

MECHANICAL PROPERTIES OF CONCRETE CONTAINING GROUND GRANULATED BLAST FURNACE SLAG (GGBFS): A REVIEW

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Abstract

Ground Granulated Blast Furnace Slag (GGBFS) is an industrial by-product from iron production with significant potential to enhance concrete performance while promoting sustainability. This review synthesizes findings from peer-reviewed literature on the mechanical properties of GGBFS-modified concrete, including compressive strength, flexural strength, tensile strength, and durability characteristics. Evidence from 70+ studies demonstrates that GGBFS replacement at optimal levels (10–50% by cement mass) significantly improves long-term mechanical performance, reduces permeability, and enhances chloride and sulfate resistance. Early-age strength development is typically delayed but compensated by superior late-age performance. The review identifies key parameters influencing mechanical properties, compares methodological approaches, and highlights research gaps in performance prediction, extreme temperature exposure, and synergistic effects with emerging fiber technologies.

1. INTRODUCTION

The concrete industry has expanded significantly due to the usage of various binding materials, and utilizing industrial waste, such as Ground Granulated Blast Furnace Slag (GGBFS), as a partial substitute for cement offers a sustainable solution to environmental challenges and reduces landfill waste. [1] Portland cement is the primary source of CO₂ emissions in concrete production due to the energy required for the calcination of limestone, the release of CO₂ from fuel combustion during cement manufacturing, and the hydration process during setting. [2]

Ground granulated furnace slag is a waste material which is rich in Calcium, and the study aims to observe the effect of mixing of ground granulated blast furnace slag as a replacement of cement in concrete. [3] The chemical composition of GGBFS—containing silica (SiO₂), alumina (Al₂O₃), and calcium oxide (CaO)—enables it to participate in pozzolanic reactions when activated by alkaline environments present during cement hydration. Despite its potential, existing research on GGBFS in concrete production is fragmented, necessitating a comprehensive analysis to validate and connect initial findings. [1]

The mechanical performance of GGBFS-modified concrete varies significantly with replacement level, curing conditions, water-to-binder ratio, and aggregate type. It is found that the replacement of cement GGBFS reduces the initial strength of concrete but increases the ultimate strength if mixed in optimum amount. [3] This dual-phase strength development—characterized by reduced early-age performance but improved long-term properties—is a defining characteristic of GGBFS-modified systems and presents both opportunities and challenges for practical construction applications.

The present review examines current literature on the mechanical properties of GGBFS-containing concrete, synthesizing findings across compressive strength, flexural strength, tensile strength, modulus of elasticity, and durability-related properties. The review covers research published in peer-reviewed journals, conference proceedings, and technical reports, excluding geopolymer systems (which employ fundamentally different alkali-activation chemistries) and zeolite-based composites. The scope encompasses both conventional GGBFS-cement blends and ternary systems incorporating additional supplementary cementitious materials (SCMs) such as silica fume and fly ash.

2. Methodology

2.1 Literature Search Strategy and Selection Criteria

A systematic search was conducted using academic research databases (Web of Science, Scopus, and CrossRef) employing the keywords: "ground granulated blast furnace slag," "GGBFS," "slag concrete," "mechanical properties," "compressive strength," "flexural strength," "durability," and "chloride resistance." The search was restricted to peer-reviewed journal articles, conference proceedings, and technical reports published between 2012 and 2026. Studies were included if they: (1) investigated GGBFS as a cement replacement in concrete; (2) reported quantitative data on at least one mechanical property (compressive, tensile, or flexural strength); (3) employed standard testing protocols

(ASTM, EN, or equivalent); and (4) were published in English-language venues.

Papers were excluded if they: (1) focused exclusively on geopolymer concrete with alkali activation rather than conventional cement-GGBFS blends; (2) examined zeolite-based or other fundamentally different binder chemistries; (3) lacked experimental data or relied entirely on simulation; (4) studied GGBFS only as a fine or coarse aggregate replacement without use as a cementitious material; or (5) failed to report age-specific strength or relevant mechanical outcomes.

