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# Toward low-carbon and sustainable concrete – carbonated steel slag as supplementary cementitious material: A review

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## ABSTRACT

This review examines in full the use of carbonate steel slag CSS in concrete through combining results from the literature and experimental studies to assess its performance, sustainability and durability. As a by-product of steel production, steel slag is generated in large quantities, posing environmental problems as a result of inadequate disposal and leaching of hazardous materials. Concurrently, the use of Portland cement in the construction sector is a major contributor to $CO_2$ emissions at global levels. Owing to its chemical similarity to cementitious materials, SS has shown that it possesses good potential as a partial replacement for cement or natural aggregates. However, its high content of free lime and magnesia may cause serious durability problems when used directly as a binder or aggregate substitute. To overcome this limitation, carbonation treatment has become an effective and validated treatment. Through the process of carbonation, the active phases of free CaO and MgO in steel slag can be transformed to stable $CaCO_3$ and $MgCO_3$, respectively. Utilizing CSS has several advantages such as volume stability, lower leaching of heavy metals, improved mechanical performance and resistance to chemical and chloride-caused corrosion. However, the transformation not only improves the stability and usability of the material, but it also enables sequestration of $CO_2$ through mineralization, which is a part of the emission reduction efforts. The present study focuses on the physico-chemical characteristics of steel slag, the carbonation behavior, the key parameters that affect the carbonation efficiency, and the possible applications of carbonated slag. Moreover, research gaps and future directions of development of steel slag carbonation are discussed.

**Keywords:** sustainable concrete, cement replacement, durability performance, recycling, $CO_2$ sequestration.

## INTRODUCTION

One of the significant environmental problems confronting modern industry is the large volumes of iron waste generated and much of which is disposed of in municipal wastes and landfills. Improper disposal of such wastes can cause soil and water contamination through heavy metal leaching (Iluţiu-Varvara and Aciu, 2022) Cement based material is still dominating the construction sector owing to its excellent strength and durability characteristics. Conversely, the manufacturing of Portland cement is extremely resource-intensive and requires large amounts of energy, and raw materials (Zhang et al., 2020). Its production also results in substantial $CO_2$ emissions, contributing to air pollution and global climate change (Gao et al., 2021).

Carbon dioxide emissions are a vital and complex worldwide challenge with far-reaching and significant consequences to the stability of the climate. The report of Intergovernmental Panel on Climate Change IPCC has stressed on the need to limit the rise in global mean temperature to below 1.5 °C by 2050 in order to limit catastrophic climatic impacts (Ryu et al., 2024). Cement industry is also a significant source of greenhouse gas emissions, and it releases about 0.79 tons of $CO_2$ for one ton of cement manufactured (Fernandez-Jimenez et al, 2023). In fact, it accounts for almost 8–9% of total global $CO_2$ emissions every kilogram of cement produced generates around 0.5–0.7 kg of $CO_2$ (Kim et al., 2022; Younsi, 2022). This increasing environmental load requires the development of sustainable low-carbon alternatives in construction materials (El Fami et al., 2022). Hence, encouraging the use of energy-efficient and environmentally responsible materials has been one of the main goals in the sustainable evolution of the construction industry and avoid soil and water pollution (Barbhuiya et al., 2024). In recent years extensive research has been aimed towards using supplementary cementitious materials like slag, silica fume and fly ash. The use of steel slag in integration, which was first investigated in the 19th century, has gained strong momentum (especially in Europe) where the use of slag-based cement in nearly 20% of the total production of cement (Hussein and Rasheed, 2023). Developing such eco-efficient alternatives plays a pivotal role in achieving low-carbon construction and reduction in the tendency of using conventional raw materials. With the acceleration of industrialization in the world, the amount of solid industrial wastes has been substantially generated (Chen et al., 2020; Nikitina et al., 2023; Khadim et al., 2026).

The buildup of such by-products poses severe problems both for waste management and for environmental protection. In Iraq, for example, iron as a content of industrial solid waste is a large chunk that comes from steel plants and workshops of small and medium scales. Although not much detailed information is available on the generation of wastes, the increase in the piles of such residues also indicates the failure of the recovery, recycling, and disposal systems generate ecological risks through soil contamination and mounting landfill demand (Ismail and AL-Hashmi, 2008).

Iron and steel slags have desirable properties for their utilization in applications in construction and environmental engineering. As environmental consciousness grows, these materials are becoming prized resources to recycle as they can reduce the environmental impact and ensure resource and energy efficiency. Steelfaking slag in particular is known for its hydraulic properties and its high load-bearing capacity (Aquib et al., 2023). Utilizing industrial byproducts like steel slag as partial replacements for cement has a number of environmental advantages. It reduces consumption of natural aggregates, conserves landfill space and supports sustainable resource management for future generations (Demirbooga and Guls, 2006; Abdalqadir et al., 2020). Moreover, incorporating steel slag in cementitious materials significantly lowers $CO_2$ emissions compared to ordinary Portland cement, thereby mitigating climate change impacts (Gao et al., 2021).

