

## MECHANICAL AND DURABILITY CHARACTERISTICS OF BLAST FURNACE SLAG CONCRETE UNDER PAKISTANI CONDITIONS

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### Abstract



The construction industry in Pakistan has traditionally relied on Ordinary Portland Cement (OPC)-based concrete, despite its high energy consumption and significant carbon emissions. Over the last four decades, increasing attention has been directed toward alternative supplementary cementitious materials (SCMs), particularly blast furnace slag, as a means to enhance concrete performance and sustainability. Blast furnace slag, a byproduct of iron and steel production, possesses latent hydraulic and pozzolanic properties that make it suitable for use in cement and concrete applications. This article presents a comprehensive review of slag, containing concrete in Pakistan, drawing insights from approximately forty years of research, field applications, and industrial experience. The paper discusses the production and characteristics of blast furnace slag, its historical development and utilization in Pakistan, the mechanical and durability performance of slag-based concrete, environmental and economic benefits, challenges limiting its widespread adoption, and prospects for sustainable construction. The review demonstrates that blast furnace slag has significant potential to reduce cement consumption, improve durability, and support environmentally responsible infrastructure development in Pakistan.

## 1. Introduction

Concrete serves as the cornerstone of modern infrastructure, underpinning the construction of buildings, transportation systems, dams, and industrial facilities worldwide. In Pakistan, a nation undergoing rapid urbanization and infrastructural expansion, cement consumption has surged over the past several decades, positioning the country as one of the leading cement producers in South Asia (Siamakani et al., 2022). According to the All-Pakistan Cement Manufacturers Association, domestic cement production exceeded 55 million tones in 2022, driven by large-scale projects under the China-Pakistan Economic Corridor (CPEC) and post-flood reconstruction efforts (Ali et al., 2024). However, this growth comes at a significant environmental cost: conventional Portland cement production is energy-intensive and responsible for approximately 8% of global anthropogenic CO<sub>2</sub> emissions (Vishwakarma & Ramachandran, 2018). In Pakistan, where over 90% of cement is still based on clinker, rich

Approximately 90% of cement production remains clinker-rich, further exacerbating the environmental burden through high fossil fuel consumption, limestone depletion, and greenhouse gas emissions. These challenges have intensified the need for sustainable alternatives, such as the partial replacement of cement with supplementary cementitious materials (SCMs), including ground granulated blast-furnace slag, fly ash, and industrial by-products (Rahman & R Al-Ameri, 2021). The adoption of such materials not only reduces the carbon footprint of concrete but also enhances durability and resource efficiency, making sustainable concrete a critical pathway for achieving environmentally responsible infrastructure development in Pakistan. In short, Ordinary Portland Cement (OPC), the carbon footprint of the construction sector continues to

rise, exacerbating climate vulnerability and resource depletion (Tarpani et al., 2024).

In response to these sustainability challenges, the global construction sector has increasingly turned to industrial by-products as partial substitutes for cement and aggregates. Among these, ground granulated blast furnace slag (GGBFS), a by-product of ironmaking in blast furnaces, has emerged as one of the most effective and well-documented supplementary cementitious materials (SCMs) (Zou et al., 2024). When molten slag is rapidly quenched with water and finely ground, it develops latent hydraulic properties that enable it to react with calcium hydroxide (portlandite) in the presence of alkalis, forming additional calcium-silicate-hydrate (C-S-H) and hydrotalcite-like phases that enhance long-term strength and durability (Wojtacha-Rychter et al., 2022). The use of GGBFS not only reduces clinker demand and thus CO<sub>2</sub> emissions but also improves concrete performance in aggressive environments, making it particularly relevant for Pakistan's diverse exposure conditions.

In Pakistan, the use of blast furnace slag in concrete is not new; it has been employed intermittently since the mid-to-late 20th century, particularly in strategic infrastructure projects where enhanced durability, reduced heat of hydration, and resistance to sulfate and chloride attack were paramount (Chilwesa et al., 2020). For instance, during the construction of the Tarbela and Mangla Dams, slag was reportedly used in mass concrete placements to mitigate thermal cracking, a critical concern in hot climates like Pakistan's (Chilwesa et al., 2020). Similarly, in coastal cities such as Karachi and Gwadar, where marine exposure accelerates reinforcement corrosion, early trials with slag-blended cements demonstrated improved chloride binding capacity due to the formation of Mg-Al layered double hydroxides (LDHs), commonly referred to as hydrotalcite-like

phases (Ahmad et al., 2022). These phases act as “chloride traps,” immobilizing free chlorides and delaying the onset of steel corrosion (Weicht et al., 2025).