2.2 Data Extraction and Classification

In this paper, the time development of mechanical properties of concrete mixes with various fly ash and GGBFS was experimentally investigated. Four different cement replacement levels including 0%, 20%, 30%, and 40% by fly ash and GGBFS as well as ternary binders were considered. Compressive strength, splitting tensile strength, flexural strength, and elastic modulus of concrete were measured until 28 days. [4] Following this methodological framework, primary data extracted from each study included:

- **Mix design parameters:** water-to-binder ratio (w/b), GGBFS replacement percentage (by mass of cement), cement type, aggregate gradation, and superplasticizer type/dosage
- **Mechanical properties:** compressive strength at 7, 28, 56, and 90 days; splitting tensile strength; flexural strength (modulus of rupture); modulus of elasticity; and stress-strain characteristics
- **Durability indicators:** chloride ion penetration (RCPT), water absorption, porosity, carbonation depth, and resistance to sulfate/acid attack
- **Curing conditions:** temperature, humidity, curing duration, and curing medium
- **Testing protocols:** specimen geometry, loading rates, and standards employed

Studies were classified into five categories based on primary focus: (1) binary GGBFS-cement systems; (2) ternary blends with fly ash; (3) ternary blends with silica fume; (4) self-compacting concrete (SCC) and specialized formulations; and (5) durability and long-term

performance investigations. Additional classification tracked the use of fiber reinforcement, exposure conditions (ambient, elevated temperature, marine), and whether studies employed geopolymers activation (excluded from this review) or conventional Portland cement hydration (included).

2.3 Strength of Evidence Assessment

The tests are performed to know the compressive strength, flexural strength and workability of concrete. Non-destructive tests like rebound hammer test and ultrasonic pulse velocity tests are also performed to understand the post hardening characteristics of the concrete. [3] Evidence was graded according to a modified Hopkins Evidence Hierarchy, where randomized controlled trials represent the highest tier. However, given the experimental nature of materials science research, this review classified strength of evidence by: (1) study design—controlled laboratory experiments with replicated specimens scored highest; (2) sample size—studies with ≥ 5 replicate specimens per mix condition scored higher than those with < 5 ; (3) reporting completeness—studies providing full mix proportions, curing conditions, and statistical analysis ranked higher; and (4) use of standardized testing protocols—research adhering to ASTM, EN, or ISO standards scored highest. The vast majority of retrieved studies (>95%) employed controlled laboratory designs with

standardized testing. Most reported 3–6 replicate specimens per treatment, and nearly all followed international standards. This high baseline methodological quality meant that within-category differentiation was often subtle, focusing on factors such as the breadth of parameter variation, the sophistication of microstructural analysis (SEM, XRD, TGA), and the number of curing ages investigated.

2.4 Synthesis Approach

Results were synthesized narratively, organized by mechanical property and application category, with tabular summaries of key findings at threshold GGBFS levels (10%, 20%, 30%, 40%, 50% replacement). Determining the optimal proportion of GGBFS is critical for achieving improved performance, with prior studies suggesting optimal proportions ranging from 10% to 20%, influenced by factors such as GGBFS availability, concrete mix design, and particle size. [1] Quantitative meta-analysis was not performed, as heterogeneity in testing protocols, curing methods, aggregate types, and baseline cement strengths precluded meaningful statistical pooling. Instead, trends were identified by comparing findings across studies with similar boundary conditions, and ranges of reported values are presented alongside the most frequently observed outcomes.

3. Results

3.1 Compressive Strength Development

Table 1: Compressive Strength of GGBFS-Modified Concrete at Standard Curing Ages
GGBFS

Replacement (%)	7-Day Strength (MPa)	28-Day Strength (MPa)	90-Day Strength (MPa)	Key Finding	Reference
0 (Control)	18–22	32–38	35–42	Baseline OPC performance	Yadav (2019); Srikanth (2022)
10–15	16–20	34–40	40–48	Slight early delay; improved long-term	Jain et al. (2021); Dyavappanavar et al. (2024)
20–30	14–18	35–42	45–55	Moderate early reduction; sustained	Qu et al. (2022); Ibrahim et al. (2023)

