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Microbial-induced mineral carbonation: A promising approach for improving Carbon sequestration and performance of steel slag for its engineering utilization

Jue Li[a,b], Qingmeng Hou[b], Xinqiang Zhang[c,*], Xiaobin Zhang[a]

[a] Engineering Research Center of Road Construction Low-carbon Materials of Anhui Province, Chuzhou University, Chuzhou, 239000, China
[b] National & Local Joint Engineering Research Center of Transportation and Civil Engineering Materials, Chongqing Jiaotong University, Chongqing, 400074, China
[c] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Steel slag, a by-product of steel production, accumulates in large quantities and poses significant environmental risks due to heavy metal ion content. Therefore, using pre-treated steel slag in construction offers a sustainable solution. This review analyzed microbial-induced mineral carbonation (MIMC) as a promising approach for steel slag utilization, highlighting the enhanced principles and influential factors of steel slag carbonation. MIMC achieves superior carbonation efficiency (up to 90–95%) under mild conditions, ensuring environmental sustainability, safety, and cost-effectiveness. Key factors include microbial characteristics, steel slag properties, and process conditions. The review discussed how MIMC can enhance the properties of carbonated steel slag by modifying mineralogy and microstructure, improving physical and mechanical attributes, and optimizing environmental performance. Moreover, the application of MIMC-treated steel slag in engineering construction was examined. Nonetheless, further research is essential to overcome challenges, fully comprehend the mechanisms and environmental impacts of MIMC, and advance sustainable development in the steel industry.

1. Introduction

The steelmaking industry is a prominent sector and a significant driver of the global economy (Winning et al., 2017). In recent decades, there has been a notable increase in worldwide crude steel production, fueled by the demand for infrastructure construction and manufacturing activities. In 2020, global crude steel output reached 1.86 billion metric tons (Fligstein, 2008), with China contributing over half of this production (Hasanbeigi et al., 2016). However, the industry faces substantial environmental challenges. Steel production, known for its high energy consumption and significant carbon emissions, accounts for approximately 7–9% of global anthropogenic CO_2 emissions. Beyond the direct release of greenhouse gases, the generation of steel slag, a residual by-product of the steelmaking process, presents further environmental concerns. Making up 5–15% of total crude steel production, untreated steel slag often accumulates in landfills, posing risks of heavy metal ion leaching (e.g., vanadium/V, chromium/Cr, arsenic/As, lead/Pb, cadmium/Cd) that can contaminate nearby water bodies and soil, leading to irreversible ecosystem damage (O'Connor et al., 2021). Fig. 1 shows steel slag production data from various countries worldwide (Jianlong et al., 2018).

Steel slag is a complex mineral by-product resulting from impurities present in raw iron and steel, which are eliminated during the smelting and refining processes in basic oxygen furnaces (BOFs), electric arc furnaces (EAFs), and ladle furnaces (Iivonen, 2019). An effective strategy to address the environmental challenges posed by steel slag is to capitalize on the inherent cementitious and pozzolanic properties (Muhmood et al., 2009). The intrinsic cementitious and pozzolanic attributes of steel slag can be attributed to its resemblance to cement clinker components (O'Connor et al., 2021). Incorporating steel slag as a partial substitute for cement or as an aggregate in concrete not only reduces the consumption of high-carbon emission cementitious materials but also provides opportunities for the beneficial reutilization of this industrial byproduct in building engineering. Furthermore, after undergoing appropriate treatment, steel slag can find applications in various sectors, including agriculture, construction materials, and

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* Corresponding author.
E-mail addresses: zhangxq0112@126.com, xinqiang.zhang@polyu.edu.hk (X. Zhang).

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marine environments, as shown in Fig. 2.

