Review

Evaluation of Potential Factors Affecting Steel Slag Carbonation

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Abstract: Steel slag is a solid waste product generated during the carbonation stage of steelmaking. It has high levels of heavy metals and substantial amounts of free calcium and magnesium oxide, making it unsuitable for use as a cement material. Furthermore, the disposal of steel slag in landfills requires many resources and can seriously contaminate the surrounding environment. One method of reducing its negative environmental impact is carbonation, which involves reacting steel slag with carbon dioxide to form stable minerals. However, many parameters influence the carbonation efficiency of steelmaking slag, including temperature, time, particle size, pressure, CO_2 concentration, liquid-to-solid ratio, moisture content, humidity, additives, etc. To this end, this paper comprehensively reviews the most important steel slag carbonation-influencing factors. Moreover, it compares the characteristics from two perspectives based on their causes and effects on carbonation. Finally, this article reviews earlier studies to identify the factors that affect steel slag carbonation and the potential of carbonated steel slag as a sustainable construction material. Based on previous research, it systematically examines all the elements for future work that need to be improved.

Keywords: steel slag; accelerated carbonation; carbonation curing; steel slag carbonations' influencing factors
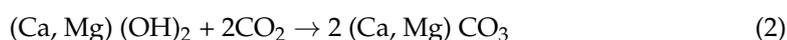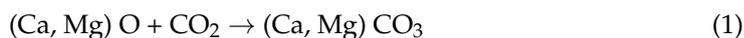
1. Introduction

Steel slag makes up approximately 15–20% of crude steel production and is a solid waste product generated during the steelmaking process [1,2]. In 2020, 160 Mt of steel slag was produced in China. However, only 30% of steel slag is used [3]. Most steel slags are stacked or landfilled, waste resources, and pollute the environment. Hydraulic components of steel slag include tricalcium (C_3S) and dicalcium (C_2S) silicates, which can cause a reaction with H_2O to generate calcium silicate hydrate (CSH). This shows that steel slag has properties that make it suitable for use in cement [4]. Because of its great mechanical efficiency and wear resistance, steel slag has significant advantages when used as an aggregate [5]. However, steel slag has insufficient hydration activity to compact during the first curing age [6].

Furthermore, the ability to recycle steel slag is restricted mainly due to two factors. Firstly, the hydration of steel slag occurs at a slow rate. Secondly, steel slag contains a significant quantity of free lime (f-CaO) and magnesium oxide (f-MgO), which can cause harmful expansion and instability in terms of volume [4,7–10]. In addition, in a humid environment, carbonation happens much faster than hydration. As carbonation of free oxide enhances the volume stability of the product, it is an effective method for overcoming these problems [8,9].

Global warming caused by greenhouse gas emissions has become a major concern recently. The cement industry [11,12] and the steel industry [13], due to their enormous

CO_2 emissions, cause global warming. Using waste from the steel industry, such as steel slag, to absorb CO_2 in steel industry exhaust gas to make suitable construction materials is an effective strategy to improve solid waste utilization, minimize carbon emissions, and decrease cement clinker consumption [5,8,14]. Carbonated structure resources are ecologically friendly and long-lasting (for instance, heavy metal fixation, pH neutral), long-lasting (i.e., corrosion-resistant, wear-resistance, and frost-thaw-resistant) [15,16].

The idea of CO_2 mineralized storage was proposed in 1990 by Seifritz et al. [17], a technique that mimics the natural weathering processes of rocks: CO_2 then reacts with oxides, hydroxides, silicate minerals, and solid waste containing Ca and Mg to form carbonates. Typical calcium-magnesium silicates are olivine (Mg_2SiO_4), serpentine ($Mg_3Si_2O_5(OH)_4$), wollastonite ($CaSiO_3$), etc. The simplified chemical reaction equation for CO_2 mineralized storage is as follows:

$$(Ca, Mg) O + CO_2 \rightarrow (Ca, Mg) CO_3 \tag{1}$$

$$(Ca, Mg) (OH)_2 + 2CO_2 \rightarrow 2 (Ca, Mg) CO_3 \tag{2}$$

$$(Ca, Mg) SiO_3 + 2CO_2 \rightarrow 2 (Ca, Mg) CO_3 + SiO_2 \tag{3}$$

CO_2 mineralized storage can be achieved in two ways: one is in-situ carbonation, that is, CO_2 is injected into the formation containing calcium-magnesium-based minerals; the second is ex-situ carbonation, that is, it is achieved in accelerated carbonization reactors in industrial processes.

Carbonated resources have been used commercially to create non-load-bearing constructions like prefabricated building walls, square blocks, flowerbeds, artificial reefs, and highways [18,19]. Due to the potential cost savings, a carbonation curing process was undertaken on steel slag that was of interest to the iron and steel processing industries [20]. Much research has been conducted to evaluate modern methods of carbonation curing for cement-based resources, including steel slag [21–23]. They all agreed that $CaCO_3$ and silicate hydraulic solutions are the most important for improving cement's mechanical characteristics and durability following carbonation curing. Li et al. [24] indicated that the CaO concentration of carbonation active minerals influenced the carbonation consolidation capability of steel slag tailings. Carbonated materials have a higher compressive strength than uncarbonated materials. This can be achieved by increasing the carbonation rate of steel slag. Some of the methods used to promote the carbonation rate of steel slag include enhancing pre-cast conditions (such as compacting pressure and water–solid ratio), curing conditions for carbonation (temperature, curing time, and moisture CO_2 partial pressure), and the pretreatment of steel slag (chemical, mechanical, and thermal activation) [19,25,26].

In addition to storing CO_2, steel slag carbonation produces carbonate compounds beneficial for increasing compressive strength, decreasing the CaO/MgO ratio, and enhancing durability. The improved quality of carbonated steel slag makes it suitable for various construction purposes. Earlier studies analyzed the critical aspects of steel slag carbonation and their influencing characteristics. For example, Song et al. [27] explore the different parameters that influence steel slag carbonation. A comprehensive range of influencing parameters, including temperature, pressure, CO_2 concentration, reaction time, moisture, steel slag particle size, additives, and gradation, are discussed as current developments using accelerated carbonation to enhance steel slag quality. Moreover, Humbert et al. [28] reviewed the ability to control factors, including temperature, carbon dioxide concentration, compacting pressure, humidity, partial pressure, carbonation time, and slag fineness, to influence the circumstances of the carbonation process. In addition, Chen et al. [29] reviewed the available works which consider three perspectives on the carbonation of steel-making slag: the mechanisms and processes involved, the impact of operational factors on carbon dioxide sequestration ratios and reactions, and the ability of various types of steel-making slag to sequester carbon dioxide.

Li et al. reviewed steel slag utilization and its environmental impact [30], with special emphasis on employing the life cycle assessment approach, which is a methical approach

to quantitatively evaluating environmental effectiveness. Wang et al., in addition, reviewed the development of steel slag in carbon dioxide sequestration [31]. Furthermore, the precipitation process of the dicalcium silicate phase in steel slag was examined by Na et al. [32].

Ragipani et al. [33] reviewed the carbonation process of steel slag, a solid waste with high calcium content generated by the iron and steel industries, highlighting that despite its potential, this waste is under-utilized in countries that are major crude steel producers. In this regard, this article provides an overview of the factors that affect steel slag carbonation. Likewise, it compares these influencing factors from various perspectives, such as the extent of their impact on the carbonation process. It compares how the carbonation of steel slag is influenced when the parameters that affect it increase or decrease. Finally, it summarizes existing studies on the influencing factors of steel slag carbonation.