Appropriately, steel slag is produced at a rate of 10–15% of the total crude steel output (Zhao et al., 2023). It is built on a base of silicate and aluminosilicate minerals, as well as free CaO and MgO phase were mounted, rather are reactivated with $CO_2$ thinkers of stable carbonates as $CaCO_3$ and $MgCO_3$. This carbonation process helps to mitigate the issues of long term instability and enhances the durability of the material in structural applications (Elyasi Gomari et al., 2024). Nevertheless, the heterogeneous nature of SS requires the specific treatment and recovery processes (Gencel et al., 2021; Baalamurugan et al., 2023; Ren and Li, 2023). Consequently, the need for developing environmentally sound management strategies for such materials is of utmost urgency to reduce the ecological footprint of such materials (Li et al., 2024). Extensive disposal and storage of SS requires significant land use and poses environmental pollution leads ecological risk due to the potential presence of harmful heavy metals like Cd, Pb, As and V. Long-term SS accumulation also leads to inhalation of hazardous substances. Besides polycyclic aromatic hydrocarbons PAHs, which contaminate soils and lead to soil structure degradation/destruction, impaired crop growth, and land infertility (Zhao et al., 2023). Using proper ways to treat, recycle, and check steel slag is important to protect the environment and keep industry sustainable. This review seeks to bring together current research on the steel slag utilization in concrete in terms of determining the ideal replacement ratios as well as performance. The overall goal is to convert iron and steel waste residues from environmentally harmful waste material into a useful construction material. Furthermore, the effect of SS as a replacement for conventional Portland cement is discussed in this work with the focus on reduction of natural resource consumption and improvement of material properties In addition using slag binders helps cut emissions and supports sustainable building.

## Physical and chemical properties of slags

Steel slag is a by-product of iron and steel production that has a complex composition that is comprised of many chemical oxides. The principal constituents are generally calcium oxide (CaO), magnesium oxide (MgO), ferric oxide ($Fe_2O_3$), silicon dioxide ($SiO_2$), aluminum oxide

($Al_2O_3$), manganese oxide (MnO), ferrous oxide (FeO) and notably, free lime (CaO) (Martins et al., 2021). The percentage of these oxides varies depending on a number of parameters, such as the composition of the raw materials, the metallurgical process used and the type of steel produced (Jonczy, 2019). The compositional ranges (wt.% wt.) of the various metallurgical slags are summarized in Table 1. The visual characteristics and bulk density of steel slag are affected by steel slag basicity and cooling conditions. In general, the color of slag changes from dark gray or brown (low basicity slag) to light gray or white in high basicity types (Yang et al., 2025).

The bulk density of steel slag generally varies about 3.1 and 3.6 g/cm$^3$ in accordance with the high mass, relative to the natural aggregates. The water content usually ranges from 3% to 8% in line with observations underlining its moderate water absorption capacity and also its role on durability and performance of the concrete these properties make SS a promising material for sustainable construction and supporting circular economy practices (Kabeta and Lemma, 2023).

## Production and classification of slag

Blast furnace slag (BFS), or iron slag (IS), is produced in pig iron production and steel slag (SS) is produced in the steel melting shops. Granulated blast furnace slag (GBFS) is a residue of the iron production process, the blast furnace is regularly supplied from the top portion with $Fe_2O_3$ (ore, sinter, pellets), limestone flux (dolomite or limestone) and fuel in the manufacturing of iron (coke, typically). The blast furnace produces two products: molten iron that gathers in the bottom of the furnace (hearth) and molten BFS that floats on the pool of molten metal due to the reduced density of slag, it floats on top of iron and can be easily removed. At a temperature of around 1500 °C, both the kinds are on routine extracted from the furnace as shown in Figure 1 (Hussein and Rasheed, 2023).

**Table 1.** Chemical composition ranges (wt.%) for various types of metallurgical slag (Xu et al., 2010)

| Oxide | Range (wt. %) |
|---|---|
| CaO | 40.04–50.64 |
| $Al_2O_3$ | 22.84–41.73 |
| MgO | 6.40–7.12 |
| $SiO_2$ | 10.25–70.00 |
| FeO | Up to 51.00 |
| PbO | Higher in Pb smelting slags |
| $TiO_2$ | Trace element |
| MnO | Trace element |
| $K_2O$ | Trace element |
| $Na_2O$ | Trace element |
| $P_2O_5$ | Trace element |
| ZnO | Trace amounts |
| Cr | Trace element |
| Ni | Trace element |
| V | Trace element |

Electric arc furnace (EAF) and basic oxygen furnace (BOF) are the two main commercial steelmaking processes. EAF steelmaking primarily uses scrap steel or directly reduced iron, while BOF steelmaking primarily uses scrap steel and liquid pig iron.

Slags are classified into types according to where they originated from as follows, BFS was categorized according to the cooling and treatment method after discharge from the oven. BFS can be segmented into the following categories (Smith et al, 2012). Air-cooled blast furnace slag (ACBFS) is a residue obtained by the cooling of the molten under natural conditions. On the other hand, GBFS is the material produced by the rapid quenching of molten slag with water to obtain a glassy granular material. When crushed into fine and cement-like particles, this material displays cementitious properties which make it a recommended substitute or additive material for Portland cement. (Ali and Shaikh, 2014). ACBFS is usually used as large aggregate, while water-cooled slag (GBFS) is used as an aggregate as in road construction, furthermore, can be mixed with clinker and calcium sulphate to use as binder for cement, mortar, concrete, and grout (Alberici et al., 2017; Raheem and Khadim, 2024). As the grain size of GBFS is less than that of the normal Portland cement, its initial strength is less but it increases gradually, excellent compressive strength, reduced heat of hydration, chemical resistance, workability is more, durability is more and economic efficiency describe the ideal GBFS replacement as a cementation material.