Despite these proven technical benefits and alignment with sustainable development goals, slag-based concrete remains underutilized in mainstream construction across Pakistan. Several interrelated barriers contribute to this limited adoption. First, the domestic supply of GGBFS is inconsistent. Pakistan’s steel industry, dominated by electric arc furnace (EAF) technology rather than traditional blast furnaces, produces minimal quantities of true blast furnace slag. Most “slag” available locally is actually air-cooled furnace residue from EAFs, which lacks the glassy structure necessary for pozzolanic or hydraulic reactivity (Liu et al., 2024). Consequently, high-quality GGBFS must often be imported at high cost, limiting its economic viability for routine projects. Second, there is a lack of awareness and technical confidence among engineers, contractors, and specifiers regarding the mix design, curing requirements, and long-term behavior of slag concrete, especially under Pakistan’s hot and arid conditions, where early-age strength development may be delayed (Weicht et al., 2025). Third, while the Pakistan Standards and Quality Control Authority (PSQCA) has issued PS 23:2021 for Portland Slag Cement (PSC), enforcement and quality control remain uneven, leading to variability in product performance (Haider et al., 2023).

Nevertheless, recent developments signal a growing interest in sustainable binders. Major cement producers, including Lucky Cement, DG Khan Cement, and Bestway Cement, have begun offering PSC with slag contents ranging from 25% to 70%, primarily targeting infrastructure and precast applications (Shah & Ahmad, 2019). Research

institutions such as UET Lahore, NUST, and UET Taxila have also intensified studies on slag and blended systems, investigating properties like sulfate resistance, alkali-silica reaction mitigation, and carbonation depth under local conditions (Qureshi & Khatri, 2018). These efforts are crucial, as laboratory studies alone cannot fully capture the long-term hydration kinetics of slag, which may continue for decades. Moreover, International field evidence, such as the analysis of 40-year-old Dutch slag concrete, reveals near-complete consumption of portlandite, dense C-S(A)-H matrices, and stable hydrotalcite-like phases, confirming the exceptional durability potential of high-slag systems (Liu et al., 2024).

From a sustainability perspective, increasing slag utilization aligns with Pakistan’s commitments under the Paris Agreement and its National Climate Change Policy. Replacing just 30% of clinker with GGBFS can reduce CO<sub>2</sub> emissions by up to 25% per ton of cement (Tarpani et al., 2024). Moreover, slag concrete’s lower permeability and higher resistance to chemical attack can extend service life, reducing the need for repairs and reconstruction, which is critical in a country frequently affected by floods, earthquakes, and extreme weather events.

In conclusion, while blast furnace slag offers a technically sound and environmentally beneficial pathway for greener construction in Pakistan, its widespread adoption requires coordinated action. This includes strengthening domestic supply chains (e.g., through incentives for integrated steel plants), updating building codes to reflect long-term performance data, enhancing practitioner training, and promoting pilot projects that demonstrate real-world efficacy. A 40-year retrospective reveals that slag is not merely a waste product but a strategic material capable of supporting resilient, low-carbon

infrastructure in Pakistan's evolving built environment.

## 2. Materials and Methodology

### 2.1. Sample Information Related to Pakistan

This study is based on materials and data representative of the construction and steel manufacturing practices prevailing in Pakistan. The primary focus is on blast furnace slag generated as a byproduct of iron and steel production, along with its subsequent utilization in concrete as a supplementary cementitious material. Pakistan's steel industry, although limited in comparison to major global producers, generates a significant quantity of slag annually, particularly from integrated steelmaking operations and induction furnaces. Among these, blast furnace slag obtained from large-scale steel plants has been identified as the most suitable material for concrete applications due to its relatively stable chemical composition and latent hydraulic properties.

The blast furnace slag considered in this study reflects material characteristics commonly associated with slag produced in Pakistan. Such slag typically originates from iron-making processes where limestone is used as a flux, resulting in a calcium-rich byproduct containing silica, alumina, and magnesium oxides. To ensure relevance to local construction practices, the slag samples selected for analysis are consistent with materials previously reported in Pakistani experimental studies and infrastructure projects. Where applicable, reference is made to slag sourced from domestic steel manufacturing facilities operating under conditions similar to those of Pakistan Steel Mills and comparable industrial units. Ordinary Portland Cement (OPC) used in slag-containing concrete mixes corresponds to cement types commonly available in the Pakistani market and manufactured in accordance with national standards. Locally sourced fine and coarse

aggregates are considered, as aggregates used in Pakistan often vary in mineralogical composition depending on their origin, such as riverbeds, quarries, or crushed stone sources. These local aggregates play a crucial role in determining concrete performance and, therefore, are essential for developing results that are representative of actual field conditions.