2. Steel Slag

2.1. Steel Slag Production

Removing contaminants from molten steel in a steelmaking furnace creates a by-product known as steel slag. Three principal varieties of steel slag produced in steelmaking operations are (EAF) slag from the electric arc furnace, (BOF) slag from the basic oxygen furnace, and (LF) slag from the ladle furnace. EAF slag and BOF slag are generated during the initial stage of steel refinement [28]. BOF slag is created by combining waste metal, pig iron, and fluxes in a furnace and initiating an oxidation reaction with pure oxygen at approximately 1600 °C [34]. When heating steel, an EAF furnace uses three graphite electrodes coupled to an electric arc transformer rather than gaseous fuels like those used in a BOF slag furnace. The waste product of BOF and EAF's secondary metallurgical processes, carried out after the steel has been desulfurized in the ladle, is LF slag [35]. An EAF furnace is scaled down to become a ladle furnace. It is commonly known that ladle furnaces have a pipeline through which argon gases are pumped to agitate the liquid steel. A ladle furnace may also have an alloy hopper for creating various degrees of steel with selected alloys such as zinc (Zn), copper (Cu), and nickel (Ni) [30], as shown in Figure 1.
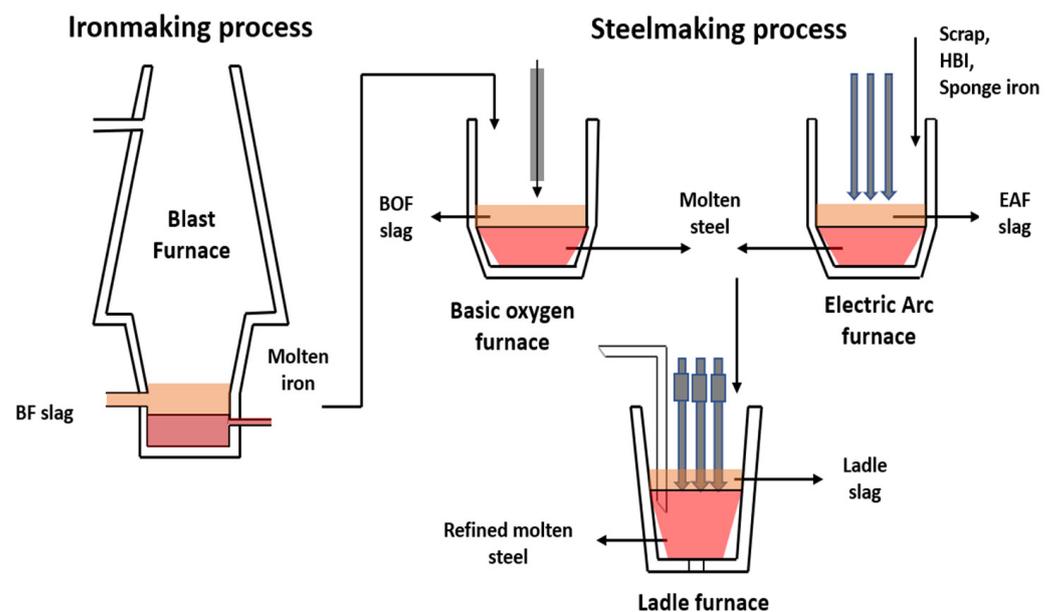

Figure 1. Generation of various slags from the steel industry.

2.2. The Composition of Steel Slag

The method of steel production (smelting technique) and its raw inputs and additives determine the quantity and quality of the associated steel slag [3]. Abundance quantity, chemical content, and mineral composition may all be influenced by the addition of lime,

and the amount is often determined by the CaO/SiO_2 ratio [36]. Steel slag is calciumsilicatic, with CaO levels ranging from 38 to 48% and SiO_2 levels ranging from 11 to 20%. Steel, FeO, and iron-bearing minerals make up the Fe in steel slag. These components can either be employed in the steelmaking process or magnetic separation to separate them from the steel slag for use in the sinter and blast furnaces. Furthermore, due to its high CaO, MgO, and MnO content, steel slag can reduce the costs of producing iron and steel by using it instead of dolomite, limestone, and manganese ore [3].

2.3. Steel Slag Treatment and Utilization

China is the world's largest steel producer. Steel slag production in China accounts for almost 50% of the world's total, and over 100 million tons are produced yearly [3]. However, only about 30% of steel slag is utilized in the country, leading to a significant accumulation. Therefore, there needs to be a better rate of steel slag usage. In addition to occupying valuable land resources, this phenomenon poses an important ecological threat [37,38]. Smelting slag storage in China is now subject to an environmental protection tax adopted in 2018 as part of a revision of the country's Environmental Protection Law [24].

Steel slag is a sound solid waste. It contains a massive quantity of slag steel and calcium oxide; available components such as iron and magnesium oxide are considered "misplaced resources". Japan's current steel slag efficiency utilization rate has reached about 98.4%. Germany presently has a practical use rate for steel slag above 90%. The utilization methods are civil construction, agricultural fertilizer, sintering, and blast furnaces. The current steel slag in the United States is more effective than the steel slag produced, with only 15.6% disposed of in landfills. The amount of steel slag in its principal applications (sintering and blast furnace reuse, road construction) accounts for the total amount of steel slag. It is known that eight major American railways use steel slag as railway slag [3].

3. Factors Affecting Steel Slag Carbonation

Due to their diverse properties, different steel slag types react differently to rapid carbonation. High carbonation rates, the rapid development of stable microstructures, and increased CO_2 sequestration levels all work together to carbonate steel slag effectively. Based on the micro-scale mechanisms of steel slag carbonation, calcium ion dissolution and CO_2 diffusion significantly impact carbonation efficiency [27].

Basic oxygen furnace slag (BOF), for example, in China, accounts for nearly 70 percent of the total steel slag produced [4]. CaO content is typically 40–60%, and MgO content is 2–10%. Consequently, it has an excess of cations capable of absorbing additional CO_2. Electric arc furnace slag (EAF) can be classified into two categories: oxidized EAF, which contains less CaO and higher iron oxide content, and reductive EAF, which has more CaO and lower iron oxide content [14]. There is a large variety in the chemical compositions of EAF. Hence, the accelerated carbonation law cannot be accurately defined. Compared to BOF and EAF, the secondary metallurgical process's waste residue, ladle furnace slag (LFS), has a greater CaO level and a lower concentration of iron field components [39]. Aside from how different steel slags vary in their mineral compositions, factors such as carbonation time, reaction temperature, CO_2 concentration, particle size, pressure, moisture content, humidity, additives, and more all influence how well the carbonation process works [27]. The following sections discuss different parameters that influence the carbonation behavior of several variations of steel slag, as presented in Figure 2.
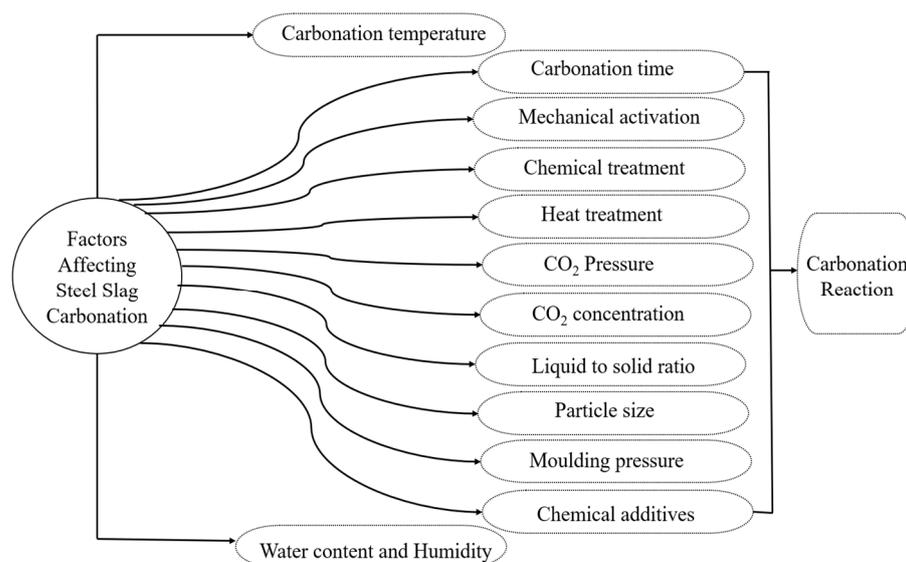
Figure 2. The influencing factors of steel slag carbonation.

3.1. Materials Pretreatment

3.1.1. Mechanical Activation

Mechanical activation, as a pretreatment method, has become a crucial factor affecting steel slag carbonation's efficiency. It plays a significant role in increasing the reactivity of the steel slag, thereby improving its carbonation performance. In a nutshell, mechanical activation refers to the process where high-energy milling methods are used to disrupt the structural order of the material, in this case, steel slag. This process results in new surfaces and defects, phase composition modification, crystallite size reduction, and in-duction of internal stresses. These changes significantly increase the surface area of the slag and its reactive sites, making it more accessible for carbon dioxide (CO_2) to react with and, as a result, enhance the overall carbonation process [40].