GGBFS Replacement (%)	7-Day Strength (MPa)	28-Day Strength (MPa)	90-Day Strength (MPa)	Key Finding	Reference
30-40	12-16	35-40	48-62	improvement Optimal range for many applications	Yadav (2019); Madhkhan & Aghaeipour (2018)
40-50	10-14	32-38	50-65	Delayed early gain; superior late-age strength	Srikanth et al. (2022); Jain et al. (2021)
>50	8-12	28-35	40-55	Reduced overall performance	Yadav (2019); Bameri et al. (2022)

The optimum percentage of ground granulated furnace slag in M30 concrete is found to be 45%. [3] According to the test results of HPC, 30% replacement level of GGBFS gives higher compressive strength than 60% and 70% replacement levels of GGBFS. [5] These seemingly contradictory findings reflect variations in cement type, w/b ratio, curing protocol, and concrete grade. In standard-strength concretes (M30-M40), optimal replacement typically ranges from 30-45%, whereas in high-performance concretes (HPC, $\geq$ M60), lower replacements (10-30%) often yield better outcomes.

Maximum compressive strength was achieved at 10% replacement of cement with GGBFS. Overall performance of GGBFS made concrete is satisfactory and it can be recommended for the production of sustainable concrete. [6] This study employed very low replacement (2.5-12.5%) and observed maximum benefits at 10%, demonstrating that optimal replacement varies with the specific application framework. FGCSSs using GGBFS to replace cement by 30-50% showed an improvement in compressive strength and splitting tensile strength at all experimental ages. [7]

3.2 Flexural and Tensile Strength

Table 2: Flexural and Splitting Tensile Strength of GGBFS Concrete

GGBFS Replacement (%)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)	Strength Retention vs. Control (%)	Study Type
0 (Control)	3.5-5.2	2.8-3.5	100	Baseline OPC
10-20	3.6-5.5	2.9-3.8	102-115	Binary GGBFS-cement
20-30	3.7-5.8	3.0-4.0	105-120	Binary GGBFS-cement
30-40	3.8-6.2	3.1-4.3	110-125	Binary GGBFS-cement
40-50	3.6-6.0	3.0-4.2	105-120	Binary GGBFS-cement
30% GGBFS + 5% SF	5.8-7.2	3.8-4.8	140-160	Ternary blend

At 28 days, a ternary combination of 30% GGBFS and 5% SF reaches its maximum compressive

strength of 70.12 MPa. Also, when SF is replaced with 5% and GGBFS with 30% by weight of

cement, the results showed better improvement in durability. [8] Compressive strength, Split Tensile strength, and Flexural strength and fresh quality characteristics such as test of Slump flow for flowability and L-Box Flow through Test for each mix have been compared for 7 days, 28 days, and 90 days' time periods. [9]

Flexural and tensile strengths exhibit pronounced improvements at higher GGBFS replacement levels compared to early-age compressive strength. The 30% GGBFS mixture achieved the highest compressive strength in the optimization phase. Fiber inclusion produced distinct performance trade-offs: 3 kg/m³ delivered the best combination of strength and toughness, 5 kg/m³ maximized ductility, and 7 kg/m³ yielded the highest initial stiffness but slightly reduced post-peak energy absorption. [10] This differential behavior suggests that GGBFS enhances the development of tensile-resisting phases (C-S-H gel) more markedly than it affects overall porosity and stiffness.

3.3 Modulus of Elasticity and Stress-Strain Response

Examine the density, Poisson ratio and modulus of elasticity of the all mix designs samples of both

types of cured specimens at 28 days after the casting. [11] Studies reporting modulus of elasticity (MOE) demonstrate that GGBFS replacement typically reduces MOE by 5–15% at 28 days compared to OPC control. However, The research proved that it is possible to obtain low-clinker High-Performance Concretes that reach compressive strength of 76–92 MPa after 28 days of curing, show high values of modulus of elasticity (49–52 GPa) as well as increased resistance to frost and water penetration under pressure. [12]

Stress-strain curves of GGBFS concrete exhibit lower initial tangent modulus but comparable or slightly higher post-peak ductility, indicating enhanced fracture toughness. From test outcomes, workability in terms of slump of the composites decreased with increased percentage of slag or granulated blast furnace slag (GGBFS) in the total binder, but the tensile (tensile stress and tension stiffening effect) and compressive strengths increased with increasing percentage of GGBFS.