From an environmental engineering perspective, the use of Steel slag not only improves concrete performance but also plays a decisive role in cutting $CO_2$ emissions and reducing the depletion of natural resources, making it a key solution for sustainable construction (Ali and Shaikh, 2014). Steel slag has more iron concentration and physical characteristics, which are similar to air cooled iron slag. The most important compositional difference between BFS and BOF is pointed out through a characteristic analysis. BFS contains higher amount of $SiO_2$ (36.08%)

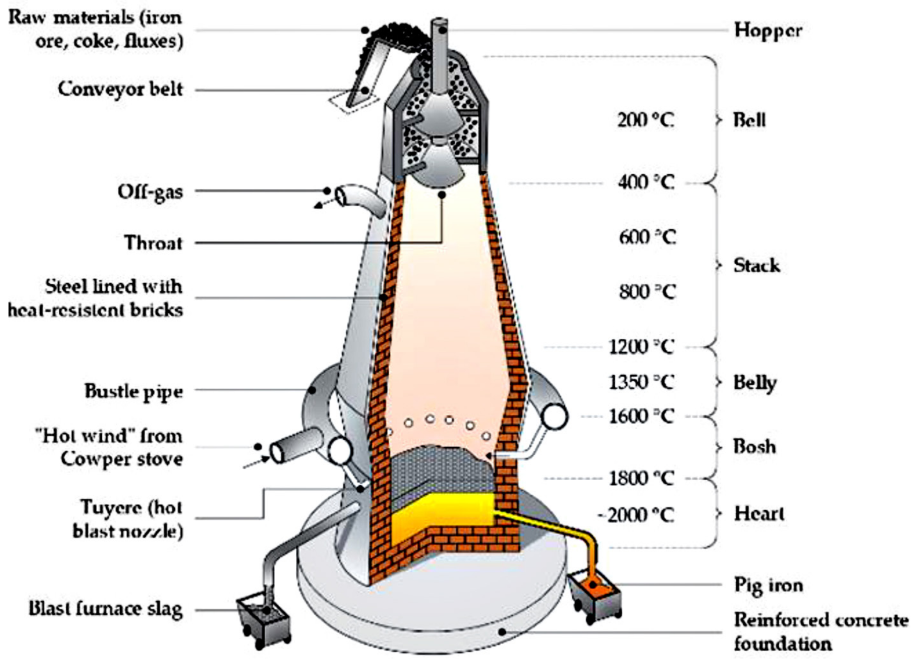


**Figure 1.** Schematic of Blast furnace (Ali and Astuti, 2025) this article is an open access article distributed under the terms and conditions of the creative commons attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0)

and $Al_2O_3$ (17.1%) about three fold and minimal $Fe_2O_3$ (0.75%) when compared to BOF. In contrast, the CaO and MgO contents of steel slags are slightly variable. The chemical composition of BOF CaO (36.03%), $Fe_2O_3$ (24.27%), MgO (15.66%), $SiO_2$ (10.17%), and $Al_2O_3$ (3.18%) were Sajid et al., 2019).

## Steel slag use in construction material

Although iron and steelmaking slags can be reused in different fields, one of the most current reuses concerned concrete manufacturing (Luciano et al., 2020). Based on their physico-chemical and mechanical characteristics, as well as pre-treatment processes, slags can be used in the replacement of cement binder, fine sand, or coarse aggregate. At the same time, it allows a significant reduction in the consumption of cement (20 to 70%). This results in a reduction of both the costs and the environmental impact of the production of cement (e.g. $CO_2$ emissions). Most countries recycle steel slag 75–80% for different uses. Utilization fields vary depending on the industrial situations of the area. For example, slag is mainly used in the production of cement, and has a wide range of uses in highway construction, and is recycled in blast furnace and sintering operations. It is used in agriculture as fertilizer and for soil amendment purposes, improvement of soil quality, high-furnace processes. Steel slag is also used as aggregate, in foundation and sub-base layers (Gencel et al., 2021). The following are some of the application of SS in engineering and construction materials.

### Utilization of steel slag as substitute for aggregates

Steel slag has been widely studied as an alternative to natural aggregates in the concrete production industry. Numerous studies have shown that the use of steel slag contributes significantly to the mechanical performance of the concrete especially in strength such as compressive and flexural strength. When using natural aggregates, replacement with steel slag up to 75% replacement levels, compressive strength has been reported to be increased by about 12% compared with conventional concrete mixtures (Abendeh et al., 2021). Moreover, combined substituted coarse and fine aggregates has given favorable results. The best replacing ratio (50% coarse and 30% fine aggregate) showed considerable improvement in compressive strength with increase of compressive strength values by 5.3%, 5.8% and 19.3% of the compressive strength of the matrix after 7, 28 and 90 days of cure respectively. These results provide the confirmation of the compatibility of steel slag as a sustainable aggregate in structural concrete. Further experimental works also show that the partial replacement levels of 30% to 45% can improve the mechanical properties such as compressive, tensile, and flexural strength, and the general optimum content should be around 45% (Ali and Astuti, 2025). While the substitution of both coarse and fine aggregates tend to reduce the workability as a result of angular and rough surface texture of steel slag, the fine aggregate replacement tends to better retain the flowability of concrete. This behavior has been explained by the fact that the particle morphology and the frictional properties of the slag (Alia and Astuti, 2025). Overall, controlled addition of steel slag as a replacement for natural aggregates has not only improved mechanical strength of a concrete construction, but also brought about the development of environmentally sustainable and resource efficient construction materials. On the other hand, the Steel Slag, compared to natural aggregate, makes it suitable for reuse in the construction sector, specifically as a potential to replace cement material and as a replacement for fine or coarse aggregates in concrete and asphalt production were summarize in Table 2. Therefore, a small percentage of steel slag is already classified as "End of Waste" and is reused as industrial aggregates for concrete mixes after undergoing simple grinding, screening, and granulometric selection treatment. Furthermore to various applications, such as mortars, concrete, and soil stabilization (Piemonti et al., 2023). In addition, this practice reduces the demand for natural aggregates and lowers waste disposal needs, supporting cleaner and more sustainable construction.

