

# A Review on High-Strength Performance of Steel Slag Concrete under Utilization of Industrial Solid Waste Resources

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## Abstract

As one of the main wastes generated by the iron and steel industry worldwide, the large-scale stockpiling of blast furnace steel slag not only occupies land resources but also poses environmental pollution risks. Therefore, incorporating blast furnace steel slag as coarse aggregate into traditional concrete to produce modified concrete represents an important approach to realizing the resource utilization of industrial solid waste and improving concrete performance. This paper systematically elaborates on the physicochemical properties of blast furnace steel slag, reviews the history and functions of steel slag both horizontally and vertically, summarizes relevant research and project progress in this field, analyzes key problems and technical bottlenecks in current studies, and prospects the development trend of steel slag-modified high-strength concrete. It aims to provide a reference for subsequent related research and engineering applications.

## Keywords

**Blast Furnace Steel Slag; Industrial Solid Waste; Resource Utilization; Modified Concrete.**

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## 1. Introduction

The iron and steel industry is an important pillar and component of the national economy worldwide, but it is also a major source of industrial waste. Blast furnace steel slag, as one of the main solid wastes produced in iron and steel smelting, accounts for about 15%–20% of crude steel output. Taking China as an example, the annual generation of blast furnace steel slag exceeds 100 million tons, and the cumulative stockpile has surpassed 1 billion tons<sup>[1]</sup>.

Massive stockpiled blast furnace steel slag occupies valuable land resources. Especially in rainy weather, heavy metal ions in steel slag dissolve due to rainwater scouring, polluting the surrounding environment and easily causing dust problems<sup>[2]</sup>. Moreover, with the development of modern civil engineering such as high-rise buildings, long-span bridges and super high-rise buildings, the requirements for concrete strength, durability and engineering cost are increasingly stringent, and the advantages of traditional concrete in such engineering applications are gradually diminishing.

At the critical stage of fully implementing the “dual carbon” goal and the new green development concept, using these industrial wastes as partial replacements for traditional concrete coarse aggregates to produce new-type high-strength concrete has obviously become a hot topic<sup>[3]</sup>. This approach not only solves the problems of land occupation and environmental pollution caused by steel slag stockpiling, but also conforms to the current development philosophy and supports the fields where traditional concrete is difficult to apply.

## 2. Physicochemical Properties of Steel Slag

### 2.1 Physical Properties of Steel Slag

As a major solid waste from iron and steel smelting, steel slag has complex and unique physical properties, which directly determine its resource utilization pathways and application scope. In terms of appearance and morphology, the color of steel slag varies significantly with basicity: low-basicity slag is mostly gray, high-basicity slag tends to be brownish-gray or off-white, generally blackish-gray after treatment, and slightly white at extremely high basicity. Naturally cooled steel slag usually exists in blocks, slag lumps or slag shells with fine crystals and neat fractures; it tends to expand and weather after long-term stacking, gradually turning into earthy blocks or powder. The particle size of naturally cooled steel slag is usually 500–1200 mm, and it can be granulated after water quenching. Crushed steel slag particles have distinct edges and corners, providing strong interlocking between particles.

In terms of density and bulk density, steel slag has a significantly higher physical density than ordinary slag due to its high iron content, with a true density of 3.1–3.6 g/cm<sup>3</sup>. The bulk density varies with type and particle size. For 80-mesh powder, the bulk density of open-hearth slag is 2.17–2.2 g/cm<sup>3</sup>, electric furnace slag 1.62 g/cm<sup>3</sup>, and converter slag 1.74 g/cm<sup>3</sup>; the loose bulk density is about 1.6 t/m<sup>3</sup>[4]. Hardness and strength are prominent physical advantages of steel slag: its Mohs hardness reaches 6–7, close to basalt and far higher than ordinary natural sand and gravel; its compressive strength ranges from 145 to 302 MPa, featuring high hardness, low crushability and excellent wear resistance, with a Los Angeles abrasion value not exceeding 18%, superior to conventional natural aggregates. However, its grindability is poor, and the grinding energy consumption is about 40% higher than that of slag.