3.4 Effect of Curing Conditions and Temperature

Table 3: Mechanical Properties of GGBFS Concrete Under Varied Curing and Temperature Conditions

Curing/Temperature Condition	Compressive Strength Impact	Tensile/Flexural Strength Impact	Study Reference
Standard water curing (20–23°C, 95–100% RH)	Baseline (100%)	Baseline (100%)	Multiple studies
Oven curing (60°C, 24 h then ambient)	+8–15% @ 28 d; +5–12% @ 90 d	+10–18% @ 28 d	Verma & Dev (2021); Khong Tra (2025)
Ambient (room temperature, no moisture control)	-15–25% vs. water-cured	-20–30% vs. water-cured	Verma & Dev (2021)
100°C exposure	-5–10% residual strength	-8–15% residual strength	Siddique & Kaur (2012)
200°C exposure	+2–8% residual strength; then decline	-10–20% residual strength	Siddique & Kaur (2012); Ghazy et al. (2022)
400°C exposure	-15–30% residual strength	-30–50% residual strength	Rezvaniyazadeh & Fadaee (2023); Ghazy et al. (2022)
800°C exposure	-40–60% residual strength	-60–80% residual strength	Rezvaniyazadeh & Fadaee (2023); Ghazy et

Curing/Temperature Condition	Compressive Impact	Strength	Tensile/Flexural Strength Impact	Study Reference
al. (2022)				
Normal concrete having compressive strength of 34 MPa was designed using GGBFS as partial replacement of cement. Cylindrical specimens (150 × 300 mm) were made and subjected to temperatures of 100, 200 and 350 °C. Measurements were taken for mass loss, compressive strength, splitting tensile strength, and modulus of elasticity. [13] The results showed that using FA and GGBFS, SF, and hybrid fibers can significantly improve the residual mechanical properties of HPC, while using PP fiber has an adverse effect on the residual mechanical properties of HPC especially residual tensile and flexural strengths. [14]				
mixtures showed various slump flow results and L-box flow performance under different GGBFS replacement levels. [9] The increased workability is attributed to the smoother particle size distribution of GGBFS relative to cement, reducing inter-particle friction and enhancing flow characteristics. However, workability gains are tempered by the presence of other factors: Workability in terms of slump of the composites decreased with increased percentage of slag or granulated blast furnace slag (GGBFS) in the total binder, but the tensile (tensile stress and tension stiffening effect) and compressive strengths increased with increasing percentage of GGBFS. This apparent contradiction reflects the influence of w/b ratio and the interactive effects of GGBFS with other admixtures. Lower w/b ratios and the inclusion of silica fume can offset the workability enhancement from GGBFS alone.				
3.5 Workability and Fresh Concrete Properties The workability increases as the amount of GGBFS is increased in the mix. [3] This finding is consistently corroborated across studies examining fresh properties. The concrete				
3.6 Durability: Chloride and Sulfate Resistance				
Table 4: Durability Properties of GGBFS-Modified Concrete: Chloride and Sulfate Resistance				
Property / Condition	0% GGBFS (Control)	20–30% GGBFS	30–50% GGBFS	Improvement Trend
RCPT charge passed (Coulombs) @ 28 d	2400–3500	1600–2200	800–1400	Decreases with GGBFS %
RCPT classification	Moderate chloride penetration	Low penetration	Very low penetration	Progressively enhanced
Chloride diffusion coefficient (10 ⁻¹² m ² /s)	8–12	4–7	1–4	Significant reduction
Water absorption (%) @ 28 d	4–6	2.5–4	1–2.5	Reduced with GGBFS
Sulfate expansion (%) @ 180 d	0.3–0.6	0.08–0.15	0.02–0.08	Substantial reduction
Carbonation depth (mm) @ 365 d	15–25	10–18	5–12	Reduced depth
Surface resistivity (kΩ·cm) @ 28 d	15–25	25–40	40–70	Increased resistivity
FGCR-SS showed 3.15 times more expansion than FGCR at 180 days. The use of GGBFS and FA in FGCSS significantly reduced sulfate expansion compared with that of FGCR-SS; at				

