	Weight Percentage (%)
Calcium Oxide (CaO)	34–43
Silicon Dioxide (SiO)	27–38
Aluminum Oxide (Al O)	7–17
Magnesium Oxide (MgO)	5–14
Iron Oxide (Fe O)	0.2–1.6
Sulfur (S)	0.7–2.2

The hydraulic reactivity of GGBS is commonly assessed through the slag activity index, determined according to standards such as ASTM C989. Research indicates that GGBS meeting Grade 100 specifications exhibits a pozzolanic activity index of 75% and a strength activity index of 85% at 28 days [15].

2.3 Mechanisms of Hydration and Pozzolanic Reaction

The contribution of Ground Granulated Blast Furnace Slag (GGBS) to concrete performance occurs through two primary mechanisms, namely hydraulic reaction and pozzolanic reaction. Owing to its latent hydraulic nature, GGBS is capable of reacting with water to form cementitious products; however, this reaction proceeds at a relatively slow rate under normal conditions. In the presence of chemical activators—most commonly calcium hydroxide released during the hydration of Ordinary Portland Cement (OPC)—the reaction rate of GGBS is significantly accelerated [11]. The hydration mechanism of GGBS involves the dissolution of its glassy structure in the highly alkaline environment generated during OPC hydration. Calcium ions present in the pore solution attack the Si–O and Al–O bonds within the slag glass, resulting in the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate phases. While these hydration products are broadly similar to those produced during OPC hydration, they exhibit distinct compositional characteristics, including a lower calcium-to-silicon (Ca/Si) ratio and partial substitution of silicon by aluminum within the C–S–H structure. This modified hydration product is often referred to as calcium–alumino–silicate hydrate (C–A–S–H) [10].

In addition to hydraulic activity, GGBS participates in pozzolanic reactions that consume calcium hydroxide generated during OPC hydration. Calcium hydroxide contributes minimally to strength and is vulnerable to leaching; its conversion into additional C–S–H gel enhances both strength and durability. This secondary reaction leads to microstructural densification, particularly within the interfacial transition zone (ITZ) between aggregate particles and the cement paste. The refined pore structure significantly reduces permeability and restricts the ingress of aggressive agents, thereby improving durability performance [9].

The reaction kinetics of GGBS are strongly dependent on temperature and are slower than those of OPC during early hydration stages. As a result, GGBS-containing concretes typically exhibit delayed early-age strength development but achieve superior long-term strength as pozzolanic reactions continue over extended curing periods. The reduced rate of reaction also lowers the heat of hydration, which is particularly advantageous in mass concrete applications where the risk of thermal cracking is high [15].

3. FRESH PROPERTIES OF GGBS-BASED HIGH-PERFORMANCE CONCRETE

3.1 Workability and Rheology

The incorporation of GGBS has a pronounced influence on the workability of fresh concrete, with numerous studies reporting improved flow characteristics compared to conventional OPC-based mixtures. Investigations on pumpable concrete containing GGBS replacement levels ranging from 0% to 90% have demonstrated enhanced rheological behavior, characterized by reductions in both plastic viscosity and yield stress. These improvements result in superior flowability and pumpability, which are critical for modern construction practices involving complex formwork or placement in restricted or inaccessible locations [10].

The observed enhancement in workability is attributed to several factors, including the smooth, glassy surface texture of GGBS particles, which reduces inter-particle friction, and improved particle packing within the cementitious matrix. Furthermore, the slower initial hydration rate of GGBS contributes to extended workability retention, making GGBS-based mixtures particularly suitable for hot weather concreting and applications involving prolonged transportation times. However, the extent of workability improvement is highly dependent on replacement level and mixture proportions. Optimal workability has been reported at GGBS replacement levels between 30% and 50%, where particle packing and water demand are well balanced. At higher replacement levels exceeding 70%, a reduction in workability may occur due to the increased fineness of GGBS relative to OPC, unless appropriate adjustments in superplasticizer dosage are made [12].

3.2 Setting Time

One of the most significant effects of GGBS incorporation on fresh concrete properties is the extension of setting time. Experimental studies involving GGBS replacement levels in the range of 30–50% indicate a progressive increase in both initial and final setting times with increasing GGBS content. This delay is primarily attributed to the slower hydration kinetics of GGBS and the dilution of rapidly reacting OPC phases.Extended setting times offer certain practical advantages, including increased time for placement, compaction, and finishing operations, particularly in large pours or complex construction scenarios. However, under cold weather conditions, excessive delays in setting may pose challenges, necessitating the use of chemical accelerators or modified curing practices. From a construction management perspective, extended setting times may also require adjustments to formwork removal schedules and construction sequencing [11].