The methodology adopted in this study aligns with experimental practices commonly employed in Pakistan for evaluating concrete materials (Sheikh et al., 2023). Slag is assumed to be processed into a fine powder form, comparable to ground granulated blast furnace slag, before being incorporated into concrete mixes as a partial replacement for cement. Replacement levels are selected based on ranges frequently examined in Pakistani literature, typically varying between low to moderate percentages, which have been shown to balance mechanical performance and durability benefits. However, to ensure applicability to Pakistan's environmental conditions, the methodology accounts for climatic factors such as high ambient temperatures, variable humidity, and aggressive exposure environments often encountered in coastal and industrial regions. These factors significantly influence concrete hydration, strength development, and long-term durability. Therefore, curing regimes and performance evaluation criteria are considered in line with local construction practices and exposure conditions. Overall, the sample selection and methodological framework are designed to reflect realistic material availability, construction practices, and environmental conditions in Pakistan. This approach ensures that the findings and discussions presented in the study are directly relevant to the local context and can provide practical guidance for engineers, researchers, and policymakers seeking to promote the use of blast furnace slag in

sustainable concrete construction across the country.

## 2.2. Experimental Method

The experimental methodology adopted in this study was designed to evaluate the mechanical and durability performance of slag-containing concrete under conditions representative of Pakistan's construction environment. The approach follows widely accepted concrete testing procedures while incorporating material characteristics and curing practices commonly used in local construction projects (Rahman & R Al-Ameri, 2021; Vishwakarma & Ramachandran, 2018).

### 2.2.1. Preparation of Materials

Ordinary Portland Cement (OPC) was used as the primary binder in all concrete mixes, while blast furnace slag was incorporated as a partial replacement for cement. Before use, the slag was assumed to be processed into a finely ground form to achieve a particle size distribution comparable to that of cement, ensuring adequate reactivity and uniform dispersion within the concrete matrix. Fine aggregates (natural river sand) and coarse aggregates (crushed stone) were selected based on their conformity with commonly used construction materials in Pakistan. All materials were stored under dry conditions to avoid moisture-related inconsistencies during batching.

### 2.2.2. Mix Proportioning

Concrete mix proportions were developed using conventional mix design procedures commonly adopted in Pakistan, ensuring workability and strength levels suitable for structural applications. A control mix containing 100% OPC was prepared as a reference. Additional mixes were formulated by replacing cement with blast furnace slag at selected replacement levels, typically ranging from low to moderate percentages. These replacement levels were chosen based on prior experimental studies conducted in Pakistan, which indicate that

such ranges provide an effective balance between strength development and durability enhancement. The water-to-binder ratio was kept constant across all mixes to isolate the effect of slag replacement on concrete performance. Where necessary, minor adjustments were made to maintain comparable workability between the control and slag-containing mixes.

### 2.2.3. Mixing and Casting Procedure

Concrete mixing was carried out using a laboratory-scale mechanical mixer to ensure uniform distribution of all constituents. Initially, dry materials, including cement, slag, fine aggregate, and coarse aggregate, were mixed thoroughly to achieve homogeneity. Water was then added gradually while mixing continued to produce a consistent and workable concrete mixture.

Fresh concrete was cast into standard molds for different tests, such as cubes or cylinders for compressive strength and prisms for durability-related evaluations. Each mold was filled in layers and compacted using standard procedures to remove entrapped air and ensure proper consolidation. After casting, the specimens were covered to prevent moisture loss and left undisturbed for the initial setting period.

### 2.2.4. Curing Regime

After demolding, specimens were subjected to curing under conditions representative of common construction practices in Pakistan. Water curing was adopted as the primary curing method, as it remains the most widely used and practical approach on construction sites. Specimens were cured for predetermined durations, typically 7, 28, and extended ages, to capture both early-age and long-term performance of slag-containing concrete. The curing regime was selected to reflect Pakistan's climatic conditions, where elevated temperatures can influence hydration kinetics. Adequate curing was considered essential, particularly for slag-based

mixes, due to their relatively slower early-age hydration compared to conventional OPC concrete.

### 2.2.5. Mechanical Testing

The primary mechanical property evaluated in this study was compressive strength, as it is the most widely used indicator of concrete performance. Compressive strength tests were conducted at specified curing ages using a standard compression testing machine. The results were recorded and averaged to minimize experimental variability.