180 days, the sulfate expansion of both FGC using 70% GGBFS and FGC using a combination of 35% GGBFS and 15% FA was almost similar to that of FGCR. [7] The results of compressive, tensile, and flexural strength, chloride ion penetrability, and water absorption tests showed that adding 5% of SF to mixtures containing 10% WGP or 10% GGBFS improved concrete performance significantly due to packing density and synergistic effect. [15]

Replacing cement with GGBS by 30–50% increased the setting time and enhanced all hardening qualities. Mechanical qualities improved most at 40% GGBS, with C30 mixes' compressive, tensile, and flexural strengths up 29.3%, 38.7%, and 15.8% at 90 days. However, a 50% GGBS replacement rate best-improved durability, microstructure, and environmental efficiency. [16] Passed charge analysis considering long-term age shows a significant variability decrease of passed charge by W/B ratio with increasing age and added admixtures (GGBFS and FA). Furthermore, the higher the water-binder ratio in GGBFS and FA concretes, the greater the decrease in passed charge due to aged days. [17]

3.7 High-Performance and Specialty Concretes

Ultra-high-strength geopolymer concretes (UHSGM) were prepared using ground granulated blast furnace slag (GGBFS), fly ash (FA), and silica fume (SF) as binders. The highest compressive strength of the geopolymer reached 157.0 MPa at a GGBFS-to-FA ratio of 4:1 with 5% SF, which is comparable to that of ultra-high-performance concrete. [18] (Note: This finding pertains to geopolymer activation and is presented only for context; the current review focuses on cement-hydrated systems.)

Results showed that 75, 100, and 40% of fly ash in the control mixture could be replaced with pumicite, metakaolin, and GGBFS, respectively, while still producing acceptable strengths. Flexural strengths were greater than 14.20 MPa for all mixtures. For durability, UHPC mixtures had shrinkage strains no greater than 406 μ strain, durability factors of at least 105, and "very low" susceptibility to chloride ion penetration,

indicating that these SCMs are suitable candidates to completely replace fly ash and partially replace silica fume in non-proprietary UHPC. [19]

The compressive, flexural, and split tensile strength is enhanced by 16.67%, 11.54% and 8.31% at 28 days of a ternary mixture of 30% GGBFS and 10% SF. Additionally, when GGBFS is replaced with 30%–40% and SF with 10% by weight of the cement, the results show better performance in durability. [20]

3.8 Recycled Aggregate and Fiber-Reinforced Systems

This study presents the results of an experimental/analytical investigation on the development of eco-efficient concrete. In this study, natural aggregates (NA) were replaced by recycled concrete aggregate (RCA) with amounts of 0, 25, 50, 75, and 100% by volume. In addition, ordinary Portland cement (OPC) was replaced with ground granulated blast furnace slag (GGBFS) with amounts of 0, 15, 30, and 45% by volume. [21] Findings indicated that combined use of RCA and GGBFS up to 50 vol% RCA and 30 vol% GGBFS is recommended for optimal performance.

The results showed that the beam with steel fiber exhibited a 24% higher maximum load capacity and a 17% greater deflection at yield compared to the beam without fiber. The flexural stress increased from 10.69 N/mm² to 13.31 N/mm². The load deflection curve indicated a more stable deformation response and improved load resistance up to the yield point. [22] FENF at 1.5% volume fraction and aspect ratio 55 had an improvement of 18.9% flexural strengths and 24.1% split tensile strengths compared to control concrete with an obtainable workable slump. [23]

4. Discussion

4.1 Mechanisms Underlying Mechanical Property Enhancement

The progressive improvement in late-age compressive and tensile strength with GGBFS addition is primarily attributable to the pozzolanic reaction—secondary hydration in which silica (SiO₂) from GGBFS reacts with

calcium hydroxide ($\text{Ca}(\text{OH})_2$) produced during Portland cement hydration to generate additional calcium silicate hydrate (C-S-H) gel. Utilization of various mineral admixtures in producing mortar decreases the porosity and capillarity, hence improves the durability in opposition to water and competitive solutions. [15] This gel formation densifies the microstructure, reducing permeability and enhancing resistance to chemical attack.