3.3 Water Demand and Superplasticizer Compatibility

The incorporation of GGBS influences the water demand of concrete mixtures, although its effect is generally less pronounced than that of highly reactive supplementary cementitious materials such as silica fume. The favorable particle size distribution and morphology of GGBS contribute to improved packing density, which can reduce the amount of mixing water required to achieve a specified level of workability. Nevertheless, the higher fineness of GGBS compared to OPC may increase water demand if not adequately addressed during mix proportioning [14].

GGBS exhibits good compatibility with commonly used chemical admixtures, particularly polycarboxylate ether–based superplasticizers. Studies on pumpable concrete mixtures have shown that by appropriately adjusting superplasticizer dosage, consistent workability corresponding to a target slump of 130 ± 15 mm can be maintained across a wide range of GGBS replacement levels from 0% to 90%. This compatibility enables the production of highly workable and stable concrete mixtures suitable for pumping and other specialized placement techniques without increasing the risk of segregation or bleeding [15].

4. MECHANICAL PROPERTIES

4.1 Compressive Strength Development

Compressive strength remains the primary design parameter for most concrete applications, and extensive research has characterized the influence of GGBS on this critical property. The strength development pattern of GGBS concrete differs notably from that of plain OPC concrete, characterized by slower early-age strength gain but enhanced long-term strength [17].

Table 2: Compressive Strength Improvement with GGBS Replacement

Concrete Class	GGBS Replacement (%)	Strength Improvement at 90 days (%)
C30	40	29.3
C30	50	Slight reduction from 40% but > reference
C40	40	21.3
C40	50	Slight reduction from 40% but > reference

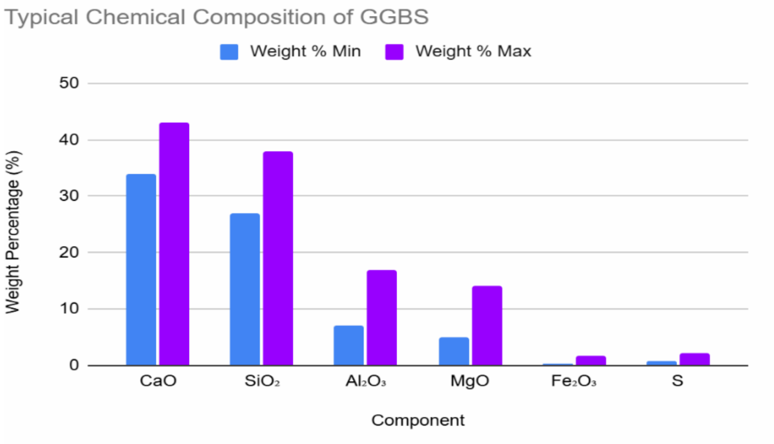

Chart -1: Typical Chemical Composition of GGBS

At early ages (7–14 days), concrete containing GGBS typically exhibits lower compressive strength than equivalent OPC concrete, with the strength reduction proportional to the replacement level. This behaviour reflects the dilution of fast-reacting cement compounds and the slower initiation of GGBS hydration. However, by 28 days, the strength gap narrows considerably, and at later ages (56–90 days), GGBS concrete often exceeds the strength of reference OPC mixtures [17].

The optimal GGBS replacement level for compressive strength varies with concrete class and testing age. For C30 concrete, 40% GGBS replacement produced the highest 90-day compressive strength, with a 29.3% improvement over the reference mixture. For C40 concrete, the same replacement level yielded a 21.3% improvement. At 50% replacement, a slight reduction in strength compared to the 40% level was observed, though values remained above the reference mixture. This pattern suggests an optimum range of 30–50% for maximizing compressive strength, with the exact optimum depending on specific materials and mixture proportions [18].

The mechanisms underlying enhanced long-term strength include the continued pozzolanic reaction that produces additional C-S- H gel, the refinement of pore structure that increases matrix density, and the improved interfacial transition zone between aggregate and paste. These microstructural improvements continue to develop over extended periods, explaining why the strength advantage of GGBS concrete becomes more pronounced with age [18].

4.2 Tensile and Flexural Strength

Tensile and flexural strengths are critical performance parameters for concrete elements subjected to bending, shear, and restrained shrinkage. Numerous studies have demonstrated that the incorporation of Ground Granulated Blast Furnace Slag (GGBS) positively influences these properties, following trends similar to those observed for compressive strength development. For C30-grade concrete with 40% GGBS replacement, increases of 38.7% in splitting tensile strength and 15.8% in flexural strength were reported at 90 days. Corresponding improvements for C40-grade concrete were found to be 19.2% and 16.2%, respectively. These enhancements in tensile performance are primarily attributed to improved matrix densification and the development of a stronger aggregate–paste bond resulting from the formation of GGBS hydration products. The relationship between compressive and tensile strength in GGBS-based concrete generally follows trends comparable to those of conventional OPC concrete. However, several studies suggest that the tensile-to-compressive strength ratio may be marginally higher in GGBS mixtures. This behaviour is associated with a more homogeneous microstructure and reduced stress concentrations within the interfacial transition zone (ITZ), which contribute to improved crack resistance and load transfer mechanisms [21].

