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REVIEW OF CONCRETE PROPERTIES MODIFIED BY THE USE OF SLAG AS FINE AND COARSE AGGREGATES

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ABSTRACT

The growing demand for sustainable and durable construction materials has intensified research into alternative cementitious and aggregate resources. This review compares the performance of major industrial slags—Blast Furnace Slag (BFS), Steel Slag, Copper Slag, Phosphorus Slag, and Ferrochromium Slag—at their optimal replacement levels, focusing on mechanical, durability, and microstructural characteristics. Studies show that steel slag performs best at 30% coarse and 40% fine aggregate replacement, significantly improving strength. Copper slag at 20% cement replacement enhances compressive strength and reduces porosity. Phosphorus slag used at 20–40% replacement improves long-term strength and lowers chloride permeability. Ferrochromium slag, blended with ferrochrome ash and lime, yields substantial strength and sorptivity improvements with confirmed environmental safety. BFS, commonly used at 30–50% cement replacement, consistently provides strong mechanical and durability performance. Microstructural analyses (SEM, XRD) show denser interfacial transition zones and increased C–S–H formation. Although most slag mixes slightly reduce workability, their overall performance supports their use in sustainable concrete.

Keywords: Slag concrete, sustainable construction, mechanical properties, durability, microstructure

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1.0 Introduction

Concrete is the most widely used construction material in the world due to its versatility, strength, durability, and relatively low cost. It forms the backbone of infrastructure development, including buildings, roads, bridges, dams, and other civil engineering structures. In developing nations such as Nigeria, the demand for concrete has surged in response to rapid urbanization, population growth, and infrastructure expansion (Nedeljković *et al.*, 2021). As a result, the Nigerian construction industry remains a significant consumer of natural resources, particularly aggregates and cement, both of which have substantial environmental footprints. The production of conventional concrete, especially Portland cement, is highly energy-intensive and contributes significantly to global greenhouse gas (GHG) emissions (Miller, Horvath and Monteiro, 2016). According to the International Energy Agency (IEA, 2023), the cement industry alone is responsible for approximately 7–8% of global CO_2 emissions. In Nigeria, where cement production relies heavily on fossil fuels and limestone calcination, the environmental burden is even more pronounced. Furthermore, the increasing demand for natural aggregates has led to extensive quarrying activities, resulting in landscape degradation, habitat destruction, and depletion of non-renewable resources.

In the context of real estate development, recent studies have shown that buildings account for nearly 40% of global energy consumption and approximately 30–35% of greenhouse gas emissions (UNEP, 2022)**.** In Nigeria, poorly regulated construction activities, coupled with a lack of sustainable practices, contribute significantly to this footprint. From the sourcing of raw materials to the life-cycle performance of concrete structures, every stage poses environmental concerns that necessitate the urgent adoption of greener alternatives. Sustainability in construction, therefore, has become a critical goal—not only for reducing emissions but also for ensuring the responsible use of natural resources. The integration of industrial by-products such as slag into concrete production presents a promising approach to this challenge. Slag, a waste material from metal production processes, offers potential environmental and performance benefits when used as a partial or full replacement for conventional aggregates. This approach not only conserves natural resources but also helps manage industrial waste, thereby aligning with circular economy principles and Sustainable Development Goals (SDGs).

1.1 Alternative Materials for Sustainable Concrete Production

In response to the growing call for sustainable construction, both researchers and industry practitioners have directed increasing attention toward the incorporation of alternative materials that can replace conventional components of concrete. This shift is largely driven by the need to reduce the environmental footprint of construction activities, particularly in light of the high energy demands and carbon emissions associated with cement and aggregate production (Odeyemi *et al.*, 2025). Within this framework, two categories of alternative materials have gained significant relevance: Supplementary Cementitious Materials (SCMs) and alternative aggregates. These materials not only offer ecological benefits, but they also contribute to the long-term performance and durability of concrete, making them viable options for sustainable construction solutions. Supplementary Cementitious Materials (SCMs) are industrial by-products or naturally occurring materials that possess cementitious or pozzolanic