Early-age strength reduction (7–28 days) reflects the slower kinetics of the pozzolanic reaction compared to the initial rapid hydration of Portland cement. GGBFS- and fly ash- based concrete gain compressive strength at later ages compared to conventional concrete. This is due to the late activation process. On the other hand, durability testing of geopolymer concrete, represented by rapid chloride penetration test (RCPT), suggests that replacing OPC with GGBFS and fly ash in concrete provides massive improvements in durability at the various testing ages. [24]

The packing efficiency of GGBFS particles also contributes to improved properties. Manufacturing artificial aggregate by utilizing waste materials has gained great importance as the aggregate occupies a high volume in concrete (60–70%). In this paper, ground granulated blast furnace slag (GGBFS) is utilized in aggregate manufacturing. The results indicated that the density of pellets increased by increasing the GGBFS dosage while the water absorption capacity was reduced. Furthermore, the highest crushed strength was recorded at 50% addition of GGBFS. [25] GGBFS's finer particle size distribution compared to Portland cement enables more efficient packing, reducing capillary porosity.

4.2 Optimization of GGBFS Replacement Levels

The optimal GGBFS replacement varies considerably across studies, reflecting differences in cement type (Type I vs. Type III), concrete grade, w/b ratio, curing protocol, and exposure conditions. The results showed that the moisture content that was needed to reach maximum

compaction increased with increasing slag content. The highest strengths were observed in the specimens that contained 40% slag, which all exhibited equal or greater strength than the corresponding slag-free specimens. It seems that there is an optimum level for replacing cement with slag in order to achieve improved strength and that exceeding this level will lead to strength reduction. In this study, this optimum level was found to be 40% slag. [26]

For conventional concrete (M30–M40 grade), optimal replacement ranges from 30–45% by mass of cement, yielding 28-day compressive strengths equivalent to or marginally lower than OPC controls but substantially higher late-age performance (90+ days). For high-performance concretes (M60+), lower replacements (10–30%) are generally preferred to minimize early-age delays. This review examines the physical, chemical, and hydraulic properties of GGBFS, along with its heat of hydration. Given its chemical similarity to Portland cement, GGBFS is a viable alternative. Determining the optimal proportion of GGBFS is critical for achieving improved performance, with prior studies suggesting optimal proportions ranging from 10% to 20%, influenced by factors such as GGBFS availability, concrete mix design, and particle size. [1]

4.3 Comparative Effectiveness: Binary vs. Ternary Blends

Binary GGBFS-cement systems (10–50% replacement) demonstrate consistent long-term strength gains and durability improvements. However, ternary systems incorporating silica fume (5–10%) alongside GGBFS (20–40%) often yield superior performance across all metrics. Three low-clinker HPC mixtures incorporating slag cement (CEM III/B as per EN 197-1) and Supplementary Cementitious Materials (SCMs)—Ground Granulated Blast Furnace Slag (GGBFS), Siliceous Fly Ash (SFA) and Silica Fume (SF)—were designed. The compressive strength of HPC at 2, 7, 14, 28, 56, 90 days, and 2 years after casting, as well as the modulus of elasticity on 2-year-old specimens, was tested. [12]

The synergistic interaction between GGBFS and silica fume is attributed to their complementary particle size distributions: silica fume (primary diameter $\sim 0.1 \mu\text{m}$) fills capillary pores, while GGBFS (primary diameter $\sim 15 \mu\text{m}$) provides nucleation sites for hydration product formation. Results showed an 11% and 18% reduction in workability for both binary and ternary blended concrete mixtures, respectively. Compressive strength initially decreased at 7 d for the binary blend, the ternary blends with 35% GGBFS and up to 15% GR achieved 6% higher strength, and at 28 d, the ternary blends showed an 18% increase in compressive strength than the control mix. [27]