4.3 Microstructural Characterization

The enhancements in mechanical performance observed in GGBS-based concrete are fundamentally linked to modifications in its microstructure. Advanced characterization techniques, such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), have been widely employed to elucidate the mechanisms responsible for these improvement. In GGBS- blended cementitious systems, hydration products primarily consist of calcium silicate hydrate (C–S–H) with a lower calcium-to- silicon (Ca/Si) ratio compared to plain OPC systems, along with calcium, Alamino, silicate hydrate (C–A–S–H) phases that incorporate aluminium into the silicate framework. These hydration products typically exhibit a more uniform and densely packed morphology than those observed in reference mixtures. The interfacial transition zone, often regarded as the weakest region in concrete, undergoes significant densification in GGBS-containing mixtures, characterized by reduced porosity and enhanced bonding between aggregate particles and the surrounding paste [20].

In addition, the pore structure is substantially refined, with a reduction in capillary porosity and the development of a more tortuous pore network that restricts the transport of aggressive agents. This microstructural refinement is a key factor responsible for the improved durability performance associated with GGBS incorporation [22].

5. DURABILITY PERFORMACE

5.1 Chloride Ion Penetration and Corrosion Resistance

Chloride-induced corrosion of reinforcing steel is one of the most prevalent and costly deterioration mechanisms affecting concrete structures, particularly in marine environments and regions exposed to dicing salts. GGBS has demonstrated high effectiveness in enhancing resistance to chloride penetration and mitigating subsequent reinforcement corrosion. Studies evaluating concrete with GGBS replacement levels between 30% and 50% reported progressive reductions in chloride penetration depth and chloride migration coefficients with increasing GGBS content. Mixtures containing 50% GGBS exhibited the lowest chloride ingress, indicating superior resistance to this deterioration mechanism. These findings are consistent with investigations on marine durability, which identified optimal GGBS replacement levels in the range of 40–60% for harsh exposure conditions [23].

The improved resistance to chloride ingress arises from multiple interacting mechanisms. Microstructural densification reduces the connectivity of pore pathways available for chloride transport. Furthermore, the chemical nature of GGBS hydration products, particularly C–A–S–H phases, promotes chloride binding, thereby reducing the concentration of free chlorides in the pore solution. The densified ITZ further restricts chloride migration by eliminating preferential transport paths along aggregate surfaces. Corrosion resistance, evaluated using impressed current techniques and corrosion rate measurements, shows corresponding improvements with GGBS incorporation. Concrete mixtures containing 50% GGBS exhibited lower corrosion rates, reduced mass loss of reinforcement, and narrower corrosion-induced crack widths compared to control mixtures. Electrical resistivity, an indirect indicator of corrosion susceptibility, increased with increasing GGBS content, reflecting the development of a more corrosion-resistant microstructure [24].

5.2 Sulfate Attack Resistance

Sulfate attack, resulting from the reaction of sulfate ions with cement hydration products to form expansive phases, can lead to cracking, spalling, and progressive loss of concrete integrity. The incorporation of GGBS has been shown to significantly enhance resistance to sulfate attack through several complementary mechanisms. Partial replacement of OPC with GGBS reduces the content of tricalcium aluminate (C A), the phase most susceptible to sulfate-induced expansion, thereby limiting the formation of expansive ettringite. Additionally, the pozzolanic reaction consumes calcium hydroxide, reducing its availability for gypsum formation. The refined microstructure restricts sulfate ingress, while the modified chemistry of C–S–H phases may alter interactions with sulfate ions [25].

Experimental evidence indicates that resistance to sulfate attack improves progressively with increasing GGBS content, with no adverse effects observed within commonly used replacement ranges. This behavior contrasts with that observed for chloride penetration, where some studies have reported optimal replacement ranges beyond which performance improvements may plateau or marginally decrease [26].