Considerable research has delved into the effects of mechanical activation on steel slag, focusing on augmenting its dissolution and carbonation rate [41,42] and improving its cementitious properties [43]. Particle size and specific surface area (Blaine number) are often used to measure mechanical activation's impact. According to Yadav and Mehra [42], smaller slag particle sizes can enhance carbonation. A similar observation was made by Humbert [26], who demonstrated that an increase in Blaine number from 125 to 529 m^2/kg led to a significant improvement in compressive strength, from 28.8 to 72.1 MPa, under identical carbonation curing conditions.

Multiple studies have suggested that optimal hydration in blended cement can be achieved when the Blaine number for steel slag is between 400 and 500 m^2/kg [44,45]. However, it is universally accepted that it is difficult to finely grind steel slag due to the RO phase [43]. Despite extensive milling, steel slag particle size may remain relatively high. Still, there could be potential alterations in the crystal structure of steel slag minerals, affecting subsequent chemical properties and applications [40]. Currently, only a few studies explore changes in the crystal structure of steel slag minerals due to mechanical activation [46] and the subsequent influence on the mechanical properties of steel slag during carbonation curing.

As for carbonation curing on steel slag, Li et al. [47] found that mechanical activation positively affects carbonation conversion and compression strength of carbonated BOF slag compacts. As grinding time increases, BOF slag passing size decreases and stabilizes while BET surface area increases and decreases. Upon grinding for 30 min, the particles of BOF slag aggregate and reach mechanical activation [48].

3.1.2. Chemical Treatment

The primary crystalline structures in steel slag are dictated mainly by its chemical makeup and the gradual cooling process used during its production [49]. Steel slag's key mineral constituents include C_3S, C_2S, magnesio-wustite, calcio-wustite, dicalcium alumino-ferrite ($Ca_2(Fe, Al, Ti)_2O_5$, and RO, with RO symbolizing a solid solution constituted by magnesium, iron, manganese oxides, and lime (CaO) [3]. An unstable steel slag's mineral content phase leads to volumetric instability [34,50]. This instability arises from free CaO and free MgO and the conversion of b-C_2S into c-C_2S. Free-CaO has the most significant impact on steel slag stability [51]. A considerable number of scientists have examined the process of CaO hydration. When submerged in water, condensed CaO can achieve near-complete hydration in just a few days, resulting in a volume expansion of 100% [3]. The lime, located within the heart of the steel slag, interacts with water and air to swiftly develop a hard, slender layer. However, hydrating the inner layer of the slag presents challenges, leading to a higher concentration of free CaO within the slag. This can render the slag unsafe for use in, for example, road or civil engineering projects [52]. As a result, it is crucial to establish an effective steel slag treatment process to transform it into usable material for various purposes.

3.1.3. Heat Treatment

Heat treatment significantly affects the steel slag carbonation process, primarily by altering the slag's physical and chemical properties. The heat-induced expansion increases the reactive surface area, promoting CO_2 adsorption [46]. Furthermore, heat can transform lower-reactivity mineral phases into more reactive ones, enhancing carbonation. Heat treatment produces dehydration, removing free and bound water molecules and additional reactive sites. At high temperatures, decarbonization can occur, potentially offering more sites for carbonation, albeit at high energy costs [53]. The solubility of silicate and aluminate phases may also increase due to heating, further facilitating carbonation. However, it is worth noting that excessive heat can cause sintering, reducing slag porosity and reactivity while influencing the crystalline structure and potentially hindering carbonation. Therefore, optimizing heat treatment parameters is vital for maximizing carbonation and minimizing negative impacts [54].

3.1.4. Particle Size

Particle size was discovered to play an important role in the process, significantly more crucial than the initial material's constituent composition [41]. According to [55], BOF slag particle size significantly affects the extent of carbonation. It was discovered that reducing the particle size increased the specific surface area of the slag and greatly improved the carbonation conversion. In addition, Han et al. [56] observed that smaller particles have more surface area on which carbonation can occur, increasing conversion. Particle size and specific surface area are the factors that impact the most on the kinetics of any material's dissolution. There is a relationship between the size and the leaching mechanism of a mineral particle that determines its reactive surface area. Grinding particles to achieve a specific particle size is common, but this process is energy-intensive. Therefore, determining the optimal particle size can help lower process costs and increase efficiency. The authors of [57,58] discovered that the extent of conversion increased from 24% to 74% by slurry carbonation of BOF slag. Furthermore, Santos et al. [55] reported that particle size was the most significant determinant of CO_2 uptake in a pressurized basket reactor when investigating the direct carbonation of BOF slag. In the case of a particle size of 0.08 mm, the free lime conversion extent increased from 8% to 43% when the particle size was decreased from 1.6 mm to 0.08 mm. Baciocchi et al. [59] indicated that particle size, particularly the particle's specific surface temperature rise, also had a favorable effect, resulting in a maximum uptake of 130 g CO_2/kg slag. In their opinion, particles should have an average size of fewer than 150 micrometers.

3.1.5. Additives

Steel slag's hydration activity is usually relatively low. Thus, chemical additives have been frequently employed to accelerate steel slag activity while increasing carbonation levels. For example, the carbonation degree was studied after 20% of steel slag (possibly BOF) was replaced by Portland cement [60]. The BSE images showed that compared with the pure steel slag, the 20% Portland cement incorporated steel slag contained more $CaCO_3$ and displayed a higher strength (63% higher than that of the pure steel slag) after carbonation. The additional Portland cement offered calcium sources for carbonation, resulting in increased $CaCO_3$ production and a denser microstructure. Concrete made with steel slag generally performed satisfactorily with additives at a particular level at an early age. In contrast, concrete cured for 28 days or more performed well. Although steel slag cement outperformed Portland cement in terms of durability and chemical properties, the alkali reaction was reduced [61,62]. The carbonation of BOF was also investigated using phosphogypsum, sodium sulfate, and sodium carbonate [63]. The strength of the BOF specimens generally increased initially and then reduced when the additive concentration was steadily raised. The carbonation activity of phosphogypsum was the greatest of the three additions, directly enhancing the carbonization ability of BOF. By creating an alkaline environment, sodium carbonate enhances BOF hydration. As a result, sodium carbonate improved the strength of the carbonated BOF through the combined effects of carbonation and hydration. Sodium sulfate, on the other hand, aided the entire rapid carbonation process by boosting BOF hydration. Steel slag hydration performance can be improved by modifying its microstructure with additives. It is also possible to employ the additives as a material with a high CO_2 absorption capacity or high carbonation reaction activity to speed up the carbonation process of steel slag [27].

3.2. Molding Conditions

3.2.1. Liquid-to-Solid Ratio

In the process of aqueous carbonation, Veetil and Hitch [62] found a direct correlation between water consumption and the degree of carbonation in steel slag. As the amount of water increased, calcium ions and CO2 dissolution also rose, leading to an increased carbonation level in the steel slag. In a related study, Huijgen et al. [57] carried out aqueous carbonation of electric arc furnace slag (EAF) in an autoclave reactor. They discovered that the CO_2 conversion rate improved when the liquid–solid ratio (L/S) was reduced if it was above 2.

However, when the L/S ratio fell below 2, achieving full stirring of the EAF within the autoclave reactor was impossible. This condition resulted in inadequate contact between the CO_2 and calcium ions, decreasing the carbonation degree. Concurrently, it was observed that higher carbonation efficiency and degree could be obtained with a larger L/S ratio. In this context, as the carbonated specimen underwent constant stirring by water, the calcium ions (Ca^{2+}) leaching process was pivotal in influencing the aqueous carbonation process. Therefore, in contrast to dry carbonation, the blockage of pores caused by excess water, which generally results in a reduced carbonation degree, did not present a significant problem in aqueous carbonation [9].

Contrary to the abovementioned studies, Baciocchi et al. [59] found a higher optimum L/S ratio for carbon sequestration. They did not detect any hydrated compounds in their findings, leading to the inference that a portion of the water participated in the hydration reaction of the silicates and oxides present in the EAF rather than being utilized for the dissolution of CO_2 and leaching of calcium ions.