properties (Adisa *et al.*, 2025). When blended with Portland cement, they can partially substitute the cement content in concrete, thereby reducing the amount of clinker required and, in turn, lowering CO_2 emissions. Beyond the environmental gains, SCMs also improve several engineering properties of concrete, including strength, permeability, and resistance to chemical attacks. A wide variety of SCMs are in use today. Ground Granulated Blast Furnace Slag (GGBFS), a by-product of steel manufacturing, is particularly notable for enhancing sulfate resistance and improving long-term strength due to its latent hydraulic properties (Malipeddi and Adiseshu, 2022). Fly ash, derived from coal combustion in thermal power plants, improves workability and extends the service life of concrete, although its availability is declining globally due to reduced coal reliance. Silica fume, a by-product from the production of silicon or ferrosilicon alloys, significantly increases compressive strength and reduces porosity, making it suitable for high-performance concrete. Metakaolin, obtained from thermally activated kaolinite clay, also contributes pozzolanic reactivity and is effective in mitigating alkali-silica reactions. Agricultural waste products such as Rice Husk Ash (RHA) and Palm Oil Fuel Ash (POFA) have also emerged as promising SCMs, especially in tropical and agrarian regions like Nigeria (Zou and Yang, 2019) (Amran *et al.*, 2021). These materials offer a sustainable use for otherwise discarded biomass residues, thus contributing to waste valorization and circular economy objectives.

In addition to SCMs, a variety of alternative aggregates have been introduced into concrete formulations with the aim of conserving natural aggregate resources and mitigating the environmental impacts associated with their extraction. These alternatives include metallurgical slags such as steel slag and copper slag, which not only offer mechanical strength but also exhibit good bonding with cementitious matrices. Recycled Concrete Aggregate (RCA), derived from demolition waste, supports material circularity in the built environment. Crushed glass, recycled plastics, rubber particles, palm kernel shells, and coconut shells are other examples that have shown potential in various experimental and real-world applications (Revilla-Cuesta *et al.*, 2020). The incorporation of these alternative aggregates offers multiple benefits, including the reduction of landfill waste, conservation of non-renewable resources, and reduction in carbon emissions. Particularly in Nigeria, where solid waste management systems remain underdeveloped and the construction industry is growing rapidly, the use of such materials could be instrumental in addressing both environmental and infrastructural challenges. By integrating industrial by-products and recycled materials into concrete, the Nigerian construction sector can align more closely with global sustainability targets while reducing its dependence on imported or finite raw materials. Given the above context, this review will now delve deeper into one particular class of alternative aggregate—slag, specifically its use as both fine and coarse aggregate in concrete. The focus will be on understanding its influence on concrete's strength, durability, and microstructural characteristics. The goal is to assess the viability of slag as a sustainable replacement for conventional aggregates, drawing from both local and international studies to inform future applications in Nigeria's construction sector.

2.0 Literature Review

In line with the growing emphasis on sustainable construction materials, numerous studies have investigated the use of various types of slag as potential substitutes for traditional concrete constituents. These slags, which are primarily by-products of metallurgical and industrial processes, offer distinct physical and chemical characteristics that may influence concrete performance in terms of strength development, durability, workability, and microstructural behavior.

This section presents a comprehensive review of the major types of slag that have been explored for use in concrete, either as supplementary cementitious materials or as fine and coarse aggregates. Particular attention will be paid to their origin, physical and chemical properties, treatment methods, and their overall influence on concrete properties as reported in the literature. By examining these materials in detail, we aim to establish a scientific foundation for understanding the suitability of slag for sustainable concrete production, particularly in contexts like Nigeria where industrial waste valorization is both an environmental and economic imperative. The slags under consideration in this review include; Blast Furnace Slag (BFS), Steel Slag, Copper Slag, Phosphorus Slag and Ferrochromium Slag.

2.1 Blast Furnace Slag (BFS)

Blast Furnace Slag (BFS), particularly in Ground Granulated Blast Furnace Slag (GGBFS), is extensively used as a partial replacement for Portland cement in concrete due to its latent hydraulic properties. Its inclusion in concrete mixtures enhances long-term strength development, particularly at later curing stages, although excessive addition may not yield proportional strength gains (Malipeddi and Adiseshu, 2022). Optimizing the BFS content is therefore essential to balance improvements in strength and durability with potential reductions in early-age performance. The benefits of BFS in concrete stem from its ability to reduce porosity, refine the microstructure, and improve the interfacial transition zone between aggregate and paste (Lee, Kim and Kim, 2021). These effects contribute to improved durability parameters, including reduced permeability and enhanced resistance to chemical attack (Dom *et al.*, 2022). However, identifying an optimal substitution ratio is crucial. Excessive proportions (e.g., above 50–60%) may lead to lower early compressive strength and, in some cases, diminished long-term performance beyond 180 days, when compared with mixes made solely with Portland cement. From a sustainability perspective, BFS contributes to eco-efficient construction. It is a cost-effective material—being a by-product of iron production—and its utilization reduces the environmental burden associated with cement manufacture and slag disposal (Yadav, 2019)**.** Its use also supports circular economy principles by transforming industrial waste into a valuable construction input. Achieving the best performance with BFS requires a thorough understanding of its interaction with cement hydration processes. Modeling the hydration kinetics and reactions of both the BFS and cement phases is necessary to predict performance outcomes. Important mix parameters such as the water-to-cement ratio, BFS-cement replacement level, and curing conditions (notably temperature and time) influence the hydration rate and strength development (Iwama, Higuchi and Maekawa, 2020)**.**