## Utilization of steel slag as cementitious substitute

The cement industry is among the biggest contributors to environmental degradation due to the high energy demands and high greenhouse gas (GHG) emission, especially $CO_2$ (Mei et al., 2022). To overcome these emissions, various approaches have been taken in the field of sustainability, such as the partial replacement of Portland cement with industrial by-products such as steel slag. The performance of steel slag as a cementitious material is closely related to the replacement ratio of steel slag in the cement matrix. Research findings suggest that strength development generally reaches a maximum at specific optimal dosage ranges. For example, by adding 10% steel slag as a partial cement replacement, a 28-day compressive strength of 49.01 MPa has been demonstrated, proving that steel slag can be used as a substitute for Portland cement while not impacting the strength of a structure (Hou and Liu, 2022). Similarly, Roslan et al. (2016) tested

**Table 2.** Summary of steel slag aggregate replacement performance and influence on the concrete strength and working property

| Steel Slag as aggregate replacement | | | | |
|---|---|---|---|---|
| Type of slag | Replacement target | Replacement [%] | Results finding | Ref. |
| Iron slag from blast furnaces in Iraq | Coarse aggregate supplement with cement kiln dust | 15%, 25%, 35% | Compression strength improved by 1.4–12.4% and splitting tensile strength by 0.4–5.34% with higher IS content. | Abd et al., 2024 |
| Iron ore tailing in India | Fine aggregate | 0%, 10%, 20%, 30%, 40% and 50% | Compression strength values up to 30% above the target mean strength. Optimum compression strength is achieved for the 10% iron ore tailings. | Krishna et al., 2024 |
| Steel slag from electric arc furnace in Korea | Fine aggregate | 30%, and 60% | Adequate slump, indicating acceptable workability | Kang et al., 2024 |
| Steel slag from EAF in China | Fine aggregate | Tested up to 60% (< 45% recommended for expansion control) | Pre-carbonation reduced f-CaO, inhibiting expansion. Strength improved (+6.8% at 45%), | Gao et al., 2024 |
| Iron slag in Bangladesh | Coarse aggregate (Stone Chips) | 17%, 33%, 50% | Compression strength shows comparable to conventional concrete at 50% replacement ratio | Karim et al., 2022 |
| Steel slag from electric furnace in Iraq | Coarse and fine aggregate | Fine (0–30%), Combined (0–15%) | Optimum 20%: compression strength +51.75%, splitting tensile strength +52.9%, flexural strength +36%. | Hussein and Rasheed, 2023 |
| Steel slag from BFS in India | Fine aggregate (Natural sand) | 100% (complete replacement) | Achieved > 90% of natural sand strength. | Thankam et al., 2021 |

steel slag powder as a cement replacement in the ratios of 5%, 10%, 15% and 20%. Their results found that 10% was the most effective proportion, where the compressive strength at 28 days was 42 MPa, and showed a 27% increase in early-age strength (3 days) when compared to the strength of standard concrete. Beyond strength improvement, this substitution reduces cement demand, lowers industrial waste disposal, and supports more sustainable construction practices.

The performance and workability of steel slag modified cementitious mixtures at the early stage has also been widely studied. A balanced concrete mix should have sufficient cohesion, when it comes to flowability and water retention, without segregation. Studies are constantly highlighting the importance of optimising steel slag replacement and processing method in order to obtain workability and mechanical characteristics desired in cement-based materials (Ali and Astuti, 2025). In case of BFS as a partial alternative to cement, an improvement of workability and longer setting times was observed. Both initial and final setting times were longer than ordinary Portland cement with the strength showing an increasing trend at the early age. Over the years, compressive strength values of slag-blended concretes were found to have become similar or even higher than that of standard mixes. This enhancement is mainly ascribed to the high $SiO_2$ content of the GBFS, which has a high pozzolanic reactivity, and this is responsible for the long-term strength gain (Piemonti et al., 2021). The summary of steel slag cement replacement effect and the properties of concrete strength and workability were displayed in Table 3.

In steel slag, the hydration of f-CaO and f-MgO induces expansion and cracking in SS-derived materials. In steel slag, phases such as portlandite, free CaO, free MgO, and calcium silicates ($C_2S$, $C_3S$) exhibit notable reactivity toward carbonation (Humbert and Castro-Gomes, 2019; Li et al., 2021; Zhuang et al., 2024). On the other hand, alkaline leachate, resulting from the dissolution of Ca oxides and silicates, and the release of potentially toxic elements like vanadium and chromium, in addition weathering of slag dumps are potential environmental issues related to slag. Leaching tests, including TCLP, EP-tox, and EN 12457, are used for regulatory compliance to predict long-term environmental behavior and classify slag for disposal as hazardous or nonhazardous (Piatak et al., 2015).

Accelerated carbonation occurs when $CO_2$ reacts with calcium- and magnesium rich phases to yield stable carbonates) He et al., 2023). Carbonation treatment reduces free CaO in steel slag, mitigating harmful volume expansion and contributing to the environmental sustainability of steel slag-based cementitious materials by enhancing durability and mechanical strength (Jang et al., 2016; Humbert and Castro-Gomes, 2019; Chen et al., 2021b). A promising eco-friendly solution by lowers emissions, manages industrial waste, and permanently stores $CO_2$ as stable carbonates, supporting mitigation in steel industries.