In certain regards, in the carbonation of steelmaking slag, the L/S ratio is more essential than temperature and CO_2 pressure [64]. When the L/S ratio is less than optimal, steelmaking slag and water do not mix well, affecting CO_2 and calcium mass transfer efficiency in the gas–liquid–solid phase [57,65]. The amount of steel slag used in a given number of aqueous media (mass/mass) defines the liquid-to-solid ratio. Rushendra et al. [66] reported that carbonation efficiency increased when the L/S ratio decreased. The results demonstrate

that increasing L/S from 5 to 10 g/g improves steel slag carbonation. The carbonation degree of steel slag decreases as the L/S ratio rises. This is due to excess liquid, which causes the calcium ion concentration in the aqueous medium to be diluted [67]. Similarly, as the L/S ratio climbed from 2 to 10, The capacity of slag water slurry to sequester carbon increased and then decreased. This is because a large amount of water inside the reactor prevents gas molecules from diffusing through the slurry [66]. However, it is critical to note that when the L/S ratio exceeds the ideal value, one of the possible causes may be (1) too much water in the system, which inhibits the mass transfer [68], and (2) in the liquid phase, lowered calcium ion concentration and ionic strength are caused by a high L/S ratio [31]. As a result, the chemical potential for carbonation has a lower driving force [69], and (3) low supersaturation at high L/S ratios is not the only cause of carbonate precipitation [70]. Li et al. [48] found that in carbonated tailings—steel slag compacts, high water–solid ratios favor long-term (12 h) carbonation reactions and long-term strength growth while inhibiting short-term (1–3 h) carbonation reactions and early strength development.

3.2.2. Molding Pressure

The extent of carbonation efficiency in a steel slag specimen is significantly influenced by its initial forming pressure. Increasing this pressure reduces the distance between individual steel slag particles, creating a denser structure. This high density, in turn, enhances the specimen's compressive strength as the close-knit structure provides higher resistance to external forces. However, while this increase in forming pressure contributes positively to compressive strength, it simultaneously poses a challenge. This is particularly apparent regarding the diffusion of carbon dioxide, or CO_2, into the specimen's interior regions. As the particle spaces in the specimen diminish, the diffusion pathway for CO_2 becomes narrower and more complex. This leads to a situation where the gas encounters difficulty permeating the complete structure, causing incomplete carbonation of the steel slag specimen. This results in a paradoxical situation where an excessive initial molding pressure, despite its beneficial impact on the compressive strength of the specimen, proves to be counterproductive for the overall strength development of the carbonated steel slag specimen. The reason is that incomplete carbonation significantly hampers the specimen's strength properties. Therefore, careful consideration must be given to the initial forming pressure applied, ensuring it balances compressive strength and the degree of carbonation. A harmonious balance will contribute to optimizing the strength development of the carbonated steel slag specimen [27].

3.3. Carbonation Conditions

3.3.1. Carbonation Temperature

Steel slag carbonation is influenced by the temperature at which it is carbonated. The CO_2 solubility and the rate of slag dissolution in aqueous carbonation are considerably affected by temperature. Furthermore, the carbonation temperature field strongly influences the carbonation crystallization products' crystallization and cell unit development rate and their microscopic morphology [71]. Increased temperature and improved carbonation reaction were observed with three different particle sizes of BOF carbonation (3.5–7 mm, 7–15 mm, and 15–25 mm), although decreased water-solubility of CO_2 was discovered [72]. However, increasing the temperature to over 200 °C caused the carbonation rate to slow down. As a result, 200 °C was found to be the ideal carbonation temperature in their investigation. Similar results were observed in a different study, with 200 °C being the ideal temperature for EAF carbonation. Raising the temperature improved the mineral dissolution [27]. The reaction temperature for dry carbonation is often higher than aqueous carbonation [73]. According to [74], the reaction temperature has a big impact on carbonation efficiency in suspended steel slag with high partial pressures of CO_2. They found that the carbonation efficiency increases from 46 to 70% when the temperature goes from 50 to 200 °C. Alternatively, steel slag is often compressed at low water-to-solid ratios and cured at low partial pressures of CO_2 when used as a building material [75]. In this case,

the possibility that the greater curing temperature will still favor carbonation development is unclear [76].

Liu et al. [77] discovered that high-temperature curing can improve the early hydration rate. However, if the hydration rate is too quick, huge holes in the hardened paste could be easily introduced, resulting in more cracks. Curing at high temperatures can also suppress the later hydration reaction, resulting in a lower cementitious material hydration degree than conventional curing. As a result, carbonation curing can have negative impacts on material characteristics. Luo et al. [76] also found that in the short-term curing stage, in addition to promoting faster carbonation, increasing the curing temperature also improves compressive strength and carbon dioxide absorption. However, a high temperature (90 °C) does not allow for additional degrees of carbonation in the future.

Consequently, rapid carbonation of the surface of the steel slag and CO_2 infiltration into holes within the slag play a significant role in preventing fast carbonation. It is recommended that the temperature of the reaction be increased at first to accelerate the surface reaction and increase carbonation. However, as the temperature rises due to the combined effects of CO_2 concentrations and humidity, the internal diffusion rate of CO_2 slows, which decreases the degree of carbonation [27]. The reaction temperature impacts the position of calcium carbonate formation. During low-temperature conditions, most $CaCO_3$ precipitates on the surface of solid and liquid slag due to the high concentration of dissolved CO_2. In contrast, at high temperatures, high concentrations of calcium dissolved in the liquid phase favor the precipitation of $CaCO_3$ during the interaction between gas and water [71], as shown in Figure 3.
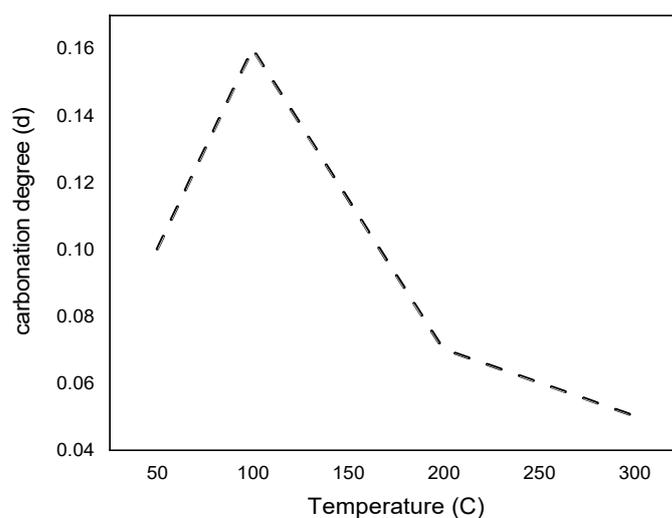

Figure 3. Relationship between carbonation degree (d) and curing temperature (C) [78].

3.3.2. Carbonation Time

The carbonation time greatly influences the carbonation depth and the steel slag strength. The carbonation of steel-making slag is influenced by the reaction time, an important element and economic indication. As a result of the formation of calcium carbonate, the CO_2 sequestration capability of steel-making slag increases as the reaction time increases [79]. Carbonation is rapid initially but decreases as the reaction time increases, eventually reaching equilibrium [29]. Huijgen et al. [57] found that carbonating the steel slag (perhaps EAF) for a longer time resulted in higher carbonation degrees.

Furthermore, the carbon fixation response was quicker initially and gradually stabilized as it progressed (40% of the calcium was carbonated in the first 2 min, with just 13% more calcium reacting throughout the next 30 min). Although rapid carbonation created a compact structure, some interior sections of the BOF concrete specimen remained uncarbonated after a long carbonation period. All types of steel slags commonly exhibit

a low degree of carbonation response. For instance, the resulting $CaCO_3$ particles may obstruct the specimen's pores and significantly impede the CO_3 diffusion [27].

Wei et al. [58] found that with increased carbonation duration, the carbonation process in steel slag-desulfurization gypsum accelerates, and the reaction eventually approaches equilibrium. For the time being, extending the carbonation process of steel slag does not significantly impact the carbonation effect. Overusing machinery and equipment can lead to the loss of resources. The best carbonation time was discovered to be 12 h. The reaction time can also represent the effect of other conditions (such as temperature, pressure, etc.) on the degree of efficiency of steel slag carbonation. For example, the carbonation degree of EAF slag was identical in the early stages under the combined influence of temperature and CO_2 concentration. However, as the carbonation period rose, the carbonation degree disparity steadily increased [27].