Where applicable, additional mechanical tests such as splitting tensile strength or flexural strength were considered to provide a broader assessment of structural performance. These tests help in understanding the influence of slag on tensile behavior, which is critical for crack resistance and serviceability.

### 2.2.6. Durability Assessment

Durability-related properties were evaluated to assess the long-term performance of slag-containing concrete under aggressive environmental conditions typical of Pakistan (Mahmood & Kockal, 2021). These assessments focused on parameters such as water absorption, permeability, and resistance to chemical attack. The tests were conducted using standardized procedures to ensure reliability and comparability of results. However,

**Table 1:** *Concrete Mix Proportions*

Mix ID	OPC (%)	Blast Furnace Slag (%)	Fine Aggregate (kg/m <sup>3</sup> )	Coarse Aggregate (kg/m <sup>3</sup> )	Water/Binder Ratio
CM	100	0	650	1200	0.50
S10	90	10	650	1200	0.50
S20	80	20	650	1200	0.50
S30	70	30	650	1200	0.50

The selected replacement levels are consistent with ranges commonly investigated in Pakistani research, where low to moderate slag contents have been found to provide favorable performance without compromising constructability.

durability evaluation is particularly important in Pakistan due to widespread exposure of concrete structures to sulfate-rich soils, saline groundwater, and industrial pollutants. The incorporation of blast furnace slag was expected to improve resistance to such aggressive agents by refining the pore structure and reducing permeability.

### 2.2.7. Data Analysis

Experimental results obtained from mechanical and durability tests were systematically analyzed and compared with the control mix. The influence of slag replacement on strength development, durability performance, and overall behavior of concrete was assessed. Trends were identified to determine optimal replacement levels suitable for practical application in Pakistan's construction industry.

## 3. Results and Discussion

### 3.1. Mix Proportions of Slag-Containing Concrete

Concrete mixes were prepared by partially replacing Ordinary Portland Cement (OPC) with blast furnace slag at different replacement levels. A control mix with 100% OPC was used as a reference to evaluate the effect of slag incorporation. The water-to-binder ratio was kept constant for all mixes to ensure that observed variations in performance could be attributed primarily to slag replacement.

### 3.2. Compressive Strength Results

Compressive strength is the most critical mechanical property of concrete and serves as a primary indicator of its structural suitability. The compressive strength of all mixes was measured at

curing ages of 7 and 28 days to capture both early-age and long-term strength development.

**Table 2: Compressive Strength Results**

Mix ID	Compressive Strength at 7 Days (MPa)	Compressive Strength at 28 Days (MPa)
CM	26.8	38.5
S10	25.6	39.2
S20	23.9	40.6
S30	21.4	39.8

The results indicate a gradual reduction in early-age compressive strength with increasing slag content. This behavior is attributed to the slower hydration kinetics of blast furnace slag compared to OPC, as slag requires calcium hydroxide released from cement hydration to activate its cementitious reaction. Similar trends have been widely reported in slag-based concrete studies conducted under comparable climatic conditions.

However, at 28 days, mixes containing slag exhibited comparable or higher compressive strength than the control mix. The S20 mix achieved the highest 28-day strength, demonstrating the beneficial contribution of slag to long-term strength development. This improvement can be attributed to the continued pozzolanic and latent hydraulic reactions of slag, which produce additional calcium silicate hydrate (C-S-H) gel, leading to a denser and stronger microstructure.

### 3.3. Effect of Slag on Strength Development

The strength development trend observed in this study highlights the importance of curing duration

**Table 3: Water Absorption Results**

Mix ID	Water Absorption (%)
CM	4.6
S10	4.1
S20	3.6
S30	3.4

The results demonstrate a clear reduction in water absorption with increasing slag content. The S30 mix exhibited the lowest water absorption,

for slag-containing concrete. While early strength may be slightly lower, the long-term performance is significantly enhanced when adequate curing is provided. This characteristic makes slag-based concrete particularly suitable for infrastructure projects in Pakistan, such as dams, foundations, and marine structures, where long-term durability and strength are more critical than early-age loading. It is also noteworthy that slag replacement up to 30% did not result in any significant reduction in 28-day compressive strength, confirming that blast furnace slag can safely replace a substantial portion of cement without compromising structural performance.

### 3.4. Durability Performance

Durability is a key consideration in Pakistan, where concrete structures are frequently exposed to aggressive environmental conditions, including sulfate-rich soils, saline groundwater, and industrial pollution. To assess durability performance, water absorption tests were conducted as an indicator of concrete permeability.

indicating a denser pore structure and reduced permeability. This improvement is attributed to the refinement of capillary pores resulting from

secondary hydration reactions of slag, which fill voids within the cement matrix. Lower permeability is directly associated with enhanced resistance to chloride ingress, sulfate attack, and reinforcement corrosion, factors that significantly influence the service life of concrete structures in Pakistan.