## Accelerated carbonation of steel slag cement production

The growing scholarly interest in steel slag can be attributed to the growing importance of steel slag as an eco-efficient material that is being fostered globally by the transition toward resource efficiency, carbon neutrality, and sustainable construction. Recent research trends indicate that the incorporation of steel slag in cement-based systems can double potentially within the next decade as supported by the development of intelligent concrete technology, carbonation-based manufacturing processes, and the circular economy models that promote efficiency of resource utilization (Ali and Astuti, 2025). Accelerated mineral carbonation, also known as mineralization, was originally conceived of by Seifritz (Seifritz, 1990), as one way to permanently store $CO_2$ through the mimicry of natural rock weathering. This is a process that consists in a chemical reaction between $CO_2$ and calcium and magnesium bearing minerals, to form stable carbonates ($CaCO_3$, $MgCO_3$). By artificially increasing the speed of this slow geologic process, mineral carbonation can turn $CO_2$ into environmentally benign and stable solid products over a short period of time, minutes or hours (Biava et al., 2024). Quantitative assessments have shown the huge potential of this approach. It has been estimated that 4.7 tons of steel slag can capture about one ton of $CO_2$ and about 2.3 tons of $CaCO_3$ is produced as a by-product. Full use of all the world's slag production in mineral carbonation has the theoretical promise for sequestering 53 million tons of $CO_2$ and producing about 120 million tons of $CaCO_3$ (Eloneva et al., 2012). Complete mineral carbonation of steel slag can store annually between 138 and 209 million tons

**Table 3.** Summary of steel slag cement replacement effect and the properties of concrete strength and workability

| Steel slag as cement replacement | | | | |
|---|---|---|---|---|
| Type of Slag | Replacement target | Replacement [%] | Results finding | Ref. |
| Steel slag from electric arc furnace in China | Cement replacement | 30% cement replacement ratio | Specific surface area 24–80% $CO_2$ uptake 2–27 g/100g; mechanical improvements under some conditions | Liu et al., 2024 |
| Steel slag from electric arc furnace in India | Cement replacement - Dry carbonation | 30% GGBS (fixed) + (10%, 20%, 30%) zeolite | Compressive and tensile strengths increased by 11.54% and 7.75%, respectively. Carbonation depth increased 5-fold, significantly enhancing $CO_2$ absorption capacity. | Sekar and Chakrawarthi, 2025 |
| Steel slag from BOF in China | Cement replacement | 10%, 15%, 20% (by mass of total binder) | 0.3 W/B Mix: 28-day compressive increased 8.45–24% and FS increased 4.84–11.3%. | Wu et al., 2025 |
| Steel (BOF) and iron (blast furnace) in India | Cement replacement | 40% combined optimum content of SS + GGBS | Long-term at 90d: compressive exceeded control. High acid/carbonation resistance & lower eco-impact. | Palod et al., 2019 |
| ladle furnace slag in UAE | Cement replacement - | 25% and 50% | 25% Replacement at 64 d: compressive +22.8%. Reduced absorption (-7.8%) and carbonation (-17.7%). | Kaddah et al., 2025 |
| GGBFS (blast furnace) in India | Cement replacement | 0–30% (optimum found at 5%) | Compressive reached 38.32 MPa and 6.98 MPa (flexural) at 28d. High freeze-thaw resistance (0.56% weight loss) | Krishna et al., 2022 |
| GGBS in China/ Ethiopia | Cement replacement | 0%, 30%, 50%, 70% | Accelerated carbonation increased compressive strengths gain for 0, 30, 70% GGBS was 8.9, 0.6, 0.3% respectively; 30% GGBS | Zhao et al., 2021 |
| GGBS in Iraq | Cement replacement | 0%, 20%, 40%, 60% (best result at 60%) | Increasing GGBS content (0-60%) reduced carbonation depth and water absorption, while increasing compressive 60% GGBS yielded the best overall performance. | Mohammed and Marhoon, 2021 |

of carbon dioxide - equivalent to about 9.110.4% of the total emissions from the iron and steel industry (Biava et al., 2024). Long-term projections put cumulative sequestration potentials between 26 and 42 gigatons of $CO_2$ during period 2020 to 2100 (Myers and Nakagaki, 2020). The accelerated carbonation of steel slag normally undergoes pretreatment processes such as crushing and grinding to enhance the reaction kinetics. The carbonation process is generally divided into two major pathways - Direct carbonation and indirect carbonation. Direct carbonation is further divided into dry carbonation (gas-solid reaction) and wet carbonation (aqueous phase reaction). The schematic representation of the total accelerated carbonation process is displayed in Figure 2.

## Direct dry carbonation

Originally put forward by Lackner et al. (1995), in the dry carbonation process natural rock weathering is replicated under controlled conditions. In this one-step reaction calcium and magnesium-bearing oxides and hydroxides react with $CO_2$ to form stable carbonate minerals, including: calcite ($CaCO_3$), magnesite ($MgCO_3$) and dolomite ($CaMg(CO_3)_2$). These types of reaction can occur via direct gas-solid or gas-liquid-solid interactions as shown in Figure 3 for steel slag powders, and mortar pastes. While the process is effective in stabilizing $CO_2$, the process usually involves the use of high pressures and temperatures which are necessary to achieve industrially relevant reaction rates (Lee et al., 2021). Some of the basic chemical reactions involved are:

$$MgO + CO_2 \rightarrow MgCO_3 \quad (1)$$

$$CaO + CO_2 \rightarrow CaCO_3 \quad (2)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

## Direct wet carbonation

Direct aqueous carbonation, also commonly referred to as wet carbonation, is one of the best-studied mineralisation techniques. This process includes several individual consecutive reactions, which are: dissolution of the $CO_2$ in water, formation of carbonic acid ($H_2CO_3$), its further reaction with oxide of metals to form stable carbonates.