In a recent study evaluating BFS sourced from various industrial plants, concrete specimens were prepared with BFS replacement levels of 0%, 20%, 30%, and 40%. Compressive strength

tests conducted at 7, 28, and 60 days indicated that high BFS content may negatively impact strength development, especially at later ages (Papadakis, Antiohos and Tsimas, 2002)**.** Another experimental study in Jordan incorporated BFS at varying levels (10% to 30%) and reported improvements in fresh concrete workability—measured through slump, workability test for low-slump concrete, and compaction factor—with optimal performance observed at 25–30% BFS. The fresh concrete density peaked at 2180 kg/m³ and hardened concrete at 2430 kg/m³, while unit weight reached up to 23.9 kN/m³. In terms of strength, mixes containing 30% BFS met early strength targets and demonstrated significant gains at 56 and 84 days. Bond and flexural strength also improved with BFS addition, suggesting enhanced structural performance across several mechanical properties.

Summarily, Blast Furnace Slag (BFS) offers promising enhancements in concrete performance when used in appropriate proportions (Beushausen, Alexander and Ballim, 2012). Its ability to improve workability, density, and long-term strength, while contributing to sustainability goals, makes it a viable supplementary material in concrete production. However, careful optimization of its dosage is crucial, as excessive replacement levels may lead to diminished strength, especially at early stages. The findings suggest that a BFS content of approximately 25–30% can strike a balance between mechanical performance, environmental benefit, and economic viability, particularly in regions with abundant slag resources such as Jordan. Figure 1 show Scanning Electron Microscopy Image of Blast Furnace Slag.

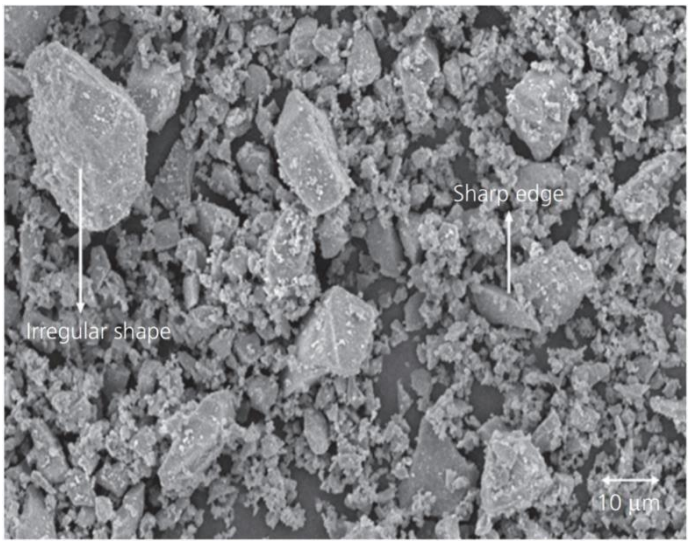


Figure 1: Scanning Electron Microscopy Image of Blast Furnace Slag (Miller, Horvath and Monteiro, 2016)

2.2 Steel Slag

This study investigates the potential of using steel slag (SS), a by-product of steel manufacturing, as a partial replacement for both fine and coarse aggregates in concrete. Employing a mix design for M20 grade concrete, the experimental program evaluates the impact of steel slag on various mechanical and durability properties of concrete (Furlani, Tonello and Maschio, 2010). The results reveal an optimum replacement level of 40% for fine aggregates and 30% for coarse aggregates, beyond which the strength begins to decline (Wu,

Zhang and Ma, 2010b). At these optimal levels, concrete demonstrated improved compressive, tensile, and flexural strengths.

Workability, assessed using the slump test, showed a consistent decline with increasing slag content. This reduction in workability is attributed to the higher water absorption capacity of steel slag compared to natural river sand and crushed stone (Demis, Efstathiou and Papadakis, 2014). As the percentage of slag increases, less water remains available for hydration, leading to lower slump values. Despite this, all mixes exhibited a true slump, indicating satisfactory consistency.