A key indicator of a reactive economy is reaction time. At 80 °C, the impact of reaction time was examined for 10, 20, 30, 60, 90, and 120 min with respective alkali to slag ratios of 0% and 4 wt%. Figure 4 shows that the slag's ability to sequester CO_2 increased when the reaction time grew. This was due primarily to the formation of $CaCO_3$ [79].
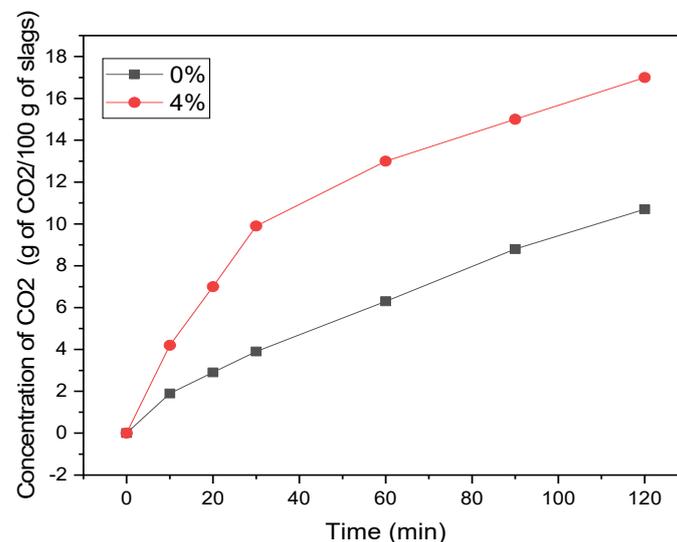

Figure 4. Effect of reaction time [79].

3.3.3. CO$_2$ Pressure

Several previous studies have demonstrated that CO_2 pressure significantly affects the carbonation of steelmaking slag. The pressure of CO_2 has a positive effect [49] but an insignificant impact on carbonation [59], which can potentially negatively affect the carbonation reaction [29]. According to Henry's law, CO_2 gas solubility increases with pressure at a constant temperature. As a result, as the pressure rises, the number of CO_2 molecules involved in the carbonation process will increase. In the same conditions (50 °C, L/S = 1), 10, 50, 100, and 150 bar pressures were tested on the CO_2 uptake [56]. Likewise, Henry's law says a linear relationship exists between the partial pressure of CO_2 above a solution and the concentration of CO_2 dissolved in it. As a result, high CO_2 pressure might hasten the carbonation process. If CO_2 dissolution is the limiting process, CO_2 pressure will not be a big deal. However, if calcium extraction is the limiting process, CO_2 pressure will be noticeable [57].

For 10 and 150 bars, the carbonation conversion was 21% and 50.2%, respectively. Ibrahim et al. [80] reported that a higher CO_2 partial pressure made more CO_2 soluble in aqueous solutions. This resulted in the creation of carbonic acid and, as a result, an increase in the formation of bicarbonate ions. Due to the increased reaction between bicarbonates and calcium ions, more bicarbonates react. Ghacham et al. [74] found that a high enough CO_2 pressure would result in exponential carbonation rates and degrees.

Furthermore, high pressure causes the reaction time to be shorter, resulting in a shorter carbonation time [81]. In conclusion, the carbonation reaction will proceed more quickly with higher CO_2 pressure and concentration under relatively mild conditions. However, at excessively high CO_2 concentrations or pressures, carbonates precipitate more quickly and cover the steel slag surface with protective carbonate layers, negatively lowering the carbonation degree. The complex metal compounds in the steel slag may function as catalysts during the carbonation reaction, even at relatively low CO_2 concentrations (which still exceeds the concentration of natural CO_2).

3.3.4. CO_2 Concentration

CO_2 diffusion and dissolving rates in steel slag directly and significantly influence the carbonation rate. Using pH change to determine the carbonation level, Ko et al. [72] found that when CO_2 concentration increased, the carbonation degree of BOF dropped. This study had a low CO_2 concentration (below 50%), so the results may be meaningless. Yu et al. [73] found that decreasing CO_2 concentrations increases the carbonization reaction rate. Regarding steel slag type, EAF steel slag outperforms BOF steel slag regarding reactivity and Ca use. Radenović et al. [35] explored the difference in the carbonation degree between stainless EAF with a lower CO_2 pressure (1.5 bar) and a higher CO_2 concentration (5% to 100%). According to the literature, a higher CO_2 level initially led to a quicker carbonation reaction rate. However, increasing the carbonation period at a lower CO_2 concentration led to the same or even higher CO_2 absorption rate than at a higher CO_2 concentration. Wang et al. [37] investigated the effect of CO_2 concentration on BOF and EAF carbonation. Their study found that CO_2 sequestration did not increase with CO_2 concentration. The lowest Ca utilization was observed when CO_2 concentrations were set at 50% for these two types of steel slags. The Ca consumption rate increased at a CO_2 concentration of 10% or 75%, which was surprising. In addition, Prigiobbe et al. [82] found that the greatest Ca conversion was obtained at a CO2 concentration of 10% at 400 °C and 450 °C.

3.3.5. Moisture Content and Humidity

Ko et al. [72] pioneered a new aqueous carbonation technology that used a stainless-steel rotary kiln to accelerate carbonation. In this procedure, CO_2, air, and gaseous water were mixed in a rotating kiln to expand the contact area between CO_2 and BOF. The relative humidity also influenced the carbonation in the rotary kiln. The reduction in pH value was utilized to represent the carbonation reaction's decline. Carbonation grew progressively as the relative humidity (RH) increased from 0 to 60% but then dropped as the RH went to 80%. This was because too much water tends to clog the pores on the surface of solids, restricting CO_2 penetration to a greater depth. Previous research has shown that a low moisture concentration lowers CO_2 and calcium ion dissolution. Contrarily, a high moisture level clogs the steel slag's pores and prevents CO_2 diffusion. Both are incompatible with rapid carbonation. For this reason, identifying a suitable moisture content in the carbonation process is the key to efficient and cost-effective carbonation [27].

3.4. Other Effects

The carbonation of steel slag is a complex process that numerous variables affect. Aside from the considerations, the pH of the environment significantly impacts steel slag carbonation by influencing the solubility of calcium ions. Bonenfant et al. [83] found that a high calcium hydroxide content and high alkalinity boosted the possibility of CO_2 sequestration. A two-stage reactor with high and low fluid flow chambers was used to test temperature, fluid flow, and reaction gradient on BOF carbonation. BOF dissolution and $CaCO_3$ precipitation happened simultaneously in a single circulation system. As a result, the carbonation stages were reduced to increase carbonation efficiency while remaining cost-effective. As a result of the forming pressure applied to the specimen of steel slag, the carbonization efficiency is also affected. However, CO_2 diffusion into the interior

regions of the sample becomes problematic, resulting in partial carbonation. The excessive initial molding pressure field affects carbonated steel slag specimen strength [27]. Furthermore, the fluid flux impacts the carbonation reaction [84]. Many elements may interact in real-world settings to affect the carbonation of steel slag in a more sophisticated fashion. Therefore, we must research how different influencing factors combine to affect steel slag's carbonation response. However, separating distinct components and determining their relative contributions to the carbonation reaction is challenging.

4. Comparison between the Influencing Factors

In many aspects, the carbonation process is affected by factors that influence the carbonation reaction. One of these aspects is the impact strength on the carbonation process and the factors that contribute to it. As a result, the contributing factors have different effects on the process. Moreover, influencing factors' impact can be linked. For example, several factors affect the relative humidity (RH) in the space where carbonation curing occurs, such as temperature and CO_2 concentration [85]. Table 1 below compares the influencing factors regarding impact strength.

Table 1. Comparison between the influencing factors of steel slag carbonation in terms of the strength of the effect on the carbonation reaction.