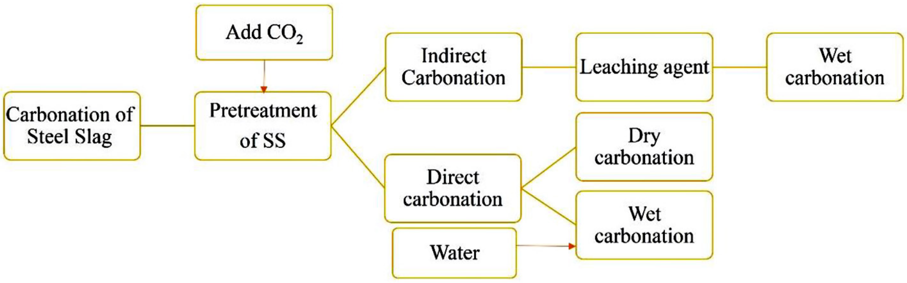


**Figure 2.** Schematic approach of the steel slag (SS) accelerated carbonation

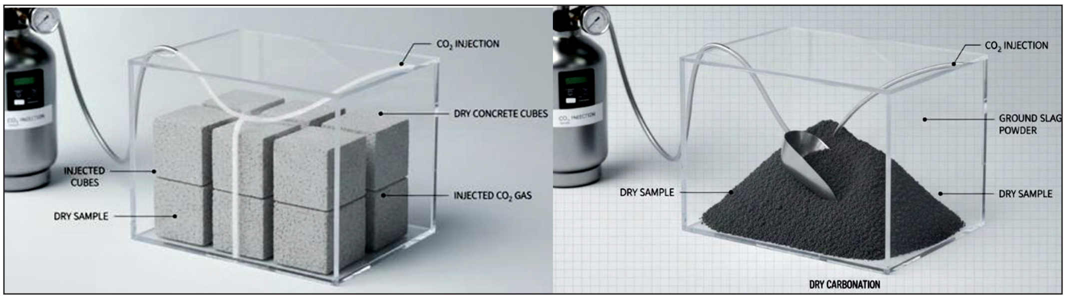


**Figure 3.** Dry carbonation method of steel slag

The reaction mechanism can be described as follows (Veetil and Hitch, 2020):

$$MO + CO_2 + H_2O \rightarrow MCO_3 + H_2O \qquad (4)$$

This is an aqueous phase carbonation mechanism presented in Figure 4 which occurs under moderate conditions often leading to the formation of fine-grained carbonates with desirable binding and stability property.

Utilizing carbonated steel slag in cement production has a number of advantages, such as volume stability, lower leaching of heavy metals, improved mechanical performance and resistance to chemical and chloride-caused corrosion. On the other hand, the expansion of untreated steel slag can result in unwanted expansion, low compressive and tensile strength, and low long-term durability (Li and Wu, 2022).

### Indirect carbonation of SS

The indirect carbonation process involves two different steps: (1) dissolving metal ions, and (2) carbonation of the dissolved ions in an aqueous solution. This two-step method allows one to achieve much higher levels of overall efficiency, since the two stages can be separately optimized. Metal ion extraction is aided by several different solvents – acidic, alkaline or chelating – with strong acids generally providing the greatest dissolution efficiency for calcium and magnesium species. Under optimized conditions, the dissolution yields of Mg and Ca are up to about 46 and 9%, respectively (Yadav and Mehra, 2021). Compared with the direct carbonation, the indirect route is frequently thought to be more feasible for the industrialisation process because of its more environmentally friendly reaction conditions, enhanced carbonation efficiency, and the possibility of yielding high-value by-products (Lee et al., 2021).

### Parameters influencing the carbonation of steel slag

Direct solid carbonation of steel slag (SS) is mainly controlled by temperature and pressure, as increasing thermal and pressure conditions will improve the process efficiency since they will favor equilibrium shifts towards $CO_2$ fixation (Biava et al., 2024).

Effectiveness of the carbonation process depends on several interacting parameters, among them temperature, reaction time, particle size, $CO_2$ pressure, pH and ratio of liquid to solid.

### Reaction time

At the early stages, the carbonation takes place quite fast thanks to the large availability of

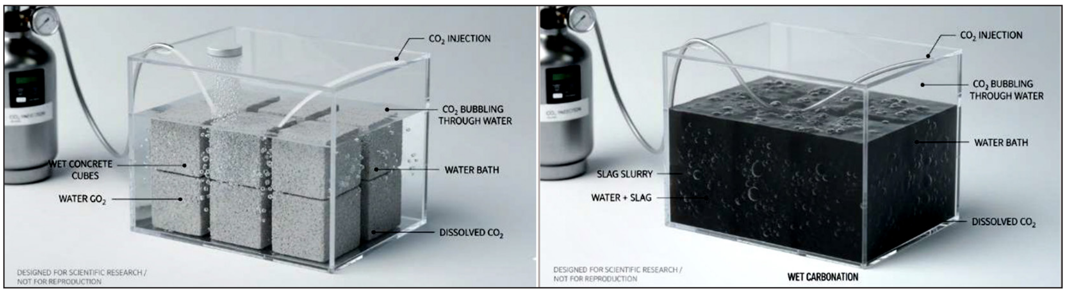


**Figure 4.** Wet carbonation process to steel slag in aqueous condition

reactive compounds (CaO and calcium silicates) and strongly alkaline conditions (pH~11) which are favourable for the dissolution of $Ca^{2+}$ and the reaction with $CO_2$. However, at the forward reaction, the concentration of available $Ca^{2+}$ ions reduces and the pH value reduces to around 6.5 which leads to a lower reaction rate until the equilibrium is reached (Chen et al., 2021a).

