Global Research journal of Natural Science & Technology (GRJNST)

Volume: 04 - Issue 2 (2026), 2049
ISSN P: 2790-7643 ISSN E: 2790-7651
www.grjnst.net
https://doi.org/10.53762/grjnst.04.02.01

Optimization of GGBS as a Partial Replacement of Cement for Enhanced Strength and Durability of Sustainable Concrete

Received: 26 December 2025. Accepted: 19 January 2025. Published: 25 March 2026

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GRJNST, Volume: 04 - Issue 2 (2026) / ISSN P: 2790-7643
Article ID: 2049
https://doi.org/10.53762/grjnst.04.02.01

***Abstract**: Concrete is one of the most common building materials in the world. It has great compressive strength, but it is not very durable or sustainable because it relies on ordinary Portland cement (OPC). Ground Granulated Blast Furnace Slag (GGBS), a by-product of the steel industry, was used as a partial replacement for Ordinary Portland Cement (OPC) to improve the mechanical and durability performance of concrete. The mass proportions for replacing cement with GGBS in concrete mixes were 0%, 10%, 20%, 30%, and 40%. The mix ratio was 1:1.5:3, and the water-to-cement ratio was 0.45. Mechanical performance was tested by measuring the compressive strength, split tensile strength, flexural strength, and surface hardness (using the rebound hammer test). For durability performance carbonation depth and water permeability tests were conducted. According to the findings, GGBS produced the highest compressive, tensile, and flexural strengths when 20% of OPC was substituted. It also improved surface hardness and decreased permeability, indicating increased durability. Mechanical strength, resistance to carbonation, and permeability all decreased above this point. The results validate the viability of employing GGBS as a sustainable binder, which lowers CO2 emissions and cement consumption in environmentally friendly building.*

***Keywords:** Concrete, GGBS, Supplementary Cementitious Materials, Mechanical Strength, Durability, Sustainable Construction*

Introduction

he most popular building material in the world, concrete is renowned for its high workability, versatility, and compressive strength. Its creation and use serve as the foundation for the development of infrastructure, particularly in developing nations. However, conventional concrete has a significant environmental cost, mostly because it uses Ordinary Portland Cement (OPC). About 7–8% of the world's CO_2 emissions come from the cement industry alone, mostly from the calcination of limestone and the use of fossil fuels in its manufacture. Because of the urgent need to slow down climate change, researchers and engineers are looking into low-carbon options like using industrial byproducts as supplementary cementitious materials (SCMs).

Ground Granulated Blast Furnace Slag (GGBS) is a very popular SCM. When molten slag, which is a by-product of making iron in a blast furnace, cools quickly, it becomes ground granulated blast-furnace slag (GGBS), which is a latent hydraulic material. The reaction of its calcium, silica, and alumina-rich composition with calcium hydroxide gives it strength and durability. This is how ordinary Portland cement (OPC) turned into more calcium silicate hydrate (C-S-H). The incorporation of GGBS into concrete mixtures has been shown to improve several performance characteristics such as permeability, chloride and sulphate resistance, reduced alkali-silica reaction and pore structure refinement.

Several studies have been undertaken on the use of GGBS in concrete mixtures. Dinakar et al. [32] in the evaluation of high-volume GGBS concrete increased the durability and porosity refinement also up to 50% replacement [1]. According to Ahmad et al. Results of previous studies showed that at 20% GGBS replacement continued pozzolanic reactions promoted compressive and split tensile strength up to 8 weeks, particularly at 28 and 56 days [2]. In the study of Habert et al., the GGBS environmental benefits were highlighted. (2020) by mentioning that significant reductions in embodied CO_2 were achieved without compromising durability. According to Kannan et al. GGBS enhances thermal cracking resistance and chemical-resistant. [3] However, the slow reactivity of GGBS relative to OPC may negatively affect the strength performance in the initial periods of life [4]. GGBS-modified concrete may show delayed strength gain, increased carbonation depth, and variable workability depending on fineness and curing conditions, according to Umapathy et al. [4] and Sequeira et al [5]. Singh et al. [6] stressed the importance of striking a balance between performance trade-offs and environmental benefits, particularly when substituting GGBS for more than 30% OPC. Many other have investigated the mechanical and durability performance of concrete by adding different SCM in concrete [7–9]