The widespread adoption of steel slag as a construction material has encountered several significant challenges, including poor volume stability, limited hydration capacity, and compositional instability (Martins et al., 2021). The inadequate volume stability of steel slag is mainly due to the presence of expansive mineral phases, such as free calcium oxide(f-CaO) and free magnesium oxides(f-MgO), which can react with water to produce $Ca(OH)_2$ and $Mg(OH)_2$, leading to undesirable volume expansion. To address the issue of volume stability and enhance the overall performance of steel slag, various strategies have been investigated, with mineral carbonation emerging as a promising approach (Li et al., 2022). Mineral carbonation involves the reaction of CO_2 with mineral compounds, such as calcium (Ca) and magnesium silicates, to form stable carbonate minerals. Previous studies have demonstrated that the introduction of carbonated steel slag as a substitute for cement in concrete can lead to the formation of new hydration products, such as C-S-H gels and ettringite (Andrade et al., 2021; Liao et al., 2020). Similarly, the replacement of traditional aggregates with carbonated steel slag aggregates has been shown to reduce the formation of micro-cracks in concrete (Miah et al., 2020). These findings highlight the potential benefits of utilizing carbonated steel slag in the construction industry.

Conventional carbonation methods for steel slag, such as direct carbonation and indirect carbonation, have been extensively studied. Direct carbonation often encounters reduced carbonation efficiency due to the limited solubility of CO_2 in water and the sluggish kinetics of the carbonation reaction (O'Connor et al., 2001). Indirect carbonation enhances carbonation efficiency by initially extracting Ca^{2+} or Mg^{2+} from the steel slag in a lower pH setting, followed by the formation of calcium carbonate($CaCO_3$) in a higher pH environment. However, the operation process of indirect carbonation is complex (Kunzler et al., 2011). Recognizing the limitations of conventional carbonation methods, recent studies have explored innovative approaches to enhance the carbonation of steel slag. One promising technique that has garnered significant attention is microbial-induced mineral carbonation (Che, 2023). MIMC utilizes microorganisms to enhance the rate of the carbonation process, leading to faster and more efficient conversion of steel slag into stable carbonate minerals (Seifan and Berenjian, 2019). This bio-mediated approach offers several distinct advantages over traditional methods, including higher carbonation rates, reduced environmental impact, and lower overall costs. By harnessing the power of microorganisms, MIMC presents a sustainable and effective solution for improving the recycling rate of large-scale solid waste, highlighting its importance in the realm of steel slag utilization and environmental sustainability.

The objective of this review was to provide a comprehensive insight into the current research landscape and the potential of microbial mineral carbonation in enhancing carbon sequestration and stabilization of steel slag, ultimately improving its performance and usability in construction applications. The review explored the fundamental principles, microbial species involved, and significant influencing factors, while evaluating the performance improvements associated with carbonated steel slag. Additionally, it investigated the utilization of carbonated steel slag in subgrade and pavement construction, identified prevailing challenges, and outlined future research directions. By highlighting the pivotal role of microbial mineral carbonation in promoting the sustainable utilization of steel slag within the construction industry, this review emphasizes its capacity to transform construction practices and foster a more environmentally conscious construction industry.

2. Conventional carbonation methods for steel slag

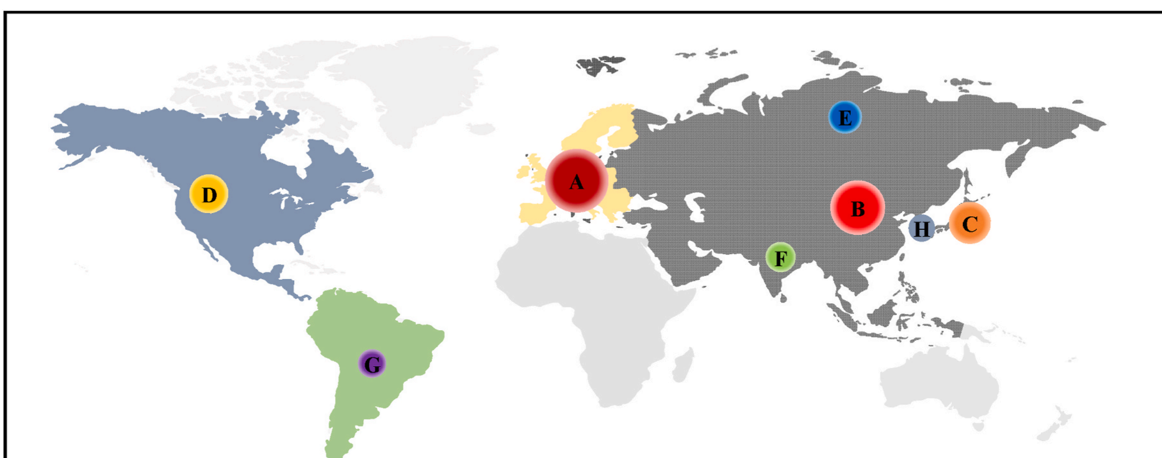
2.1. Direct carbonation

Direct carbonation is the most straightforward approach for the mineral carbonation of steel slag, involving the direct exposure of steel slag to CO_2 under controlled conditions. This method can be further categorized into dry carbonation and wet carbonation, depending on the presence or absence of an aqueous phase (Luo and He, 2021b).

