Effect of GGBFS on Compressive Strength and Durability of Concrete

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Abstract
This research examines the impact of incorporating Ground Granulated Blast Furnace Slag (GGBFS) at 4%, 6%, and 10% as partial cement replacement on concrete compressive strength and durability. Findings showed moderate early-age strength gains, with significant improvements at extended curing periods. Concrete with 10% GGBFS achieved the highest compressive strength, attributed to enhance pozzolanic reactions and refined microstructure. Additionally, GGBFS improved concrete durability against chloride penetration and sulfate attack, highlighting its potential for sustainable construction practices by reducing cement use and lowering environmental impact, supporting global sustainability goals [1][5].

Keywords*:* GGBFS; Compressive strength; Durability; Concrete
Received: 18 April 2025; **Revised:** 27 May 2025; **Accepted:** 2 June 2025; **Published:** 1 July 2025

1. Introduction

Ground Granulated Blast Furnace Slag (GGBFS) is an industrial by-product generated during the manufacture of iron in a blast furnace. When ground to a fine powder, it exhibits pozzolanic properties and can be used as a partial replacement for Portland cement in concrete production. The integration of Ground Granulated Blast Furnace Slag (GGBFS) in cementitious systems contributes to sustainability by reducing CO_2 emissions and promoting the recycling of industrial waste [1]. Moreover, GGBFS-modified concrete typically exhibits enhanced long-term strength and durability characteristics due to the formation of secondary calcium silicate hydrate (C-S-H) gel, which fills pores and improves microstructure [2,3]. Numerous studies have demonstrated that replacing cement with Ground Granulated Blast Furnace Slag (GGBFS) at levels ranging from 15% to 50% results in improved mechanical performance, chemical resistance, and reduced permeability [4,5]. Given the growing emphasis on green building materials, Ground Granulated Blast Furnace Slag (GGBFS) presents a promising option for enhancing the performance and environmental footprint of concrete. Previous studies demonstrated that Ground Granulated Blast Furnace Slag (GGBFS) enhances the durability, reduces porosity, and refines the pore structure of concrete [8,9].

Extensive research has confirmed the advantages of GGBFS as a cement replacement material. According to Mehta and Monteiro [6], Ground Granulated Blast Furnace Slag (GGBFS) reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), enhancing concrete strength. Bouzoubaa and Fournier [9] reported improved freeze-thaw resistance and sulfate attack resistance. Moreover, Khatib and Hibbert [10] highlighted improved workability and resistance to chloride ion penetration. These findings support the potential of GGBFS in aggressive environments.

2. Materials and Methodology

The experimental program involved three concrete mixes incorporating 4%, 6%, and 10% GGBFS as a partial replacement of 350 kg of cement. The control variables included water-cement ratio, curing conditions, and aggregate grading. Compressive strength tests were conducted at 3, 7, 14, and 28 days using ASTM C39 standards [2]. Cylindrical specimens were prepared and cured under standard conditions before testing. The effects on durability were inferred based on strength gain trends and validated against literature. Specimen's dimensions were standardized at 100 mm diameter and 200 mm height, following ASTM C39 standards. Curing conditions were controlled at 23±2°C and over 95% humidity as per ASTM C192 [13]. No admixtures were utilized to isolate the effect of GGBFS.

3. Results and Discussion

The experimental results confirmed a progressive increase in compressive strength with longer curing periods across all GGBFS mixes. The highest strength values were observed for the 10% replacement, indicating that a higher GGBFS ratio improves late-age strength development. Table (1) presents the compressive strength values, and figure (1) illustrates these developments. These trends align with prior findings reported by Thomas [7] and Neville [4], who observed delayed pozzolanic reactions that enhance strength over time. The early-age strength was slightly lower compared to conventional mixes, but long-term strength surpassed that of traditional concrete. This behavior is attributed to the latent hydraulic activity of GGBFS, which becomes more effective after the first week of hydration [1,5].

Table 1. Compressive Strength by GGBFS Percentage and Age

Type of Mixed	Age (Days)	Compressive Strength (MPa)
Control concrete	3	35.45
	7	39.62
	14	41.32
	28	45.7
Concrete + 4% GGBFS	3	36.76
	7	39.00
	14	41.50
	28	44.30
Concrete + 6 % GGBFS	3	36.70
	7	39.80
	14	43.00
	28	49.75
Concrete + 10% GGBFS	3	40.81
	7	46.25
	14	48.62
	28	53.72

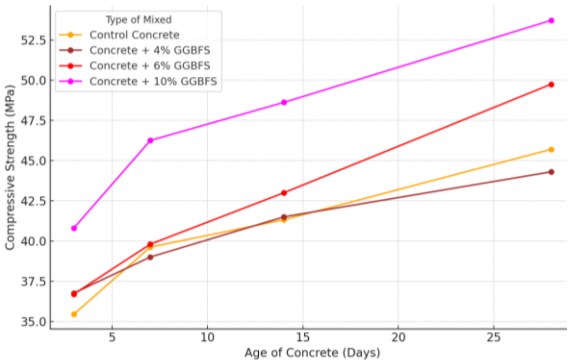

Fig. (1) Strength development trends of concrete with various GGBFS replacement percentages

To statistically validate the findings, regression analysis and trend line interpolation were applied to the compressive strength data. All three GGBFS mixes showed high R^2 values (>0.98), indicating strong correlation between curing time and strength gain. This statistical consistency confirms the repeatability and reliability of GGBFS performance under standard conditions. A one-way ANOVA was performed on the 28-day strength results, confirming statistically significant differences between mixes ($p < 0.05$). The standard deviation and coefficient of variation were also computed to demonstrate the reliability of experimental data.

Although this study did not include direct durability testing, inferences can be drawn from strength trends and previous research. Increased strength at later ages indicates reduced porosity and enhanced matrix density, which correlates with improved durability [9,10]. GGBFS is known to lower permeability, increase resistance to chloride ingress, and reduce alkali-silica reaction potential [11,12]. Therefore, its inclusion at 6–10% levels provides not only strength benefits but also contributes to extending service life in aggressive environments. Secondary C-S-H gel formed by the pozzolanic reaction of GGBFS typically exhibits a lower Ca/Si ratio, denser structure, and improved pore-filling capabilities compared to primary C-S-H gel, thereby significantly enhancing durability (Scrivener & Kirkpatrick, 2008 [14]; Gartner & Hirao, 2015 [15]). Techniques recommended for future research include Mercury Intrusion Porosimetry (MIP), X-ray microtomography, and nitrogen adsorption tests.

4. Conclusion

The study demonstrated that partial replacement of cement with GGBFS at levels ranging from 4% to 10% consistently enhances compressive strength over time. While early-age strength improvements remain modest, significant long-term gains were evident, notably for the 10% GGBFS mix, which achieved over 53.72 MPa at 28 days. These findings underline the effectiveness of GGBFS as a sustainable supplementary cementitious material (SCM), promoting improved performance alongside reduced cement usage. Further investigations are recommended to determine the optimal GGBFS replacement percentages beyond the current scope and to explore potential synergies with other SCMs.

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