### Reaction temperature

In aqueous carbonation systems, temperature influences both the reaction equilibrium and kinetics parameters as well as carbon dioxide solubility. An increase in temperature increases the solubility of metal cations such as $Ca^{2+}$ and $Mg^{2+}$ leading to an increase in reaction rate. However, too high temperatures decrease the solubility of $CO_2$ in the aqueous phase. Therefore, finding the optimal range of temperature, which depends on the composition of materials and specific testing conditions, is very important for maximizing the rate of carbonation (Biava et al., 2024).

### Particle size

One of the most important factors in determining the efficiency of carbonation is particle size. Finer slag particles have more surface area for reaction and hence, higher $CO_2$ uptake. During carbonation, the increase of the surface area of slag is likely to occur due to (1) the porosity formation resulting from $Ca^{2+}$ extraction from the solid matrix, and (2) the deposition of uneven calcite layers on the particle surface (Ibrahim et al., 2019).

### $CO_2$ pressure

At a constant temperature the solubility of $CO_2$ in the aqueous phase is proportional to the applied $CO_2$ pressure according to Henry's law. When $CO_2$ dissolution is the rate controlling step, an increase in pressure drives the increase in mineral dissolution and carbonate precipitation. Therefore, increasing the power of the $CO_2$ partial pressure increases the overall rate of carbonation and level of mineral conversion (Khudhur et al, 2022).

### pH value

The pH of the system has a dynamic influence on the carbonation mechanisms. In environments with low pH, i.e. acidic environments, the process is favorable for dissolution of metal cations – critical precursors for carbonate formation. On the other hand, in alkaline environments, carbonate is favoured in the precipitation of carbonate minerals for example, $CaCO_3$ and $MgCO_3$. Therefore, keeping a controlled pH balance is critical to get an optimal interplay between dissolution and precipitation (Khudhur et al., 2022).

### Liquid to solid (L/S) ratio

The L/S ratio has an important effect on the mass transfer and ionic strength in the aqueous carbonation system. When the L/S ratio is less than the optimum L/S ratio, sluggish slag dissolution takes place, limiting $CO_2$-$Ca^{2+}$ interactions. On the other hand, too large L/S ratios lead to lower ionic strength and to decreased $Ca^{2+}$ availability due to dilution, which may retard the precipitation of carbonate. Optimal amount of ratios facilitate the dissolution of CaO as well as the formation of stable calcite ($CaCO_3$) with not so much mass transfer resistance (Wang et al., 2021).

### Advantages of steel slag carbonation

The carbonation of steel slag has significant advantages in economic, environmental and social conditions. By facilitating the $CO_2$ capture in industrial by-products, this process builds on a lower reliance on expensive carbon capture facilities and encourages sustainable resource use (Sarperi et al., 2014). Not only does carbonation stabilize steel slag, it also immobilizes heavy metals, greatly reducing the problems with their leaching and making the environment safer (Boone et al., 2014). In addition, carbonation improves the physical-mechanical properties of steel slag making it amenable to its reuse as a construction aggregate or supplementary cementitious material. These improvements lead to a reduction of the needs for virgin raw materials, which helps with circular economy efforts and the reduced environmental footprints with regard to transportation and material extraction (Biava et al, 2024). The process is regarded as technically viable, economical and widely applicable in the industrial and construction sectors.

## Steel slag carbonation as cementitious substitute

Accelerated carbonation of steel slag (SS) is effective to decrease contents of free CaO and MgO to mitigate the volumetric instability of slag-based cementitious materials (Moon and Choi, 2018). The formation of $CaCO_3$ particles in carbonation process serves as nucleation sites for the hydration process to foster the formation of additional calcium silicate hydrates and increases the strength at early ages (Huesca-Tortosa et al., 2024). Consequently, carbonated steel slag (CSS) can be used as a supplementary cementitious material (SCM), providing both total valorization of steel slag and high reductions of $CO_2$ emissions (Humbert and Castro-Gomes, 2019). The mechanical performance of CSS in cementitious systems is determined by carbonation parameters, microstructural features and dosage levels (Huesca-Tortosa et al., 2024; Fang et al., 2022; Liang et

**Table 4.** Summary of carbonated steel slag (CSS) cement replacements performance and influences on concrete strength and workability properties