Detailed studies assessing the combined mechanical and durability properties, particularly under standardized curing conditions, are still scarce, despite the fact that the advantages of GGBS have been widely publicized. Numerous earlier studies concentrate on mechanical performance or particular durability metrics, such as chloride ingress or sulfate resistance. Furthermore, the majority of research uses materials from particular geographical areas, which makes it challenging to generalize the findings. Regionally based studies that employ locally accessible OPC, aggregates, and GGBS are obviously needed. These studies should provide a comprehensive performance evaluation that includes slump, compressive, tensile, and flexural strength in addition to carbonation and permeability resistance.

The present study aims to bridge the research gaps identified through a comprehensive experimental program that assesses concrete mixtures with partial cement replacement with GGBS. Goals: To assess the influence of varying percentages of GGBS replacement (10%, 20%, 30%, and 40%) on various test parameters including mechanical and durability were evaluated. To determine the effects of GGBS on durability indices such as surface hardness, water permeability and carbonation resistance of concrete.

The aim is to establish in local material and curing conditions the optimum level of replaceable GGBS that provides the best combination of durability, mechanical performances, and yes sustainability.

2. Experimental Program

2.1 Materials

The experimental program included materials obtained from local suppliers to ensure that it was realistic and appropriate. Below is a list of the components that were used:

Cement: The main binder was OPC Type I, which complied with ASTM C150 standards. Its compressive strength, consistency, and setting time were evaluated.

Fine Aggregates: Good workability and gradation were guaranteed by a 50:50 blend of natural sand from local market.

Coarse Aggregates: 5–19 mm crushed stones from the local marker were used for making of concrete samples. The specific gravity of the aggregates ranged from 2.64 to 2.69.

Water: ASTM C1602-compliant clean tap water that can be used to mix and cure concrete.

GGBS: A nearby steel mill provided the ground granulated blast furnace slag. It met ASTM C989 standards with a Blaine fineness of 410 m²/kg and a specific gravity of 2.89.

2.2 Mix Proportions

All mixes had a consistent water-to-cement ratio (w/c) of 0.45 and a volumetric ratio of 1:1.5:3 (cement: fine aggregate: coarse aggregate). At 0% (control), 10%, 20%, 30%, and 40% by weight, GGBS was added to partially replace OPC. The mix proportions and identification labeling are compiled in Table 1.

Table 1: Mix proportions of materials used in this study

Mix ID	Cement (%)	GGBS (%)	OPC (kg)	GGBS (kg)	Fine Agg. (kg)	Coarse Agg. (kg)	Water (kg)
M0	100	0	350	0	525	1050	157.5
M10	90	10	315	35	525	1050	157.5
M20	80	20	280	70	525	1050	157.5
M30	70	30	245	105	525	1050	157.5
M40	60	40	210	140	525	1050	157.5

2.3 Specimen Preparation

A revolving drum mixer was used to mix and batch the concrete for each mix. For the first two minutes, the dry ingredients OCC, GGBS, sand, and coarse aggregates were combined. To create a consistent, homogenous mixture, water was then added gradually while the mixture was being mixed for an additional three minutes. Standard steel molds were used to cast the concrete samples as shown in Figure 1. 150 mm x 150 mm x 150 mm cubes: For tests of water permeability, carbonation, rebound hammer, and compressive strength. For split tensile strength tests, use cylinders that measure 150 mm in diameter by 300 mm in height. For testing flexural strength, use prisms (160 mm x 40 mm x 40 mm) as shown in Figure 1. To guarantee compaction and remove air voids, all specimens were vibrated with a table vibrator after casting. After covering the molds with plastic sheets, they were left alone for a full day. Specimens were then demolded and moved to a curing tank where the water was kept at 23 ± 2°C until they were tested at 7 and 28 days.

(a) (b) (c)

Figure 1: Specimen details (a) cube sample (b) cylindrical sample (c) beam sample

2.4 Testing Methods

The mechanical and durability properties were examined considering the following standard operating procedures:

Slump Test (ASTM C143): Determined how workable and consistent fresh concrete was [10].