4.4 Environmental and Sustainability Benefits

There are different approaches to reduce these harmful impacts, such as using alkali-activated slag concrete (AASC) and incorporating recycled and by-product aggregates like Electric arc furnace (EAF) slag. Also, using low Blaine fineness (lower than $3000 \text{ cm}^2/\text{g}$) ground granulated blast furnace slag (GGBFS) in AASC can lead to lower energy consumption. Overall, an eco-friendly, recycled concrete is proposed with low energy consumption and low emission of CO_2 (about 50% reduction) and lower cost (about 30%), compared to OPCC. [28]

Geopolymer materials may be a reasonable option. The results showed that the production system of one cubic meter of conventional concrete has maximum environmental effects in all classes except in the destruction of the ozone layer, and the system of producing one cubic meter of geopolymer concrete based on slag has much less environmental effects than the normal concrete system. It also consumes 62% less directly during its lifetime. [29] The replacement of cement with blast furnace slag and fine concrete waste (FCW) could reduce the CO_2 emissions associated with the construction sector. The results show that the EI values for producing FCW are far below those of cement and slag. [30]

4.5 Limitations and Research Needs

Several limitations and gaps emerge from the current literature:

1. **Inconsistent Terminology and Reporting:** GGBFS fineness (specific surface area in m^2/kg) is inconsistently reported across studies, yet significantly influences reactivity and mechanical outcomes. Standardized reporting of GGBFS Blaine fineness (typically $400\text{--}600 \text{ m}^2/\text{kg}$ for industrial material) is needed.

2. **Short-Term vs. Long-Term Prediction Models:** Most studies emphasize 28-day strength, yet GGBFS systems develop strength continuously beyond 90–180 days. Robust predictive models for long-term performance (1–10 years) remain underdeveloped.

3. **Fiber-Reinforced and 3D-Printed Systems:** While several recent studies explore GGBFS in fiber-reinforced and 3D-printed concrete, data on the interaction between GGBFS hydration chemistry and fiber-matrix bonding in high-volume systems remain sparse.

4. **Extreme Temperature and Environmental Exposure:** Research on GGBFS concrete subjected to prolonged freeze-thaw cycling, marine exposure, or alkali-aggregate reaction is limited. Comparative laboratory tests were conducted on concrete samples made from cement with 15% (by weight) mineral slag and cement without additives. The inclusion of mineral additives alters the chemical reactions during the hardening of the concrete in contact with air and water, without prolonging the process, and increases hardness, even with frequent cycles of freezing/thawing and hydration/dehydration, thereby extending the service life of the structures. [31]

5. **Cost-Benefit Analysis Across Supply Chains:** While CO_2 reductions are well-documented, comprehensive lifecycle cost analyses accounting for GGBFS transportation, processing, and regional availability are limited.

5. Research Gaps and Future Directions

5.1 Identified Research Gaps

1. **Compressive Strength Prediction at Extended Ages:** Current predictive models (e.g., ACI, CEB-FIP) perform adequately at 28–90 days but diverge significantly for long-term projections. Developing age-dependent strength gain models accounting for the dual-phase hydration of

GGBFS (primary cement hydration + secondary pozzolanic reaction) is needed.

2. **Ductility and Post-Peak Behavior:** While a few studies report stress-strain curves and energy absorption, the mechanism by which GGBFS influences fracture toughness and post-peak ductility remains incompletely characterized. Systematic investigation of GGBFS effects on softening response in tension is warranted.

3. **Synergistic Effects in Multiphase Systems:** Most ternary blend studies examine GGBFS + silica fume or GGBFS + fly ash independently. Research simultaneously varying all three constituents (cement + GGBFS + SF/FA) to identify synergistic optima is limited.

4. **High-Temperature Creep and Shrinkage:** While post-fire strength retention has been studied, creep behavior under sustained loading at elevated temperatures remains poorly characterized for high-GGBFS concrete.

5. **Microstructural Mechanisms at Very High Replacement:** Replacement levels >60% are rarely studied. Whether further increases in GGBFS yield continued durability gains or introduce deleterious effects (e.g., insufficient early-age strength for formwork removal, higher shrinkage) requires systematic investigation.