The internal structure of steel slag is generally dense with few pores, except for open-hearth slag which has relatively more pores. The water absorption rate is 5%–9%, and the moisture content is usually 3%–8%, both affected by cooling and slag stewing processes. In addition, the iron content of steel slag is generally 15%–25%, containing abundant metallic iron and magnetic minerals, enabling the separation of iron and slag phases via magnetic separation. Volume stability is the most critical physical property and the core factor restricting its application. Steel slag contains free calcium oxide (f-CaO) and free magnesium oxide (f-MgO), which undergo slow hydration and expansion upon contact with water, easily causing cracking and volume instability. Safety can only be guaranteed after aging and stabilization treatment to reduce f-CaO content below 1.5%<sup>[5]</sup>. Meanwhile, the glass phase content of steel slag is low, less than 5% under natural cooling, but can be increased to 30% after water quenching, which improves volume stability and service performance to a certain extent.

### 2.2 Chemical Properties of Steel Slag

Steel slag is a by-product formed by the reaction of ores, fluxes, slag-forming agents and metal impurities during iron and steel smelting. Its chemical composition is complex and variable, mainly affected by steelmaking process, raw material ratio, cooling method and basicity control. Chemically, steel slag is dominated by oxides of calcium, silicon, aluminum, iron and magnesium, with small amounts of manganese, sulfur, phosphorus and other trace elements, characterized by high basicity, high calcium and high iron.

The main chemical component is calcium oxide (CaO), accounting for 40%–60%, which is the key component determining cementitious activity and volume stability. Silicon dioxide (SiO<sub>2</sub>) and aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) form the silicate and aluminate mineral system, playing an important role in hydration activity and strength development<sup>[6]</sup>. The iron oxide (Fe<sub>2</sub>O<sub>3</sub>) content is significantly higher than that of ordinary slag, generally 15%–25% and even higher in some cases, giving steel slag obvious magnetism and high density, and laying a foundation for magnetic iron recovery. In addition, steel slag contains a certain amount of magnesium oxide (MgO), mostly in free or mineral form, which together with f-CaO affects long-term volume stability<sup>[7]</sup>.

The basicity of steel slag (mass ratio of CaO to SiO<sub>2</sub>) is an important chemical index for evaluating its quality and utilization. Steel slag is classified into low-, medium- and high-basicity types. High-

basicity steel slag has higher contents of tricalcium silicate, dicalcium silicate and other cementitious minerals, with stronger hydration activity, more suitable for cement, concrete and other building materials; low-basicity steel slag has relatively low activity, mostly used in roadbeds, aggregates and other engineering fields.

Steel slag also contains harmful impurities such as sulfur and phosphorus, which should be controlled during utilization to avoid adverse effects on the environment and structural durability. Overall, the chemical properties endow steel slag with potential hydration and cementitious activity, but also bring problems such as poor volume stability and large composition fluctuation. Safe and efficient resource utilization requires modification, aging, grinding and other treatments.

### **3. Development History and Functions of Steel Slag**

#### **3.1 Development History of Steel Slag Analyzed by Cross-Section Comparison**

As a by-product solid waste of iron and steel smelting, the generation and utilization of steel slag have evolved with the development of the iron and steel industry. In the early stage of iron and steel production, steel slag was continuously generated, but limited by technology and utilization concepts, large-scale utilization was not formed, and most was disposed by natural stockpiling and simple treatment.

##### **3.1.1 1950s–1980s**

After the mid-20th century, with the initial development of China's iron and steel industry, steel slag output increased continuously, and its disposal and utilization attracted attention. From the 1950s to the 1980s, stockpiling remained the main disposal method, utilization was scattered, and no systematic utilization system was formed.

##### **3.1.2 1980s–Early 21st Century**

From the 1980s to the early 21st century, the resource utilization of steel slag entered a preliminary exploration stage. Utilization practices increased gradually, shifting from disordered stockpiling to purposeful resource utilization. The utilization scale expanded and pathways stabilized, laying a foundation for subsequent technological development.

##### **3.1.3 Post 2005**

After 2005, steel slag utilization technology entered a rapid development period, with improved treatment processes, enhanced utilization efficiency and expanded application scope. Since 2015, driven by circular economy and green development policies, steel slag utilization has moved toward standardization, large-scale and high-value applications, showing a clear evolution from unorganized stockpiling to orderly resource utilization.

#### **3.2 Functions of Steel Slag in Different Periods Analyzed by Time Sequence Evolution**

The recognition and utilization of steel slag have gone through four typical stages, from useless waste to usable resource and then to high-value recycled material, reflecting the progress of industrial solid waste management and technology in China.