Factor	Level	Effect	Ref.
Carbonation temperature	Increase	Facilitated CO_2 diffusion, which improved the steel slag's carbonation response and mechanical properties.	[86]
Carbonation time	Increase	The CO_2 sequestration capability of steelmaking slag increases as the reaction time increases.	[79]
Particle size	-	The ability to absorb CO_2 is largely dependent on the particle size of steel slag.	[59]
		In the liquid phase, calcium ion concentration is more sensitive to particle size than other mineral ions; this impact is amplified at higher S/L ratios.	[87]
CO_2 pressure	Decrease Increase	An important factor in influencing the ability of porous carbon compounds to absorb CO_2. The proportional contribution of pressure decreased.	[88]
CO_2 Concentration	Decrease	Reduced CO_2 pressure affects carbonation in EAFs. CO_2 content speeds up the first phase of carbonation. Lower CO_2 needs a longer time for equivalent or greater CO_2 absorption.	[71]
Liquid-to-solid ratio	Decrease Increase	A reduced L/S ratio improves carbonation efficiency. Higher L/S decreases carbonation due to a drop in calcium ions.	[80] [67]
Moisture content and humidity	Decrease Increase	Low moisture concentration reduces CO_2 and calcium ion dissolution. Excessive moisture clogs steel slag pores, hindering CO_2 diffusion.	[27]
Additives	Increase	Adding chemicals to steel slag improves microstructure, promotes hydration, and speeds up carbonation.	[27]
Other effects	Increase -	pH affects calcium ion solubility. High alkalinity and calcium hydroxide increase CO_2 sequestration potential. Furthermore, the fluid flux has an impact on the carbonation reaction.	[83] [84]

The authors searched databases like the Web of Science, Google Scholar, Science Direct, and Springer to obtain the related studies for this review article. The authors used the following keywords: steel slag, carbonation curing, and the influencing factors

on steel slag carbonation. We arranged the literature in Tables 1 and 2 based on the following classifications according to the factors' impact strength and the variety of steel slag carbonation behavior when the influencing factors are increased or decreased.

Table 2. Comparison between the influencing factors of steel slag carbonation when the influencing factors are increased or decreased.

Factor	Level	The Carbonation Behavior	Ref.
Carbonation temperature	High	Ca leaching	[89,90]
	Low	Restrict Ca	[91,92]
Carbonation time	Increase	The CO_2 sequestration capability of steelmaking slag increases	[79]
	Decrease	Carbonation occurs rapidly at first but slows as reaction time increases, eventually reaching equilibrium.	[93]
Particle size	Increase	Carbonation reaction slowed down with increasing grain size in stainless EAF of four grain sizes.	[59]
	Decrease	A higher conversion rate.	[80]
Pressure	High	The carbonation process can be enhanced by high CO_2 pressure.	[57]
	low pressure	Influencing the ability of porous carbon compounds to absorb CO_2. Moreover, shorter reaction times have been found as CO_2 partial pressure is increased.	[9]
CO_2 Concentration	Increase Decrease	Has no positive effect on Ca use. The reaction rate of carbonation increases, and higher Ca use rates occur.	[73]
Liquid-to-solid ratio	Increase	Improves the solution's ability to precipitate magnesium and calcium.	[94]
	Decrease	Can have a negative effect on the reaction rate, although a higher solvent concentration can offset the impact of a decreased L/S ratio on the reaction rate.	[95]
Moisture content and humidity	Increase Decrease	Carbonation increased with increasing relative humidity from 0 to 60% but decreased after 80%. Low moisture reduces CO_2 and calcium ion dissolution. Excess moisture clogs steel slag pores, negatively affecting CO_2 diffusion.	[27]
Additives	Increase	The strength of the BOF specimens initially increased and subsequently dropped.	[27]
Other effects	Increase	The capacity for CO_2 sequestration was boosted by high alkalinity and a high calcium hydroxide concentration.	[83]

Thus, influencing factors affect carbonation reactions differently during the carbonation process. In addition, it continuously affects carbonation behavior. The influencing factors on steel slag carbonation when increasing or decreasing and how carbonation will behave during this process are shown in the table below.

5. Ongoing Developments in Steel Slag Carbonation for Building Materials

Many studies have investigated different aspects related to steel slag carbonation influencing factors. These studies helped reach several concepts and, to some extent, led to an understanding of this scientific process. However, this process is complex and still needs further investigation. In Table 3 below, we summarize various studies that have investigated different aspects related to the influencing factors on steel slag carbonation.

Table 3. Selected previous reviews related to the influencing factors on steel slag carbonation.

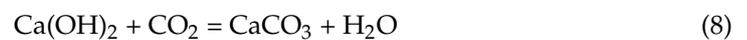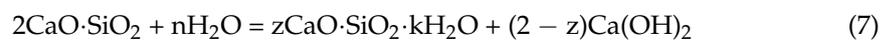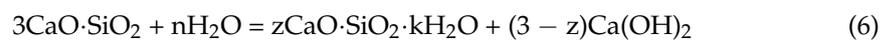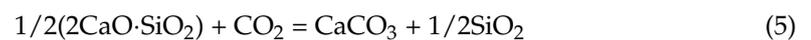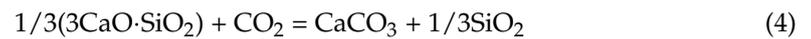| Main Topic	Review Approach	Year	Ref.
Using steel slag as a sustainable building material	Reviewed factors, including a variety of influencing factors, as well as a wide range of other factors, discussed in conjunction with new advancements in accelerated carbonation for enhancing steel slag quality.	2021	[27]
Carbonation of steelmaking slag presents an opportunity for carbon-neutral	This review focuses on the carbonation mechanisms and processes of steelmaking slag, as well as how operational factors affect the ratio and pace of carbon dioxide sequestration.	2021	[29]
Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites	Reviewed the carbonation-cured cement-based composites with fibers as well as the process and reaction processes, optimization of carbonation curing, mechanical properties, microstructure, and durability.	2021	[23]
CO_2-activated steel slag-based materials	Reviewed the ability to control factors, including temperature, carbon dioxide concentration, compacting pressure, humidity, partial pressure, carbonation time, and slag fineness, to influence the circumstances of carbonation.	2019	[28]
Environmental benefit assessment of steel slag utilization and carbonation	Reviewed the utilization of steel slag and its environmental impact	2022	[30]
The application of steel slag in CO_2 fixation	Reviewed the development of steel slag in carbon dioxide sequestration	2021	[31]
Hydration activity and carbonation characteristics of dicalcium silicate in steel slag	Reviewed the precipitation process of the dicalcium silicate phase in steel slag	2021	[32]
Steel slag valorization via mineral carbonation	Reviewed the carbonation process of steel slag, a solid waste with high calcium content generated by the iron and steel industries. Despite its potential, this waste is underutilized in countries that are major producers of crude steel.	2021	[33]

Moreover, Song et al. [27] reviewed the different parameters that affect steel slag carbonation. In the context of numerous influencing factors, it also emphasizes current developments in the application of rapid carbonation to enhance the quality of steel slag. In [29] Chen et al.'s study, they discussed three topics: the mechanisms and processes involved in the carbonation of steelmaking slag, the impact of operational factors on the ratio and response rate of carbon dioxide sequestration, and the ability of various types of steelmaking slag to sequester carbon dioxide. Liu et al. [23] reviewed and focused on (1) the optimization of carbonation curing processes for high CO_2 sequestration rates without sacrificing mechanical strength and durability and (2) the effects of carbonation curing on various aspects of durability and the mechanisms involved. Humbert et al. [28] controlled variables such as temperature, humidity, carbon dioxide concentration, partial pressure, compacting pressure, slag fineness, and carbonation duration to study the effects of carbonation conditions.

In recent times, there has been a significant advancement in carbon curing techniques applied to alkaline industrial by-products for the dual purposes of constructing materials and capturing CO_2. Earlier studies indicated that factors (i.e., CO_2 concentration and pressure, temperature, relative humidity, duration of the reaction, water-to-solid mass ratio, additives, and the granularity of the carbon-capturing material) play a role in the carbon-curing process [27]. Due to the high reactivity of these wastes and to conserve energy, most experiments are conducted at room temperature. The key materials used in

CO$_2$ capture include recycled concrete aggregates [96], blast furnace slag [97], fly ash [98], and steel waste [19]. Most of these studies have shown that carbon curing can bolster the strength of these materials and increase their environmental resilience [99].