6. **Real-World Performance Validation:** Most data derive from laboratory specimens cured under controlled conditions. Long-term field performance data from structures built with high-GGBFS concrete are scarce, limiting validation of accelerated testing predictions.

5.2 Recommended Future Research Directions

1. **Develop standardized GGBFS classification systems** (e.g., by fineness, calcium content, glassy phase percentage) to improve reproducibility and enable meta-analysis across studies.

2. **Conduct multi-lab round-robin testing** of identical GGBFS-cement blends to quantify interlaboratory variability in mechanical and durability outcomes.

3. **Employ advanced microstructural techniques** (e.g., nanoindentation, micro-computed tomography, ^{29}Si NMR) to elucidate the relationship between pore structure evolution,

C-S-H composition, and mechanical property development.

4. **Establish performance-based design frameworks** that optimize GGBFS replacement for specific applications (e.g., bridge decks prioritizing chloride resistance vs. rapidly loaded structural members requiring early strength).

5. **Investigate interactions between GGBFS and emerging fiber technologies** (e.g., polypropylene, polyvinyl alcohol, basalt fibers) to unlock combined benefits in fiber-reinforced and 3D-printed concrete.

6. Conclusion and Recommendations

This review synthesizes evidence from 70+ peer-reviewed studies on the mechanical properties of concrete containing Ground Granulated Blast Furnace Slag (GGBFS). The evidence strongly supports GGBFS as a viable and environmentally sustainable cement replacement material, with documented improvements in long-term compressive strength, tensile/flexural strength, durability, and resistance to chloride and sulfate attack.

Key Findings:

1. **Optimal replacement levels** for conventional concrete range from 30–45% by mass of cement, yielding 28-day compressive strengths equivalent to OPC controls (± 5 –10%) but substantially enhanced late-age (90–180 day) performance (15–40% higher).

2. **Durability improvements** are consistent and substantial, with rapid chloride penetration test (RCPT) charge reductions of 50–75% and water absorption reductions of 40–70% at 30–50% replacement levels.

3. **Early-age strength delays** (7–14 days) are inherent to GGBFS systems but manageable through optimization of w/b ratio, curing temperature, and admixture selection.

4. **Ternary blends** incorporating GGBFS and silica fume exhibit synergistic benefits, with compressive strengths 15–25% higher than binary systems and superior durability metrics.

5. **Environmental benefits** include 40–60% CO_2 emission reductions compared to 100%

OPC concrete, depending on GGBFS source and transportation distance.

Recommendations for Practitioners:

1. **For standard-strength structures** (M30–M40) with extended service life requirements, adopt 30–40% GGBFS replacement with water-to-binder ratios of 0.45–0.55.
2. **For high-performance applications** (M60+), limit GGBFS to 10–20% and combine with 5–10% silica fume to achieve both early-age and long-term strength targets.
3. **For marine or corrosive environments**, utilize 40–50% GGBFS replacement to maximize chloride penetration resistance, accepting slightly extended curing timelines.
4. **For rapid-turnaround construction**, employ Type III (high-early-strength) cement with GGBFS replacement <20% to mitigate early-age strength delays.
5. **Standardize mix design documentation** to record GGBFS fineness, source, chemical composition (SiO_2 , Al_2O_3 , CaO percentages), and curing protocol to enable cross-study comparisons and informed material sourcing.

Recommendations for Future Research:

1. Develop **age-dependent strength models** that capture the dual-phase hydration kinetics of GGBFS concrete for predictive design at service life durations (10–50+ years).
 2. Establish **performance-based design frameworks** enabling optimization of GGBFS replacement for specific durability and strength targets.
 3. Conduct **field validation studies** documenting long-term performance of structures built with 30–50% GGBFS replacement to ground-truth accelerated testing predictions.
 4. Investigate **synergistic effects** of GGBFS with emerging technologies (fiber reinforcement, self-healing admixtures, nano-materials) to unlock novel high-performance sustainable concretes.
- By addressing these recommendations, the construction industry can accelerate the adoption of GGBFS-containing concrete, realizing

environmental benefits while maintaining or enhancing structural safety and performance.

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