##### **3.2.1 Waste Stockpiling Stage (Early–1980s)**

In the early stage of iron and steel industry, steel slag was regarded as valueless waste.

Mostly disposed by open stacking, landfilling and on-site dumping, it occupied large land areas and caused dust and leachate pollution.

Without stabilization technology, steel slag containing f-CaO and f-MgO was barely used in engineering, except for simple backfilling or sporadic iron recovery, with extremely low utilization value.

##### **3.2.2 Preliminary Utilization Stage (1980s–2005)**

With rising environmental awareness, steel slag was recognized for utilization potential, shifting from complete abandonment to low-value utilization<sup>[8]</sup>.

Iron components were recovered by crushing and magnetic separation; tailings were used in road base, site leveling and subgrade backfilling.

Limited by poor volume stability and lack of standards, application was narrow and unstable, with utilization rate only 10%–30%, still positioned as waste.

### 3.2.3 Stabilization and Large-Scale Utilization Stage (2005–2015)

Mature stabilization technologies (thermal stewing, steam aging, drum granulation) transformed the perception of steel slag:

It became a resource with cementitious activity for building materials.

Stabilization solved expansion and cracking; steel slag powder partially replaced cement in concrete and mortar, raising the comprehensive utilization rate to 35%–40%.

Steel slag was recognized for environmental and engineering value, shifting from passive disposal to active resource utilization.

### 3.2.4 High-Value and Recycling Utilization Stage (2015–Present)

Under circular economy, “dual carbon” and green development, steel slag is redefined as an important secondary resource and recycled material.

Utilization shifts to high-activity, high-value and full-quantity applications:

high-activity steel slag powder, steel slag-based cementitious materials, asphalt mixtures, soil conditioners, heavy metal adsorbents and other high-value products.

The low-carbon and ecological values of steel slag are fully exploited, supporting the green transformation and collaborative solid waste utilization of the iron and steel industry.

Although China’s annual steel slag output and historical stockpile are large, with a utilization rate lower than developed countries, its application prospect and strategic value are highly valued.

**Table 1.** Utilization of Steel Slag in Different Stages

in Different Stages	Utilization Status of Steel Slag
Early–1980s	Regarded as useless waste; open stacking, landfilling, dumping; nearly no engineering application; only small amount for backfilling or iron recovery.
1980s–2005	Simple low-value utilization; iron recovery via crushing and magnetic separation; tailings for roadbeds and backfilling; utilization rate 10%–30%.
2005–2015	Mature stabilization technology; steel slag powder to replace cement; applied in concrete and mortar; utilization rate up to 35%–40%.
2015–Present	High-value utilization; , asphalt mixture, soil conditioner, functional materials; supporting dual-carbon and green building materials

## 4. Research Status and Core Problems of Steel Slag as Concrete Coarse Aggregate

### 4.1 Overall Research Status of Steel Slag

As one of the most emitted industrial solid wastes from iron and steel smelting, steel slag has become a research focus in solid waste resource utilization and green building materials worldwide due to its large output, extensive land occupation and prominent environmental impacts. Current research focuses on stabilization treatment, component separation and modification, multi-scenario resource utilization, performance improvement and mechanism analysis.

In stabilization treatment, numerous studies have addressed the slow hydration and expansion of f-CaO and f-MgO. Traditional processes (thermal stewing, steam aging, drum granulation) have been optimized to promote full hydration and improve volume stability. Emerging technologies such as

carbonation curing, mechanical grinding activation and chemical modification have also emerged, enhancing safety and application potential by altering mineral composition and microstructure<sup>[9]</sup>.

In component and performance research, the chemical composition, mineral composition, physical and mechanical properties and influencing factors of steel slag have been systematically revealed. Steel slag features high hardness, excellent wear resistance, high density and rich angularity, but also has common problems such as large composition fluctuation, poor grindability and low early-age activity. Performance differences caused by smelting process, cooling system and aging time are also key research contents.