Compressive Strength (ASTM C39): Using a hydraulic compression machine, cube specimens were tested at 7 and 28 days [11].

Split Tensile Strength (ASTM C496): Measured on cylindrical specimens after 28 days [12].

Flexural Strength (ASTM C78): Tested on prism specimens at 28 days using the third-point loading method. The surface hardness of the top face of concrete cubes was measured using the rebound hammer test (ASTM C805) [13].

Carbonation Depth: After 28 days, the color change was measured after cubes were split and a phenolphthalein indicator solution was sprayed on them [14].

3. Results and Discussions

3.1 Workability-Slump Test:

Figure 2 shows the slump test results; slump test results demonstrate a definite decline in workability as the amount of GGBS increases. High workability was indicated by the control mix (M0), which had the highest slump value of 110 mm. For GGBS-modified mixes, the slump values gradually dropped to 70 mm (M40), 80 mm (M30), 90 mm (M20), and 100 mm (M10). This decrease is explained by the GGBS particles' finer size and larger surface area, which absorb more water and lower the amount of free water that can flow. Umapathy et al. (2014) reported similar trends, finding that a higher GGBS content reduced slump because of its slower early reactivity and higher water demand. All mixes retained workable consistencies appropriate for construction in spite of this reduction.

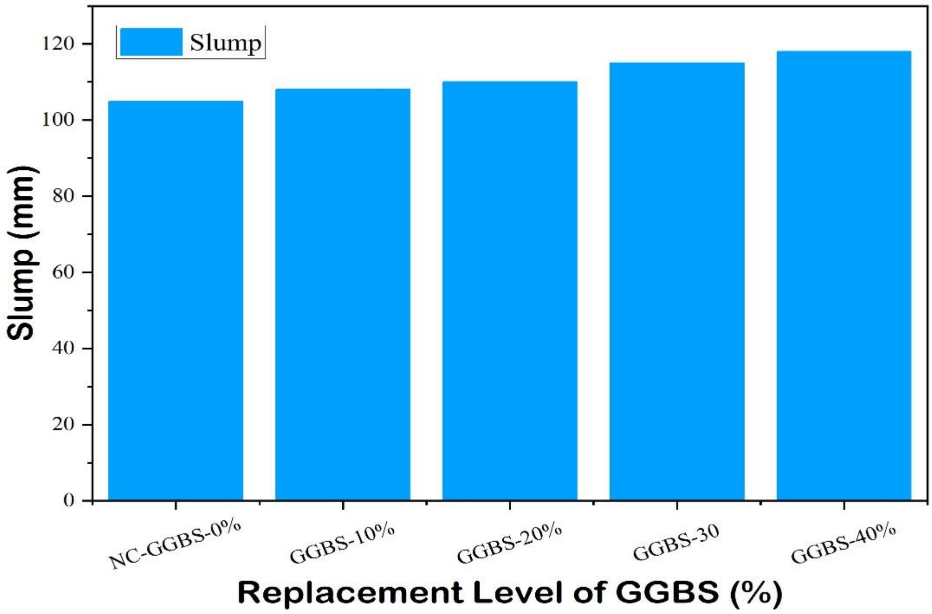


Figure 2: Slum test results for each concrete mix made with GGBS

3.2 Compressive Strength:

Figure 3 shows how the compressive strength changed over 7 and 28 days. The control mix (M0) reached 30.5 MPa at 7 days and 39.8 MPa at 28 days. The highest strength, with compressive strengths of 35.2 MPa at 7 days and 45.1 MPa at 28 days, was 13.3% higher than the control M20. Improved particle packing and initial hydration are responsible for the early-age gain, whereas the pozzolanic reaction that forms more C-S-H is responsible for the long-term strength. Compressive strength dropped to 40.7 MPa and 36.2 MPa at 30% and 40% replacement levels, respectively, as a result of slower GGBS reactivity and cementitious content dilution.