5.3 Permeability and Water Absorption

Permeability is a fundamental indicator of concrete durability, governing the transport of aggressive agents through the cementitious matrix. The incorporation of GGBS consistently reduces permeability, with improvements generally increasing with replacement level up to certain limits. Water absorption and porosity measurements conducted on concrete containing 30–50% GGBS revealed progressive reductions with increasing GGBS content, with 50% replacement yielding the most significant improvement. Similarly, sorptivity values, representing the rate of capillary water absorption, were substantially reduced in GGBS-based mixtures, reflecting effective refinement of capillary pores. These improvements are attributed to the pore-filling effect of additional hydration products, enhanced particle packing resulting from the combined use of OPC and GGBS with different particle size distributions, and reduced pore connectivity. Studies on nano-GGBS systems have reported even more pronounced reductions in sorptivity up to 64% compared with conventional concrete—due to the superior pore refinement achievable through nanoparticle incorporation [27].

5.4 Performance in Aggressive Environments

Marine environments impose particularly severe durability demands on concrete structures, as they involve simultaneous exposure to chlorides, sulfates, cyclic wetting and drying, and, in some cases, abrasion. Research focusing on marine applications has consistently demonstrated the superior performance of GGBS-based high-performance concrete under such conditions. The influence of GGBS content varies depending on the specific durability parameter considered. For chloride diffusion and gas permeability, performance improvements may either increase progressively or reach an optimal range beyond which further gains are limited. In contrast, sulfate resistance generally exhibits a continuously improving trend with increasing GGBS content.The water-to-binder ratio plays a crucial role in determining durability performance in aggressive environments and interacts strongly with GGBS content. Lower water-to-binder ratios enhance the beneficial effects of GGBS by reducing initial porosity and providing a denser matrix within which GGBS hydration products can further refine the microstructure, thereby maximizing long- term durability [28].

6. OPTIMAL GGBS REPLACEMENT LEVELS

6.1 Synthesis of Research Findings

The determination of optimal GGBS replacement levels requires consideration of multiple performance criteria, including fresh properties, mechanical strength, durability characteristics, and economic and environmental factors. Table 3 synthesizes findings from recent research to identify optimal ranges for different performance objectives.

Table 3: Optimal GGBS Replacement Levels for Different Performance Criteria

Performance Criterion	Optimal Replacement Range (%)	Key Findings
Workability/Rheology	30–50	Best balance of flowability and stability
Compressive Strength (C30)	40	29.3% improvement at 90 days
Compressive Strength (C40)	40	21.3% improvement at 90 days
Chloride Resistance	50	Lowest penetration depth and migration coefficient
Marine Environment Durability	40–60	Optimal for harsh conditions
Combined Micro GGBS + Nano GGBS	60% micro + 1% nano	38% strength improvement over control

The 30–50% replacement range emerges as broadly optimal for balanced performance across multiple criteria . Within this range, workability is well-maintained, mechanical properties show significant enhancement, and durability improvements are substantial. For applications prioritizing durability in aggressive environments, particularly marine exposure, the 40–60% range may be more appropriate [29].

The finding that 50% GGBS replacement provided the best durability performance, while 40% was optimal for mechanical properties , illustrates the importance of application-specific optimization. For structures where durability is the primary concern—such as marine structures, wastewater treatment facilities, or bridges in chloride-rich environments—higher replacement levels may be justified even if they entail a slight compromise in peak mechanical properties [30].

7. CONCLUSIONS

This review synthesized recent research (2023–2025) on high-performance concrete incorporating Ground Granulated Blast Furnace Slag (GGBS) and demonstrates that GGBS significantly enhances concrete performance in terms of workability, long- term mechanical strength, and durability due to its latent hydraulic and pozzolanic behavior, which promotes microstructural densification and improved aggregate–paste bonding. Optimal GGBS replacement levels depend on performance objectives, with 30–50% providing balanced performance, approximately 40% yielding optimal mechanical properties for many concrete classes, and higher replacements of 40–60% offering superior durability in aggressive and marine environments. Substantial improvements in resistance to chloride ingress, sulfate attack, and reinforcement corrosion are consistently reported, primarily attributed to pore refinement and the modified chemistry of hydration products. Emerging technologies further enhance performance, particularly nano-GGBS systems, where the incorporation of about 1% nano-particles into mixes containing 60% micro-GGBS results in remarkable gains in strength and durability, while geopolymer and alkali-activated binders provide alternative pathways toward high-performance sustainable concrete. From a sustainability perspective, GGBS use can reduce CO emissions by up to 1.55 times compared with conventional concrete, divert industrial by-products from landfills, and lower life-cycle costs by nearly 40% due to improved durability and extended service life. Nevertheless, challenges related to early-age strength development, curing sensitivity, carbonation resistance, and material variability remain and require careful mix design, construction control, and quality assurance. Overall, GGBS-based high-performance concrete represents a mature and effective technology with proven benefits in both structural performance and environmental sustainability, and continued research into long-term behavior, standardized testing, advanced material characterization, multi-SCM optimization, and scalable nano-technologies will further strengthen its role in future infrastructure development.

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