| Carbonated steel slag application as cement replacement | | | | | |
|---|---|---|---|---|---|
| Type of slag | Carbonation type and time | Replacement target | Results finding | $CO_2$ g/100 g of SS | Ref. |
| SS from BOF in China | Wet carbonation (4 hr) | 30% with mortar, 0.5 W/C with 90d cured | Carbonation increased compressive by 8.5% vs. uncarbonated slag. Retained ~85% of OPC strength (51.1 MPa), volume stability significantly improved. | 13.2 | Liu et al., 2023 |
| SS from BOF in China | Wet carbonation (4 hr) | 30% with paste, 0.3W/C with 90d cured | Carbonation increased strength by 19.5% vs. uncarbonated slag. Retained ~96% of OPC strength (129.4 MPa), volume expansion stabilized at 0.17%. | 13.2 | Liu et al., 2023 |
| SS provided by Eastran Company | Accelerated carbonation (30 hr) | 30% with paste, 0.28W/C with 90 day cured | Carbonation increased compressive strength by 15.4% vs. uncarbonated slag. Retaining ~87% of OPC, specific surface area increased 77.1%, volume expansion stabilized at 0.17%. | 6.14 | Liu et al., 2021 |
| SS provided by Eastran Company | Accelerated carbonation (30 hr) | 15%, 30% mortar, 0.5 W/C with 90 day cured | Strength increased 4.7% (at 15%) – 5.7% (at 30%) vs uncarbonated. Retained 87.5% (at 15%) & 74.6% (at 30%) of OPC strength. Retained 91.5% (at 15%) & 78.9% (at 30%) of OPC strength. | 6.14 | Liu et al., 2021 |
| SS from BOFS in China | Accelerated (high-gravity RPB) | 10% at mortar, 0.485 W/C with 90 day cured | Strength increased by 15.7% vs uncarbonated Retained 84.8% of OPC strength. Retained 98.2% of OPC strength (Almost equal to cement). | 2.03 for SS 20.3 for CSS | Pan et al., 2016 |
| SS from EAFS in China | Accelerated carbonation | 80% paste , 0.4 W/C with 90 day cured | Strength increased drastically by 155.6% (from 17.1 to 43.7 MPa). Achieved high strength (43.7 MPa) via microstructure densification & $CaCO_3$ pore filling. | 67.0 | Luo et al., 2023 |
| SS from LFS in China | Accelerated (high-gravity) (60 hr) | 5%, 10%, 15%, 20% mortar | Strength increased by 14.7% vs uncarbonated. At 28d, 5% replacement achieved the highest strength retention of 90.1% vs OPC. At 28d, 5% replacement achieved the highest strength, exceeding OPC by 3.4% (103.4% retention). | ----- | Chang et al., 2020 |

al., 2012). The direct use of untreated steel slag often restricts the mechanical strength, which is caused by its low hydration reactivity (Liu et al., 2023). In contrast, carbonation treatment increases compressive strength, matrix density and interfacial bonding (Pan et al., 2015). The summary of CSS cement replacements performance and influences on concrete strength and workability properties was presented in Table 4.

The enhanced strength of CSS is the combination of physical and chemical mechanisms (Liu et al., 2023). Physically, carbonation changes the structure of the slag with the formation of a porous textured surface with the formation of $CaCO_3$ and silica gel deposits which function as nucleation sites for cement hydrate formation. These features serve as nano-fillers between cement particles, which generates a denser matrix at the early stage of hydration (Pan et al., 2015; Liu et al., 2021). Chemically speaking, $CaCO_3$ reacts with tricalcium aluminate ($C_3A$) in cement to produce monocarbonaluminate, a denser and mechanically better phase than the sulfoaluminate phase. This reaction is strong and makes the bond between CSS particles and cement matrix stronger (Liu et al., 2023; Li et al., 2023; Thongsanitgarn et al., 2014), While the high $CO_2$ uptake may lead to the low early age compressive strength, it will greatly improve the mechanical performance of the long term (Liu et al. 2023). The high increased surface area of carbonated slag provides an increased water adsorption capacity which prolongs the setting time slightly, but provides a fast hydration as there are many $CaCO_3$ nucleation sites (Chen et al., 2016).

### Limitation of carbonated steel slag

Despite its obvious benefits, however, there are a number of limitations of steel slag carbonation that need careful attention and innovative solutions. The chemical composition of steel slags is by their very nature variable, and this creates significant complexity in the accurate modelling of dissolution kinetics. This heterogeneity of compositions makes the prediction of the carbonation behavior difficult and the development of advanced modelling techniques is required to capture the dynamic reactions involved (Ragipani et al., 2021). Furthermore, the relatively slow kinetics of carbonation at atmospheric conditions is a significant challenge that further studies are working on overcoming. For our purposes, increasing the reaction rate is crucial for increasing the efficiency of the process and making it industrially feasible. Understanding and quantifying the rate limiting mechanisms as well as the role of product layers in controlling the reaction kinetics are areas of active research (Ragipani et al., 2021). Although the indirect carbonation method has high conversion rates and alkaline earth ion leaching is favorable, it typically requires chemical reagents to boost the reaction speed, which also raises operational costs (Luo and He, 2021). In addition, carbonation of natural minerals and industrial by-products such as steel slag involve supplementary processes, including the extraction, transportation and grinding, which increases the energy demands and the overall costs (Wang et al., 2023). To establish the steel slag carbonation process as feasible large-scale technology, these challenges seem to be overcome by optimization of process parameters, energy efficiency analysis and comprehensive sustainability analysis. Life cycle assessment may give quantitative understanding of environmental impacts, but existing studies are still limited and preliminary in nature, and more systematic studies are needed.

## CONCLUSIONS

The present work gives an overview of the CSS process by showing its advantages and constraints. The results underscore its twin opportunities for waste valorization and $CO_2$ sequestration, although it needs to be acknowledged that much more research should be done to enhance economic viability and technical efficiency. Direct gas sold carbonation in which $CO_2$ gas reacts with solid oxides to produce stable carbonates is a relatively simple process but the reaction mechanisms depend on the composition of the feed, which is the oxide. Efforts to speed up carbonation (i.e. by increasing pressure, elevating temperature and/or by improving mixing, or by chemical additives) have shown promise but often come with increased energy use and thereby decreased sustainability. As a result, it is a critical yet difficult goal to optimize the carbonation process to achieve maximum efficiency with the least amount of energy input. Future research efforts should focus on improvement of carbonation parameters for large-scale application, improvement of reaction kinetics and assessment of the process through comprehensive environmental assessments. Ultimately, mineral carbonation of steel slag is a sustainable solution to climate change by facilitating $CO_2$ sequestration and circular resource utilisation. Despite the obstacles that persist, the large environmental and economic potential of this process makes it an interesting field to continue exploring as a scientist.

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