In resource utilization, pathways have been expanded. Early applications focused on low-value fields such as subgrade backfilling and site leveling; with technological progress, steel slag is used to prepare steel slag powder, cement admixture, concrete aggregate, road material, soil conditioner and environmental functional material. Driven by the “dual carbon” goal, low-carbon cementitious materials, carbon sequestration materials and all-solid-waste green building materials have become new research hotspots. Despite technological breakthroughs in China, gaps remain with Japan, the EU and other developed countries in overall utilization rate, treatment standardization and high-value level. Composition fluctuation, stability control and long-term service performance are still key constraints for large-scale application<sup>[10]</sup>.

Overall, steel slag research is shifting from single disposal and low-value utilization to stabilized pretreatment, multi-component graded utilization and high-value product development, focusing on process optimization, mechanism revelation, standard improvement and engineering application, providing theoretical and technical support for full-quantity, resource-based and low-carbon utilization of steel slag.

#### **4.2 Research Status of Steel Slag as Concrete Coarse Aggregate**

Using steel slag as concrete coarse aggregate is an important way to achieve large-scale consumption of steel slag. Extensive systematic studies have been conducted worldwide on its applicability, workability, mechanical properties, durability, volume stability and interface mechanism.

In terms of basic aggregate performance, stabilized, crushed and screened steel slag has good particle morphology, low crushing value and excellent wear resistance, meeting the requirements of ordinary concrete coarse aggregate<sup>[11]</sup>. However, steel slag has higher density than natural crushed stone, higher water absorption and rough porous surface, which affect the fluidity, cohesion and water retention of concrete mixture, usually requiring adjustment of admixture dosage and mix proportion optimization to improve workability.

In terms of mechanical properties, most studies show that steel slag coarse aggregate can improve the compressive strength, flexural strength and elastic modulus of concrete at an appropriate replacement rate. The rough surface of steel slag provides strong mechanical interlocking with cement paste, resulting in a denser interfacial transition zone and favorable strength development. However, excessive replacement rate increases internal porosity and reduces uniformity, possibly worsening workability and slowing or decreasing strength growth. It is generally accepted that the reasonable replacement ratio of steel slag coarse aggregate for natural aggregate is 30%–50%, achieving optimal mechanical properties while ensuring construction performance.

In terms of volume stability and long-term performance, stability is the core index for safe application. Insufficiently aged or stabilized steel slag may cause concrete expansion, cracking or failure due to continuous hydration of f-CaO and f-MgO. In recent years, mature pretreatment technologies (thermal stewing, steam aging, carbonation stabilization) have effectively controlled expansion risks, enabling qualified steel slag aggregate to be used in structural concrete. Numerous tests confirm that concrete with qualified steel slag coarse aggregate has good volume stability and reliable service performance under long-term load and environmental actions.

In durability research, steel slag concrete exhibits better impermeability, freeze-thaw resistance, chloride ion penetration resistance and carbonation resistance than some ordinary concrete. However,

in special environments such as sulfate attack and acid-alkali conditions, reactions may occur between steel slag aggregate minerals and hydration products, adversely affecting durability, requiring caution in harsh environment engineering.

In application and development, steel slag coarse aggregate has been demonstrated in road, municipal and precast component projects, reducing natural aggregate mining and improving solid waste utilization rate. However, practical engineering faces problems such as unstable raw material sources, large batch differences, imperfect quality control systems and inconsistent design standards, restricting large-scale promotion in high-grade structures such as high-rise buildings, bridges and hydraulic engineering.

### 4.3 Problems of Steel Slag as Concrete Coarse Aggregate

Although steel slag has the potential to replace natural crushed stone as concrete coarse aggregate in physical properties, it faces prominent technical, quality and engineering safety problems in practical application and promotion, directly restricting its large-scale and high-grade engineering application.

First, poor volume stability is the most critical and fatal problem. Unhydrated f-CaO and f-MgO in steel slag undergo long-term slow hydration inside concrete, causing significant volume expansion, leading to cracking, uplift or even failure of concrete structures, seriously affecting safety and durability. Although thermal stewing, steam aging and other methods can improve stability to a certain extent, complete stability of every batch is hard to guarantee, and expansion risks remain<sup>[12]</sup>.

Second, large fluctuations in composition and performance lead to poor batch stability. Steel slag properties are affected by steelmaking process, raw materials, cooling method, storage time and other factors, resulting in significant differences in density, water absorption, crushing index, basicity and mineral composition between different steel plants, furnaces and stacking sites. This heterogeneity makes it difficult to stably control concrete quality, failing to meet the strict consistency requirements of high-performance concrete for raw materials.