The compressive strength tests at 28 days showed that partial replacement with steel slag enhances the strength characteristics of concrete. A maximum increase in compressive strength was observed at 40% fine aggregate and 30% coarse aggregate replacement levels. Specifically, a 4.6% increase in strength was noted for 30% coarse aggregate replacement, while 40% replacement of fine aggregate led to a significant 27.04% strength gain. This enhancement is partly due to the formation of secondary calcium silicate hydrate (C–S–H) gel over time, which contributes to a denser microstructure and better strength development (Subathra Devi and Gnanavel, 2014).

In addition to strength parameters, durability was examined by Subathra Devi and Gnanavel (2014) through acid resistance tests (using HCl and H_2SO_4) and Rapid Chloride Penetration Tests (RCPT). Concrete samples with steel slag exhibited minimal weight loss after acid exposure, indicating good chemical resistance. However, resistance was found to be more effective against hydrochloric acid than sulfuric acid. In terms of chloride penetration, concrete with 40% fine aggregate replacement showed low permeability, while 30% coarse aggregate replacement was categorized under moderate penetrability. These findings suggest that fine aggregate substitution provides superior durability performance compared to coarse aggregate replacement.

Furthermore, structural behavior was evaluated by measuring deflection in reinforced concrete beams under load. An increase in deflection was observed with increasing load across all mixes, including those with slag replacements. Nonetheless, the incorporation of steel slag appeared to enhance the overall resistance to deformation and vertical strain. Figure 2: Scanning Electron Microscopy Image of Steel Slag.

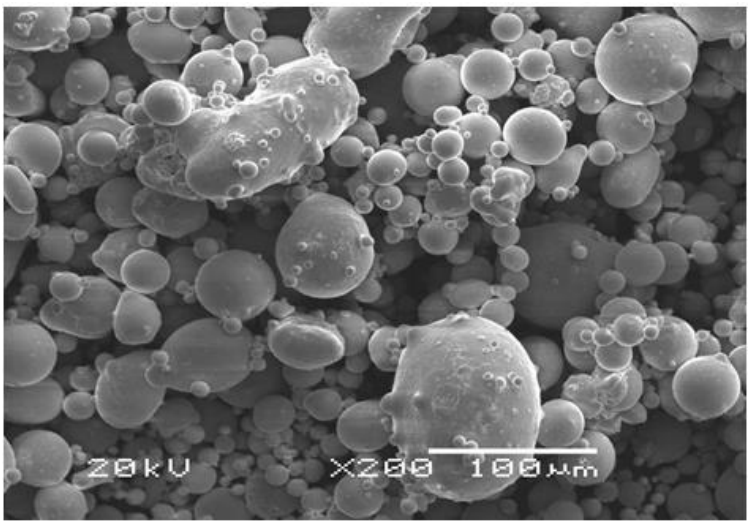


Figure 2: Scanning Electron Microscopy Image of Steel Slag (Pettinato *et al.*, 2015)

2.3 Copper Slag

The growing demand for sustainable construction materials has driven the use of industrial waste in concrete production. Among such wastes, copper slag—a by-product of the copper refining process—has emerged as a promising supplementary cementing material (Panda, Sarkar and Davis, 2021). This study explored the potential of finely ground copper slag, used at a 20% replacement level by weight of cement, to enhance both the mechanical and durability properties of concrete.

Copper slag exhibits favorable physical and chemical characteristics, making it a suitable pozzolanic material. After optimal grinding, it achieved an average particle diameter of approximately 27.2 µm and a pozzolanic activity index of 87%, meeting the requirements for mineral admixtures (Gong, Chen and Miao, 2021). Its high specific gravity (3.87 g/cm^3) and the presence of minerals like fayalite and magnetite contribute to its density and reactivity. Scanning electron microscopy revealed that the slag particles are spherical, nonporous, and smooth, which supports efficient packing within the concrete matrix and contributes to reduced porosity.

Concrete mixes incorporating 20% copper slag showed improved mechanical performance compared to control mixes. Notably, compressive strength increased across all water-to-cement (w/c) ratios tested (0.40, 0.50, and 0.60) (Rohini and Padmapriya, 2023). The strength gains were more pronounced at higher w/c ratios, with increases of up to 30.4% observed at w/c = 0.60. Splitting tensile strength also improved, although the rate of increase was lower than that for compressive strength. These improvements were attributed to both the pozzolanic reactions between the slag and calcium hydroxide, leading to the formation of additional calcium silicate hydrate (C–S–H), and the filler effect, which densified the matrix and transition zones.