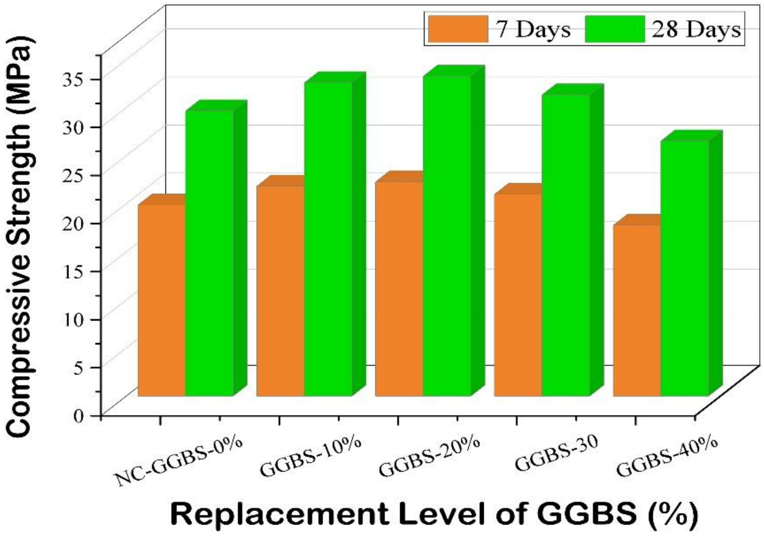


Figure 3: Compressive Strength values of each concrete mix made with GGBS

These findings support optimal performance at 20% GGBS replacement and are in line with those of Dinakar et al. (2013) and Hussain et al. (2020).

3.3 Split Tensile Strength:

Similar patterns to compressive strength were observed in the split tensile strength results at 28 days (Figure 4). M20 showed the highest strength of 3.92 MPa, a 14.6% increase, while the control mix reached 3.42 MPa. At 3.75 MPa, M10 exhibited enhanced tensile strength as well.

Tensile strength decreased to 2.98 MPa (M40) and 3.25 MPa (M30) after 20%. Although lower contents indicate inadequate hydration of GGBS (at 28 days), the improvement at 20% is attributed to denser matrix and bond strength. Ahmad et al. The same trends were documented by (2022), who found that the greatest compressive strength was for 15–C20% GGBS.

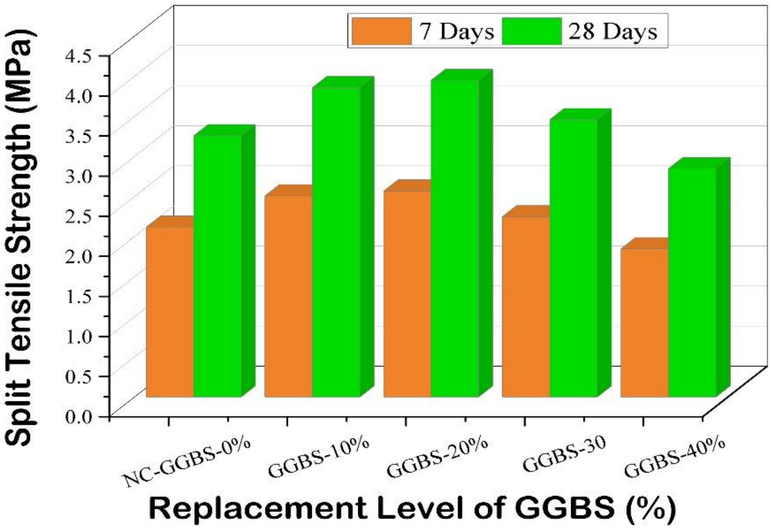
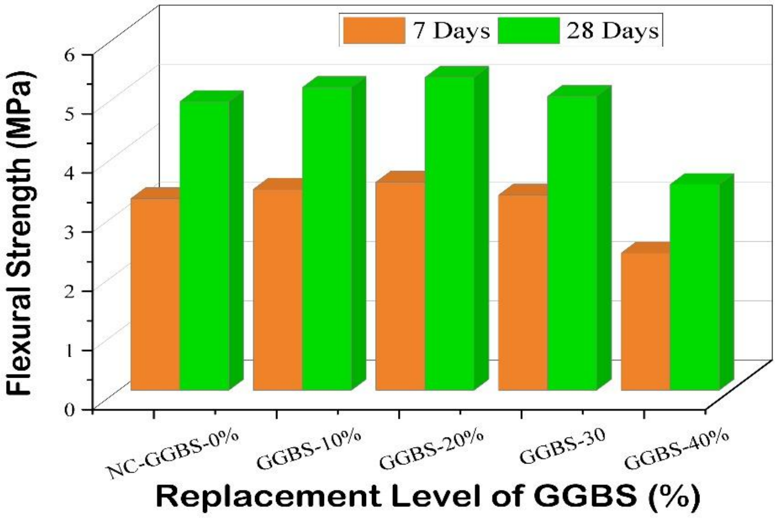