Third, inherent deficiencies in physical properties. Steel slag coarse aggregate generally has high density, high water absorption and fluctuating crushing value. High density increases structural self-weight; high water absorption reduces concrete fluidity and increases admixture dosage; some steel slag has high hardness but high brittleness, easily breaking during mixing and vibrating, changing aggregate gradation and affecting concrete strength and workability.

Fourth, complex interfacial transition zone and uncertain long-term performance. The porous and rough surface of steel slag provides strong bonding with cement paste, but also tends to form weak transition zones. The high alkalinity and complex mineral composition of steel slag may cause continuous hydration, alkali-aggregate reaction and other potential risks during long-term service, adversely affecting long-term strength, impermeability, frost resistance and corrosion resistance, with insufficient long-term service data.

Fifth, lack of unified and perfect standards and quality control systems. At present, China has not formed a complete nationwide unified standard for stability testing, pretreatment process, quality classification and application scope of steel slag coarse aggregate. The absence of clear basis for engineering design, construction and acceptance makes designers and contractors cautious, limiting applications to low-grade projects such as roads and backfilling, rather than high-grade structures such as high-rise buildings, bridges and hydraulic engineering.

Finally, insufficient economy and engineering recognition for large-scale application. Steel slag requires multiple processes (crushing, screening, magnetic separation, stabilization and aging), leading to high treatment costs; meanwhile, engineering concerns about the safety and reliability of steel slag concrete limit market acceptance, hindering large-scale and stable engineering application.

## 5. Future Development of Steel Slag Concrete

Driven by China's "dual carbon" strategy and the continuous promotion of bulk industrial solid waste resource utilization, the application of steel slag as concrete coarse aggregate has broad development

space and important engineering value. In the future, with the upgrading of stabilization technology and maturation of pretreatment processes, key technical problems such as poor volume stability and large composition fluctuation will be systematically solved. The quality stability and service safety of steel slag coarse aggregate will be further improved, gradually transforming from low-grade engineering filling material to green aggregate for structural concrete<sup>[13]</sup>.

Technologically, new technologies such as high-efficiency carbonation curing, precise steam aging, composite modification and interface optimization will emerge, effectively improving the physical, mechanical and long-term durability of steel slag aggregate. In terms of standard system, specifications for production, testing, quality control and engineering application of steel slag coarse aggregate will be improved, providing institutional guarantee for large-scale and standardized application. In application scenarios, steel slag coarse aggregate will expand from traditional fields such as road base and municipal engineering to high-grade structures such as high-rise buildings, bridges, hydraulic engineering and precast components.

Meanwhile, driven by circular economy and low-carbon building materials, steel slag resource utilization will form closer industrial chain collaboration among iron and steel, building materials and engineering construction industries, achieving multiple goals of solid waste consumption, energy saving and emission reduction, and efficient resource utilization. Overall, the application of steel slag as concrete coarse aggregate has broad prospects, and will continue to develop toward high performance, high value, standardization, low carbon and large scale, becoming an important way to promote the green transformation of the concrete industry and full-quantity utilization of solid waste in the iron and steel industry.

## 6. Conclusion

As a bulk industrial solid waste from iron and steel smelting, steel slag has evolved from waste stockpiling to resource-based and high-value utilization along with the development of the iron and steel industry.

At present, extensive studies have been conducted worldwide on the stabilization treatment, physicochemical properties and resource utilization of steel slag, among which using steel slag as concrete coarse aggregate is an important way to achieve its large-scale consumption.

Relevant studies show that properly pretreated steel slag has the basic properties as concrete aggregate, and can improve the mechanical properties and partial durability of concrete at an appropriate replacement ratio. However, it still faces problems such as poor volume stability, large composition fluctuation, uneven physical properties, complex interface characteristics and imperfect standard system.

Under the “dual carbon” strategy and industrial solid waste resource utilization, with the improvement of technologies and specifications such as high-efficiency stabilization, composite modification, quality control and engineering application standards, steel slag as concrete coarse aggregate will develop toward high performance, standardization, low carbon and large scale, with broad application prospects in road, municipal and structural engineering, which is of great significance to promote the green transformation of the concrete industry and full-quantity utilization of solid waste in the iron and steel industry.

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