Durability assessments demonstrated that the addition of copper slag positively influenced concrete's resistance to water absorption and carbonation (Chen, Gong and Miao, 2022). The copper slag concrete showed reduced total porosity, evidenced by lower water absorption and capillary suction rates. For instance, at a w/c ratio of 0.60, the copper slag mix had a 13.5%

reduction in absorption and a 24.1% decrease in capillary suction compared to its control counterpart. These enhancements in pore structure refinement contribute to long-term durability by minimizing the ingress of harmful agents (Shi, Meyer and Behnood, 2008). Accelerated carbonation tests over a 240-day exposure period confirmed that copper slag addition reduced the depth of carbonation. The reduced carbonation front in copper slag concretes, especially at w/c ratios of 0.50 and 0.60, indicated lower CO_2 permeability due to the denser internal structure formed by the slag addition. The use of copper slag at 20% replacement of cement enhances both the strength and durability of concrete. Its performance improvements are due to the combined effects of pozzolanic reactivity and microstructural densification (Wu, Zhang and Ma, 2010a). These findings support the viability of copper slag as an environmentally friendly cement substitute in sustainable concrete production, and future research could explore the effects of different replacement levels and combinations with other industrial by-products (Panda *et al.,* 2022).

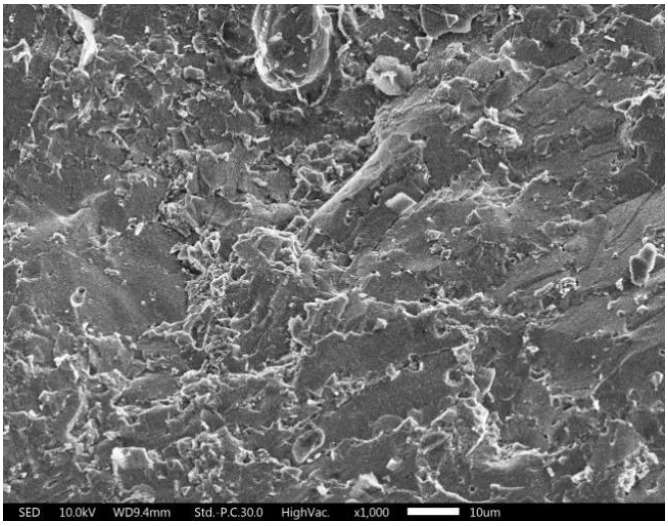


Figure 3: Scanning Electron Microscopy Image of Copper Slag (Rajeeth *et al.*, 2021)

2.4 Phosphorus Slag

Phosphorus slag (PHS), a by-product of yellow phosphorus production, offers significant potential as a supplementary cementitious material (SCM) for use in concrete. Predominantly composed of calcium oxide (CaO) and silicon dioxide (SiO_2), with minor amounts of alumina, iron oxide, and phosphorus pentoxide (P_2O_5), PHS is largely vitreous and reactive (Wang, Wang and Wang, 2020). China, the largest producer of yellow phosphorus, generates millions of tons of PHS annually, much of which remains underutilized and poses environmental hazards. The study examined the influence of PHS fineness and content on hydration behavior, strength development, pore structure, chloride permeability, and fractal characteristics of concrete, particularly in hydraulic infrastructure applications (Deliang *et al.*, 2020). The investigation revealed that incorporating PHS at levels of 20% and 40% by weight of cement influences both the early-age and long-term behavior of concrete (Liu & Li, 2020). While early hydration and strength are adversely affected due to the retarding influence of residual phosphorus, particularly in the form of P_2O_5, mechanical activation of the slag via grinding significantly improves its reactivity. PHS ground to a Blaine surface area of 505 m^2/kg (PHS-H) demonstrated markedly higher pozzolanic activity compared to the lower fineness variant (302

m^2/kg, PHS-L), which led to enhanced strength and denser pore structures at later ages. Compressive strength development showed a consistent trend across all mixtures: strength increased with age, and finer PHS improved performance. At 180 days, concrete containing 20% PHS-H surpassed the control mix, with up to 11% higher compressive strength. In contrast, early-age strengths at 3 days were substantially reduced—up to 53.9% lower for the 40% PHS-L mix—due to both the dilution of cement content and the delay in hydration kinetics. However, this early setback was offset by the pozzolanic reaction of PHS at later ages, which consumed calcium hydroxide ($Ca(OH)_2$) and generated additional C–S–H gels, thereby enhancing strength and densifying the matrix(Chen, Zeng and Fang, 2009). Durability, evaluated through chloride permeability and pore structure analysis, also benefited from the use of PHS, particularly when highly ground. At early ages, PHS increased porosity and the size of capillary pores, resulting in higher chloride diffusion coefficients. However, by 180 days, concrete mixes with PHS—especially those with PHS-H—exhibited lower chloride diffusion values than the control (Yang *et al.*, 2022). The 20% PHS-H concrete, for instance, recorded a 36% lower diffusion coefficient at 180 days compared to plain concrete. This improved performance was attributed to the densification of the microstructure and refinement of pore sizes over time due to continued hydration and pozzolanic activity.