6. Executive Summary

Wei et al. [58] studied the carbonation reactions, particularly concerning liquid–solid ratios, carbonation times, and cured methods. Therefore, the study showed increased carbonation efficiency and CaCO$_3$ generation (5%) when the curing process includes hydration before carbonation.

$$1/3(3CaO \cdot SiO_2) + CO_2 = CaCO_3 + 1/3SiO_2 \tag{4}$$

$$1/2(2CaO \cdot SiO_2) + CO_2 = CaCO_3 + 1/2SiO_2 \tag{5}$$

$$3CaO \cdot SiO_2 + nH_2O = zCaO \cdot SiO_2 \cdot kH_2O + (3 - z)Ca(OH)_2 \tag{6}$$

$$2CaO \cdot SiO_2 + nH_2O = zCaO \cdot SiO_2 \cdot kH_2O + (2 - z)Ca(OH)_2 \tag{7}$$

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \tag{8}$$

$$12CaO \cdot 7Al_2O_3 + 3CaSO_4 \cdot 2H_2O + 53H_2O = 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O + 3Al_2O_3 \cdot 3H_2O + 3(3CaO \cdot Al_2O_3 \cdot 6H_2O) \tag{9}$$

$$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O + 3CO_2 = 3CaCO_3 + 3CaSO_4 \cdot 2H_2O + Al_2O_3 \cdot xH_2O + (26 - x)H_2O \tag{10}$$

Moreover, Humbert et al. [100] investigated the influence of partial pressure and temperature on the carbonation reaction to achieve optimal conditions for the mechanical properties of the carbon dioxide-activated binder, and the findings discovered that 60 °C and 97.4 MPa were ideal for the carbonation reaction; pressure affects compressive strength (128.1 MPa at 2.5 bars), minimal increase beyond 2 MPa. In addition, Luo et al. [76] investigated how curing temperature affected the carbonation behavior of prefabricated products made from compacted steel slag. According to the results, increasing curing temperature benefits compressive strength and CO$_2$ absorption of steel slag compacts; 0 °C and 90 °C result in lower strength and CO$_2$ absorption than intermediate temperatures (30 °C and 60 °C) as curing time increases. Moreover, Polettini et al. [41] presented an in-depth analysis of the influence of particle size distribution on carbon sequestration. The result shows that the CO$_2$ absorption varies by two orders of magnitude based on particle size (from 0.47 percent to 46.5 percent). Furthermore, Zhong et al. [86] use parametric analysis to identify the dominant and interplaying effects of temperature, carbonation time, and CO$_2$ pressure on the compressive strength, mineralogy, calcium conversion, and microstructure of carbonated steel slag blocks. The results show that temperature and CO$_2$ pressure affect strength development and Ca conversion differently. Strength development and Ca conversion were aided by a mild increase in the first 30 min. Furthermore, Ma et al. [101] attempted to determine how different reaction parameters, such as solid-to-liquid ratio, CO$_2$ flow rate, temperature, water volume, and carbonation time, affect the effective CO$_2$ sequestration of basic oxygen furnace slag (BOF) aqueous carbonation. The findings showed that adding a modest amount of carbonated BOF (10–20%) accelerates early heat development in cement paste, and a higher carbonated BOF ratio decreases total heat of hydration and mechanical strength. Moreover, Huijgen et al. [57] present alkaline Ca-rich industrial residues as a possible feedstock for mineral CO$_2$ sequestration in their study. The findings show that 74% carbonation of calcium content was achieved at 19 bar CO$_2$ pressure, 100 °C, and 38 m particle size in 30 min. The reaction rate was affected by temperature (25–225 °C) and particle size (2–38 m). Chang et al. [93] assessed the performance of the carbonation process on operational conditions, such as the kind of steelmaking slag, reaction temperature, reaction time, and CO$_2$ flow rate. Moreover, the results show that due to its greater BET surface area than UF, FA, and BHC slags, BOF slag exhibited the maximum carbonation conversion at 72 percent at 1 h, 101 kPa, and

60 °C. Furthermore, Humbert et al. [26] determined the optimal reaction conditions for steel slag carbon dioxide-cured binders by varying slag fineness, water content, compacting pressure, CO_2 partial pressure, chamber temperature, and carbonation duration to achieve compressive strengths greater than 150 MPa. The findings indicate that steel slag is 76% stronger than CO_2-cured Portland cement, has a low environmental impact, and is a potential replacement for Portland cement. In addition, Baciocchi et al. [59] studied four particle sizes to see how they react to accelerated carbonation. The findings indicate that the process kinetics took 2 h at a CO_2 pressure of 3 bar and a liquid-to-solid ratio of 0.4, with the temperature being the major factor for CO_2 uptake due to its effect on silicate dissolution. Moreover, Wei et al. [102] explored the maximal calcium conversion (50.4%, 15.9 g CO_2/100 g slag) and decalcification rate (87.1%) at 80 °C, 10 L/kg, 60 min—high correlation (0.94 and 0.98) between calcium conversion and decalcification rate as per Aspen simulation. Furthermore, Li et al. [103] compared the effects of carbonation temperature, CO_2 pressure, and duration on the mechanical characteristics and carbonation efficacy of EAF and BOF-pressed blocks, focusing on how well these materials function at high temperatures. The results show that steel slag block strength increases with heat exposure up to 400 °C, and residual strength remains higher than at room temperature (20 degrees Celsius) after 600 °C exposure. Furthermore, Nielsen et al. [71] investigated how CO_2 uptake and strength development were impacted by moisture content, CO_2 concentration, temperature, and exposure period. The results show that CO_2 absorption is linked to monolith compressive strength, with temperature impacting the strength–CO_2 uptake connection—maximum CO_2 uptake at 60 °C, with lower compressive strength, compared to lower temperature trials. Moreover, Polettini et al. [104] performed a comprehensive investigation of the carbonation performance of the slag, as well as changes in particle size and mineralogy. Experiments showed operating parameters affecting 6.7–53.6 g CO_2/100 g slag range, with the notable highest carbonation performance under gentle conditions. In addition, Liu et al. [77] investigated the impact of curing conditions on the mechanical properties of steel slag cement-binding materials using higher temperatures and carbonation curing. According to the findings, the best results were achieved through curing at 60 °C with 7 h of carbonization, resulting in higher flexural compressive strengths. Moreover, Ragipani et al. [33] studied the reaction mechanisms of ground steel slag carbonated in aqueous solutions. Several variables were carefully altered to investigate their effects on carbonation rate, including particle size, temperature, carbon dioxide pressure, and reaction time. Furthermore, Shen et al. [63] illustrate that a parametric analysis was conducted to highlight the influence of temperature and carbonation time on carbonated steel slag block compressive strength, CO_2 pressure, calcium conversion, mineralogy, and microstructure.

Li et al. [47] investigated the effects of mechanically activating BOF slag and its impact on subsequent carbonation curing. The investigation shows that the 24 h carbonation of BOF slag is not improved with mechanical activation. A high water–solid ratio enhances compressive strength through activation. Moreover, Li et al. [20] investigated market stakeholders in China for the deployment of steel slag carbonation curing. The investigations show that the carbonation curing of steel slag is superior in quality, efficiency, cost-effectiveness, and carbon reduction compared to alternatives. Furthermore, Zod et al. [105] found that slag-bonded strand boards can be made utilizing carbonation curing to improve their mechanical and physical properties. To study the viability of employing steel slag as the sole binder, the results show that carbonation curing shortens production time, stimulates latent-C_2S, improves dimensional stability, and sequestrates 10.8% CO_2 by dry slag mass. In Li et al. [48], using orthogonal testing, their research improves carbonated tailings—steel slag material preparation conditions. Results show factors affecting compressive strength slag/tailings ratio, carbonation time, grinding time, and water-solid ratio (most to least significant). A high water–solid ratio slows first carbonation but speeds up secondary reactions. Furthermore, Wei et al. [58] investigated the effects of liquid–solid ratios, carbonation periods, and curing methods to improve the efficiency and strength of steel slag-desulphurization gypsum carbonation. The find-