Figure 4: Split Tensile Strength values of each concrete mix made with GGBS

3.4 Flexural Strength:

At 28 days, moderate GGBS contents remarkably improved flexural strength (Figure 5). M20 increased 5.42 MPa (12.4% from 4.82 MPa for M0.) This enhancement has been connected to better matrix continuity and a more refined pore structure.



https://doi.org/10.53762/grjnst.04.02.01

Figure 5: GGBS Mixes showing Flexural strength at different levels

The lesser flexural strengths of 5.10 MPa and 4.65 MPa for M30 and M40 mixes respectively can be attributed to the delayed pozzolanic reactivity and less number of available OPC. The patterns are consistent with findings from Kannan et al. (2021), who found that GGBS produced maximum flexural strength of 15–25%.

3.5 Rebound Hammer Test:

Figure 6 displays the surface hardness findings from the rebound hammer test. For the control mix, the rebound number averaged 32. The mixes M10 and M20 recorded a value of 33 and 34 respectively, reflects increased surface hardness.

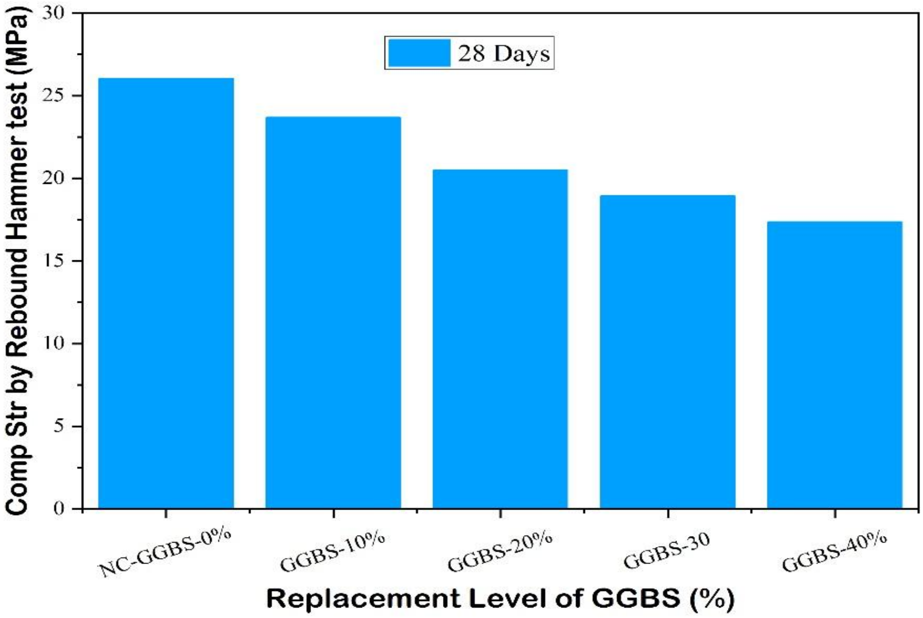


Figure 6: Rebound hammer test values of each concrete mix made with GGBS

However, M30 and M40 reduced to 30 and 28 respectively, which proved the physical test results that showed the strength decrease. These findings align with the results by Sequeira et al. As observed by [25], incomplete hydration at higher GGBS content was linked to lower surface hardness.