Analysis of pore structure through mercury intrusion porosimeter revealed that PHS incorporation led to coarser pore structures initially, but these became significantly refined with age. The proportion of harmful large capillary pores decreased, while beneficial gel pores and medium capillary pores increased. The most pronounced improvements were seen in the mixes with high-fineness PHS, confirming the importance of particle size in optimizing SCM performance. Fractal analysis further reinforced these findings. The pore surface fractal dimension (Ds) increased with hydration time and was consistently higher in concretes containing PHS at later ages. A higher Ds indicates a more complex and denser pore structure, which aligns with reduced porosity and permeability. Notably, Ds was negatively correlated with both porosity and the most probable pore diameter, indicating that fractal dimension is a reliable index for assessing pore structure quality and concrete durability. Phosphorus slag is a viable alternative SCM in concrete, especially for large-scale infrastructure projects requiring high durability. Its successful application depends largely on its fineness and dosage. When finely ground and used at appropriate levels (20–40% by weight of cement), PHS enhances the long-term mechanical and durability properties of concrete, mitigates environmental pollution from industrial waste, and supports the development of sustainable construction materials. Figure 4: Scanning Electron Microscopy Image of Phosphorus Slag (Liu & Wang, 2017)

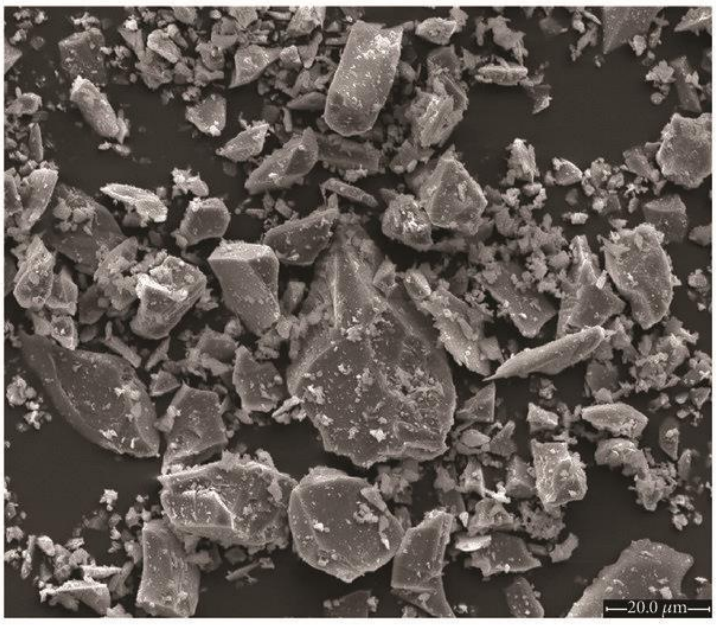


Figure 4: Scanning Electron Microscopy Image of Phosphorus Slag (Liu & Wang, 2017)

2.5 Ferrochromium Slag

Ferrochromium slag (FS), a by-product of stainless steel production, has emerged as a promising alternative to natural aggregates in concrete. Alongside ferrochrome ash (FA), a fine residue collected from the gas cleaning systems in ferroalloy plants, these industrial wastes offer dual benefits: managing hazardous waste and conserving diminishing natural resources used in concrete production (Meiyan *et al.*, 2020). FS, owing to its mechanical strength and mineral composition, particularly lends itself to the replacement of coarse aggregates in concrete mixes. In this study, FS was used to fully replace natural coarse aggregates, while FA was incorporated up to 40% as a partial replacement of ordinary Portland cement (OPC), complemented with 7% lime (Sahu, Biswas and Kapure, 2016). The concrete produced with these substitutions not only achieved comparable mechanical properties to conventional concrete but, in many cases, exceeded them. FS showed excellent compatibility as a coarse aggregate, improving strength and workability due to its favorable physical properties such as specific gravity (2.84), low water absorption (0.63%), and superior abrasion resistance compared to natural granite (Ojha *et al.*, 2021).