ings show that optimizing the liquid–solid ratio to 1:5, carbonation time to 12 h, and the curing method to 1dW + 2dC increases compressive strength to 57.56 MPa. Direct carbonation is less efficient, producing less $CaCO_3$ than curing. Furthermore, steel slag specimens were subjected to various calcination temperatures (200, 300, 400, 500, 600, 700, and 800 °C) by Zhang et al. [106] to examine the influence of clinoptilolite-type zeolite on compressive strength and carbonation degree. Findings show the tetrahedral framework of clinoptilolite-type zeolite robust after low-temp calcination but degrades at 400 °C and collapses at 800 °C. Quartz peak intensity is consistent across the calcination temperature range. Li et al. [24] examined the mechanism by which slag tailings from iron recycling are treated to induce carbonation, as well as the potential benefits of doing so to create artificial reefs; the results show that steel slag powder undergoes carbonation and hydration during curing while steel slag mud only undergoes carbonation. Moreover, Li et al. [103] found that the strengths of steel slag-pressed blocks increased with higher temperatures (up to 400 °C) due to hydration. Wang et al. [107] found that CO_2 mineralization of MAS-gypsum is viable for construction, with a substantial increase of 1.57–3.64 after carbonation. Furthermore, Zhang et al. [108] found that carbonation curing improves the compressive strength of steel slag binders—raising carbonation to 55 °C leads to a 73% increase in the power of high-lime LSS paste (91.2 MPa) and a 48% increase in low-lime ESS paste (39.9 MPa). Zhang et al. [109] found that steel slag's tensile strength improves with carbonation, but only until a certain point. At S/C 0.11, L/S 0.20, and 28-day cure, strength rises from 47.51 MPa to 69.24 MPa with 3–7% carbonation to 23–27%. Moreover, Li et al. [30] found that to reduce carbonation's energy use and pollution production, optimizing energy-intensive processes such as those that take a long time or require a high temperature is important. In addition, Dai et al. [110] found that wet-grinding steel slag has a lower setting time and expansion rate than raw slag. After a 28-day cure, a constraint specimen with 10% wet-grinding steel slag has 68.5 MPa compressive strength, 9.3% higher, and peak impermeability. Furthermore, Li et al. [111] found that carbonating steel slag boosts pozzolanic activity. The best results were achieved with 10% water and a 2 h cure at 20% CO_2 concentration. Moreover, Li et al. [112] found that particle size and temperature are most important in carbonation. Pressure and CO_2 concentration affect speed, not the capacity of CO_2 sequestration. Finally, Kassim et al. [113] studied EAFS as a cement substitute for alkali-activated mortars—longer cure time increases strength with a strong reaction after 24 h thermal cure.

7. Suggestions for Future Work

It is commonly understood that certain challenges and issues necessitate additional research and investigation. For instance, (i) optimal carbonation conditions: the carbonation process is influenced by various factors such as temperature, pressure, CO_2 concentration, and moisture content. Further studies are needed to identify the optimal carbonation conditions for steel slag, considering different slag types and compositions. (ii) reaction kinetics: understanding the kinetics of the carbonation reaction is crucial for process optimization and scale-up. Further research is needed to explore the reaction mechanisms, reaction rates, and the factors affecting the kinetics of steel slag carbonation. (iii) long-term performance and durability: although carbonation curing enhances the material properties of steel slag-based products, long-term performance and durability assessments are necessary. Studies should focus on the durability of carbonated slag under different environmental conditions, including freeze-thaw cycles, chemical exposure, and aging effects. (iv) economic viability: the economic feasibility of large-scale steel slag carbonation processes needs to be evaluated.

Further studies should investigate the cost-effectiveness, potential market demand, and scalability of carbonation technologies for steel slag. Environmental impacts: while carbonation-curing offers ecological benefits, comprehensive life cycle assessments are needed to evaluate its overall environmental impacts, including energy consumption, water usage, and potential emissions associated with the process. Standards and regulations:

Developing standardized testing methods and regulations for carbonated slag-based materials is essential for widespread adoption. Further studies should focus on establishing quality control measures, performance standards, predictive models by modern artificial intelligence (AI) tools, and guidelines for their incorporation into construction practices.

8. Conclusions

In this review, we summarize the factors that affect steel slag carbonation and then compare their impact from two perspectives: the strength of the effect and the change in carbonation behavior when the factors are increased or decreased. Lastly, we consider previous studies and reviews on the factors that impact steel slag carbonation.

The carbonation of steel slag is a promising method of reducing its negative environmental impact by sequestering carbon dioxide and stabilizing potentially hazardous materials. However, the efficiency of the process depends on several factors that should be carefully considered when designing carbonation systems. The type of steel slag is one of the main factors that affect carbonation, as different types of slag have different mineralogical compositions that can influence carbonation reactions. A deeper reflection with values on various parameters that affect steel slag carbonation and their mutual effects has been summarized in the practical context, as the ideal carbonation rate is 200 °C. However, increasing temperature improves the carbonation of BOF only at three different particle sizes (3.5–7 mm, 7–15 mm, and 15–25 mm) and enhances the growth of compressive strength and carbon dioxide absorption. The low temperature does not favor carbonation due to precipitates of $CaCO_3$. Carbonation time is crucial for steel slag carbonation; e.g., the carbonation of steelmaking slag starts swiftly but slows with time, enhancing CO_2 sequestration as reaction time increases. Extended carbonation can leave some steel slag uncarbonated, with optimal results achieved at around 12 h.

Additionally, mechanical activation, particularly after grinding for 30 min, boosts the carbonation conversion and strength of carbonated BOF slag. Steel slags typically have a low carbonation response for long-term carbonation, with the formation of $CaCO_3$ particles potentially blocking specimen pores and hindering CO_3 diffusion. Similarly, particle size is pivotal in carbonation processes, as smaller particles offer a larger specific surface area, thereby boosting carbonation conversion. Achieving the optimal particle size enhances efficiency and reduces process costs. For best carbonation results, particles should have an average length of less than 150 micrometers.

In the same way, the carbonation reaction is accelerated by increasing CO_2 pressure and concentration. High CO_2 levels or coercion, however, cause carbonates to precipitate more quickly and cover the steel slag surface in protective carbonate layers, which reduces carbonation. Even at low CO_2 concentrations (which still exceed naturally occurring CO_2), the complex metal compounds in steel slag may function as catalysts during the carbonation reaction. For 10 and 150 bars, the carbonation conversion was determined to be 21% and 50.2%, respectively. At 50% CO_2 concentration, the carbonation is the lowest. At a CO_2 concentration of 10%, the greatest Ca conversion (carbonation) can be obtained at 400 °C and 450 °C. Carbonation grew progressively as the relative humidity (RH) increased from 0 to 60% but then dropped as the RH went to 80%. Low moisture concentration lowers CO_2 and calcium ion dissolution.

Contrarily, a high moisture level clogs the steel slag's pores and prevents CO_2 diffusion. Furthermore, the L/S ratio is more important than temperature and CO_2 pressure. The CO_2 conversion rate improves when the liquid–solid ratio (L/S) is reduced if it is above 2. High water–solid ratios favor long-term (12 h) carbonation reactions and long-term strength growth while inhibiting short-term (1–3 h) carbonation reactions and early strength development. A harmonious condition for the molding pressure is important for optimizing the strength of the carbonated steel slag specimen. When the molding pressure is increased, the distance between the steel slag increases, creating a dense structure (paradoxical situation) that hampers the diffusion of CO_2, resulting in a decline in carbonation.

To increase the activity of steel slag and its carbonation, additives are added to it. Some additives favor the activity, while others hamper the activity. e.g., adding Portland cement increases steel slag's carbonation rate and strength. The commonly used additives are phosphogypsum, sodium sulfate, and sodium carbonate. These additives increase the BOF strength first and then decrease it. Among them, phosphogypsum increases the carbonation rate as compared to the others. Steel slag hydration performance can be improved by modifying its microstructure with additives. It is also possible to employ the additives as a material with a high CO_2 absorption capacity or high carbonation reaction activity to speed up the carbonation process of steel slag. The pH of the environment significantly impacts steel slag carbonation by influencing the solubility of calcium ions. High calcium hydroxide content and high alkalinity boosted the possibility of CO_2 sequestration.

In this paper, we have reviewed and collected all the data about the potential factors affecting slag carbonation in one document. This will open new paths for practical applications of steel slag and researchers in this field.

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