3.6 Carbonation Depth:

However, the carbonation test results (figure 7) confirm that carbonation depth was gradually heightened with the rise in GGBS proportion. The depth was 1.8 mm for M10 and 1.9 mm for M20 while it was found to be 1.7 mm for control mix. M30 and M40 deep measured are 2.4 mm and 3.1 mm respectively. As depth increased, higher GGBS levels decreased the amount of $Ca(OH)_2$ available to buffer carbonation. However, good performance was confirmed by the carbonation resistance at 20% replacement, which remained acceptable. These findings are in line with those of Habert et al. (2020), who found that GGBS contents above 25% increased carbonation susceptibility.

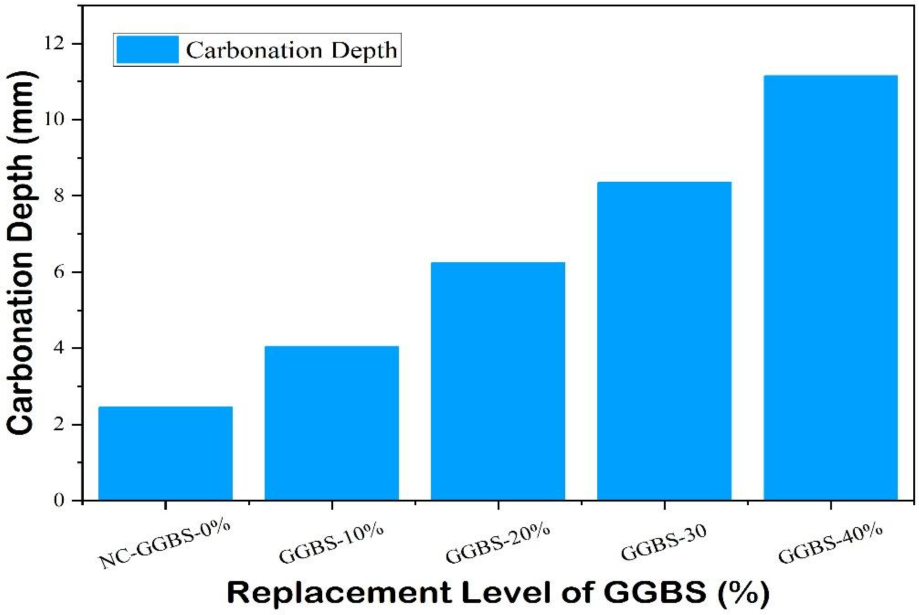


Figure 7: Carbonation depth values of each concrete mix made with GGBS

4. Conclusions

The mechanical and durability properties of concrete that used 10%, 20%, 30%, and 40% replacement levels of ground granulated blast furnace slag (GGBS) as a partial cement substitute were investigated in this study. The results demonstrated that, when applied sparingly, GGBS can greatly improve concrete's performance. The following are the main conclusions:

- ✓ Test results indicated that a 20% replacement level (M20) exhibited the most balanced and superior performance across all parameters tested. Besides having the lowest carbonation depth (1.9 mm), this mix achieved the highest compressive strength (45.1 MPa at 28-day), optimal split tensile (3.92 MPa) and flexural strength (5.42 MPa). Most of these improvements are linked to the synergistic impact of GGBS induced microstructural compaction and pozzolanic activity as well as a better matrix, fines pore structure, and denser interfacial transition zones (ITZs).

- ✓ In contrast, due to the lower reactivity of GGBS and the lower cementitious content with higher levels of replacement (at levels above 20%), the performance decreased (particularly at 40%). Higher replacement levels also correlate with increased carbonation depth and water permeability, which further suggests that as slag content increases without long curing times, limitations appear.
- ✓ 35% replaced with GGBS achieved structural function with lower OPC consumption (20%>) bringing down the carbon footprint in the construction process which had an influence environmentally.
- ✓ Future work, therefore, must focus on (i) long-term performance for field exposure conditions, (ii) application of hybrid use of GGBS with other SCMs, and (iii) microstructural characterization (SEM/XRD) for a better understanding of the observed trends in durability and hydration kinetics. One approach to developing strong and sustainable infrastructure systems is to blend GGBS into conventional concrete.

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