Compressive strength increased with the inclusion of both FS and FA. The concrete mix with 10% FA and 7% lime (M-2) recorded the highest compressive strength, surpassing the control mix made with natural aggregate. Even at the highest FA replacement level of 40%, the compressive strength remained higher than that of control mixes across all curing ages (28, 91, and 180 days) (Panda *et al.*, 2022). The strength development was attributed to the pozzolanic activity of FA, enhanced by the presence of lime which activated silicate phases and promoted the formation of additional calcium-silicate-hydrate (C–S–H) gel, as confirmed by X-ray diffraction analysis. Flexural and splitting tensile strengths followed similar trends. At 28 days, mixes with FS and FA demonstrated an increase in flexural strength ranging from 4.34% to 8.69% compared to the FS-only control. Improvements continued at 91 and 180 days, with the

best performance again observed in mixes with lower FA content. Splitting tensile strength also increased with FS use and peaked at 10% FA content, after which it declined with higher FA proportions but still remained superior to the control. These enhancements in strength properties were linked to the refined microstructure and improved interfacial bonding, as observed in petrographic examinations. Durability was assessed using sorptivity tests, which measure the capillary absorption of water. The incorporation of FS and FA led to a substantial reduction in sorptivity, especially at later ages, indicating a denser and less permeable concrete matrix. The synergistic effect of FA and lime further reduced the water ingress by forming dense hydration products that blocked pore connectivity. The flocculation of hydration products reduced effective porosity and improved overall impermeability.

Environmental safety was evaluated through the Toxicity Characteristic Leaching Procedure (TCLP). Despite the inherent chromium content in FS and FA, particularly trivalent chromium (Cr III), leachate levels for all tested heavy metals, including hexavalent chromium (Cr VI), remained well below regulatory thresholds. The stable C–S–H network in the concrete matrix effectively immobilized these elements, minimizing potential leaching and environmental hazards. The study confirms that ferrochrome slag can effectively replace natural coarse aggregates, and ferrochrome ash, when blended with lime, can partially substitute cement in concrete production. These combinations yield concrete with improved strength, durability, and environmental soundness. Figure 5 (a-c) show Scanning Electron Microscopy Image of Ferrochromium Slag (Mahamaya and Das, 2020) Their application not only addresses solid waste management challenges but also contributes to sustainable and low-cost construction materials suitable for structural and infrastructural applications.

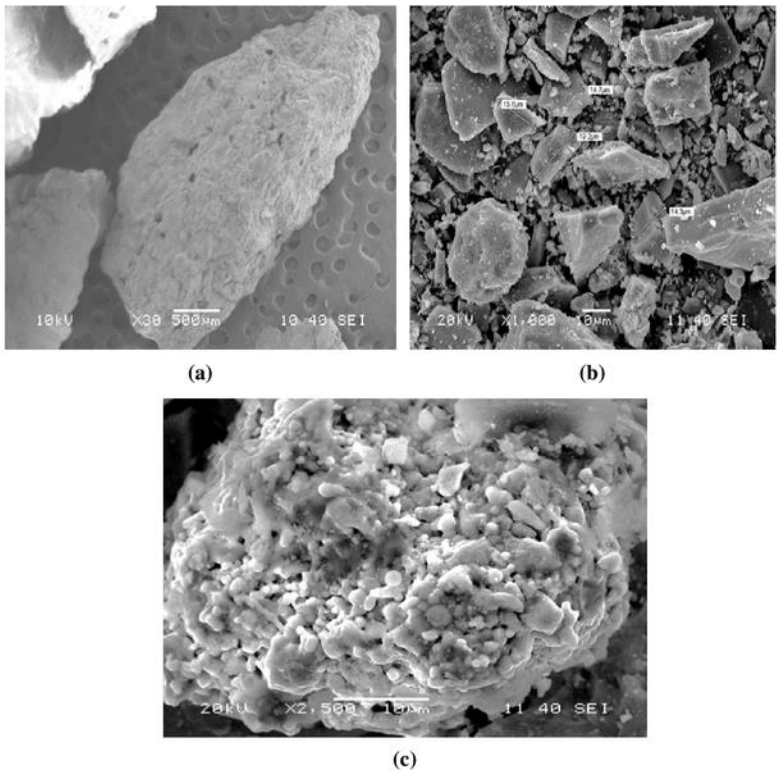


Figure 5 (a-c): Scanning Electron Microscopy Image of Ferrochromium Slag (Mahamaya and Das, 2020)

2.6 Comparative Properties of Different Slag Types in Concrete at Optimal Replacement Levels

Before evaluating the individual performance of different types of industrial slag in concrete, it is important to establish a comparative understanding of their optimal usage levels and corresponding influence on concrete properties. Table 1 below presents a comprehensive comparison of five commonly studied slag types—Steel Slag, Copper Slag, Phosphorus Slag, Ferrochromium Slag, and Blast Furnace Slag—each analyzed at its experimentally determined optimal replacement level. The comparison focuses on key parameters including compressive strength, split tensile strength, durability, workability, and microstructural behavior, with all values reported at replacement percentages that yielded peak or near-peak performance in their respective studies.