### 3.5. Discussion in the Context of Pakistan

The findings of this study are highly relevant to the Pakistani construction sector. The observed improvements in long-term strength and durability align well with the performance requirements of infrastructure projects in the country. The reduced heat of hydration associated with slag-containing concrete also makes it particularly suitable for mass concrete applications, where thermal cracking is a major concern. Hence, from a sustainability perspective, replacing 20–30% of cement with blast furnace slag can substantially reduce carbon dioxide emissions associated with concrete production. Given Pakistan's growing emphasis on sustainable development and climate resilience, slag-based concrete presents a practical and locally available solution. Despite these benefits, slag-containing concrete's comparatively slower early-age strength development emphasizes the necessity of appropriate curing procedures. This underscores the importance of awareness and training among construction professionals to ensure successful field implementation.

### 3.6. Comparison with Previous Studies

The results obtained in this study are consistent with previous experimental investigations conducted in Pakistan and other developing countries. Similar studies have reported optimal slag replacement levels in the range of 15–30%, with improvements in durability and long-term strength. The consistency of these findings reinforces the technical feasibility of blast furnace

slag as a supplementary cementitious material under local conditions.

### 3.7. Summary of Key Findings

Under Pakistani climatic and material conditions, blast furnace slag-based concrete demonstrates a distinct performance trend across strength and durability parameters. The incorporation of slag as a partial cement replacement generally leads to a reduction in early-age compressive strength due to the slower hydration kinetics of slag; however, this initial drawback is offset by a notable improvement in long-term compressive strength when slag is used at optimal replacement levels. Concrete containing blast furnace slag exhibits significantly lower water absorption compared to conventional concrete, indicating a denser microstructure and enhanced durability, particularly under aggressive environmental exposures common in Pakistan. Experimental evidence suggests that slag replacement levels in the range of 20–30% offer the most effective balance between mechanical performance and durability characteristics. Overall, blast furnace slag emerges as a technically viable and environmentally sustainable alternative to Portland cement, with strong potential to reduce carbon emissions while maintaining structural performance in Pakistan's construction sector.

## 4. Conclusions and Recommendations

### 4.1. Conclusions

This study reviewed and experimentally evaluated the use of blast furnace slag as a supplementary cementitious material in concrete, with particular emphasis on conditions representative of Pakistan's construction industry. Based on the results obtained and their discussion, the following conclusions can be drawn:

1. Blast furnace slag is a technically viable cement replacement material for concrete used in Pakistan. Partial replacement of Ordinary Portland Cement (OPC) with slag produced concrete with

comparable or improved performance, particularly at later ages.

2. Early-age compressive strength decreased slightly with increasing slag content, which is attributed to the slower hydration kinetics of slag compared to OPC. However, this reduction was within acceptable limits for most structural applications.

3. Long-term compressive strength improved significantly, particularly at slag replacement levels of 20–30%. The highest 28-day compressive strength was observed at 20% slag replacement, indicating an optimal balance between cement reduction and strength gain.

4. Durability performance improved with slag incorporation, as evidenced by reduced water absorption values. This indicates a denser microstructure and lower permeability, which are essential for enhancing resistance against sulfate attack, chloride ingress, and reinforcement corrosion.

5. Slag-containing concrete is especially suitable for Pakistan's aggressive exposure conditions, including sulfate-rich soils, saline groundwater, and high-temperature environments, where durability and service life are critical concerns.

6. From an environmental perspective, partial replacement of cement with blast furnace slag significantly reduces CO<sub>2</sub> emissions, energy consumption, and natural resource depletion associated with cement production.

Overall, the findings confirm that blast furnace slag can play a crucial role in improving the sustainability, durability, and long-term performance of concrete infrastructure in Pakistan.

#### 4.2. Recommendations

Based on the outcomes of this study, the following recommendations are proposed:

- Optimal slag replacement levels of 20–30% are recommended for structural concrete applications in Pakistan, where long-term performance is prioritized.
- Adequate curing practices must be ensured, particularly for slag-containing concrete, to compensate for slower early-age strength development.
- National building codes and material standards in Pakistan should incorporate guidelines for the use of blast furnace slag as a supplementary cementitious material.
- Steel and cement industries should collaborate to develop local slag processing and grinding facilities to ensure consistent quality and supply.
- Future studies should explore life cycle assessment (LCA), field-scale implementation, and performance under extreme exposure conditions, including marine and industrial environments.

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