This side-by-side evaluation provides a clear view of how each slag type contributes uniquely to concrete performance, especially in terms of strength development and durability. It also highlights the trade-offs in workability and microstructural densification observed through SEM and XRD analyses. The purpose of Table 1 is to serve as a foundational reference for selecting suitable slag types and replacement levels based on specific performance targets in sustainable concrete design.

Table 1: Comparative Properties of Different Slag Types in Concrete at Optimal Replacement Levels

Property	**Steel Slag (30% CA / 40% FA)** (Baalamurugan *et al.*, 2024)	**Copper Slag (20% Cement)** (Chakrawarthi *et al.*, 2022)	**Phosphorus Slag (20–40% Cement)** (Wang *et al.*, 2021)	**Ferrochromium Slag (40% FA + 7% Lime + 100% FS)** (Salihpasaoglu and Sengul, 2020)	**Blast Furnace Slag (30–50% Cement)** (ACI 233-17, 2017)
Compressive Strength	up to 27% at 28 days (FA)	up to 30% (at w/c = 0.6)	up to 11% at 180 days (high fineness)	up to 26.3% at 180 days	15–25% (typical GGBFS results)
Split Tensile Strength	noticeable improvement	moderate increase	Not directly reported	up to 11% over control	consistent improvement
Durability	Improved acid (HCl) & chloride resistance	absorption, suction, carbonation	chloride diffusion, denser structure	sorptivity, low Cr leachability	Excellent sulfate & chloride resistance
Workability	with % replacement; FA better than CA	slightly due to density	with %; more effect at higher P_2O_5	with FA & lime; with FS alone	unless superplasticizer is used

Microstructure (SEM/XRD)	Dense ITZ, C-S-H, $Ca(OH)_2$	C-S-H, portlandite, refined pores	C-S-H, fractal Ds, minimal CH	C-S-H, microcracks, tight bonding	slag rim, C-S-H, dense gel phase
Optimal Replacement Level	30% CA / 40% FA	20% Cement	20–40% Cement (with fine grinding)	40% FA + 7% Lime + 100% FS	30–50% Cement (GGBFS)

3.0 Conclusion and Recommendation

The comparative evaluation of Steel Slag, Copper Slag, Phosphorus Slag, Ferrochromium Slag, and Blast Furnace Slag in concrete applications reveals the significant potential of each material to enhance the performance and sustainability of cementitious composites. When used at their respective optimal replacement levels, these industrial by-products not only improve mechanical properties but also contribute to durability, microstructural densification, and environmental conservation.

Among the materials studied, Steel Slag demonstrated notable improvements in compressive and tensile strength, particularly when 40% of fine aggregate or 30% of coarse aggregate was replaced. Its performance in resisting acid attack and chloride penetration was also superior, although a trade-off in workability was observed due to its high-water absorption.

Copper Slag, optimally used at 20% replacement of cement, significantly enhanced compressive strength, especially at higher water-cement ratios. It also improved durability through reductions in porosity, water absorption, and carbonation depth. However, its high density slightly affected workability.

Phosphorus Slag, when finely ground and used at 20–40% cement replacement, improved long-term strength and reduced chloride ion permeability. Despite early-age strength limitations due to slower hydration, its microstructure became increasingly refined with age, as confirmed by SEM and XRD analyses.

Ferrochromium Slag, used in conjunction with 40% Ferrochrome Ash and 7% lime as a cement substitute, and 100% FS as coarse aggregate, produced concrete with superior strength and low sorptivity. This mix maintained excellent performance across all durability parameters and posed no significant environmental threat, as validated by leaching tests.

Blast Furnace Slag (GGBFS) remains the most widely accepted slag material, offering consistent gains in compressive strength and superior resistance to sulfate and chloride ingress at replacement levels between 30–50%. Its extensive historical use further validates its suitability in structural concrete.

Overall, the findings highlight that optimal utilization of slag materials can lead to high-performance, durable, and environmentally friendly concrete. Selection of slag type and replacement ratio should be guided by specific performance requirements, availability, and processing conditions. Future research should focus on hybrid combinations of these materials,

long-term field performance, and life cycle assessments to further optimize their use in sustainable construction.

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