2.1.1. Dry carbonation

Dry carbonation is the simplest form of direct carbonation, where steel slag is exposed to a CO_2-rich atmosphere without the addition of water (Song et al., 2021). The carbonation reaction can be represented by the following equation:

$$CaO + CO_2 \rightarrow CaCO_3 \tag{1}$$



	A	B	C	D	E	F	G	H
The production area	Europe	China	Japan	United States	Russia	India	Brazil	South Korea
Slag production	149.062Mt	139.28Mt	31.218Mt	28.687Mt	21.093Mt	12.093Mt	5.625Mt	4.5Mt

Fig. 1. Map of steel slag production by country.

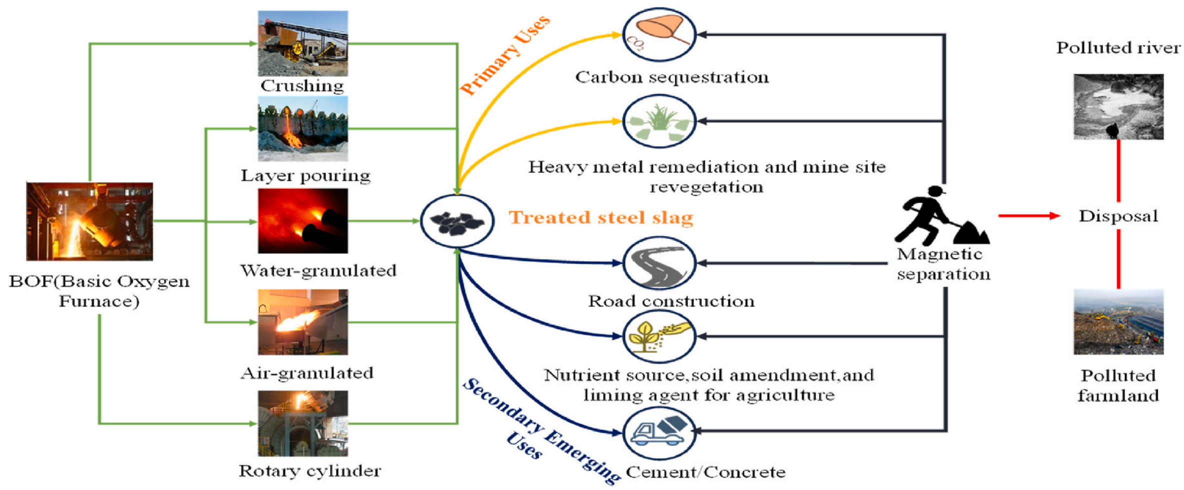


Fig. 2. Production, treatment and diversified utilization of steel slag.

$$MgO + CO_2 \rightarrow MgCO_3 \quad (2)$$

The driving force for the dry carbonation of steel slag is the difference in partial pressure between the CO_2 in the gas phase and the CO_2 dissolved in the pore water of the slag. As the CO_2 diffuses into the slag particles, it reacts with the CaO and MgO to form stable carbonate minerals, such as calcite and magnesite. The key advantages of dry carbonation include its simplicity, low operational cost, and the potential for the direct utilization of the carbonated slag in various applications without the need for additional processing. However, the main limitation of dry carbonation is its relatively low carbonation efficiency, typically ranging from 30% to 60%. This is due to the limited mass transfer of CO_2 into the slag particles and the slow kinetics of the carbonation reaction in the absence of an aqueous phase.

To improve the carbonation efficiency of the dry process, researchers have explored various strategies, such as increasing the specific surface area of the slag through mechanical pretreatment (e.g., milling, grinding), enhancing the CO_2 diffusion by applying pressure, and utilizing flue gas containing CO_2 directly from industrial sources (Liu et al., 2021). These modifications have been shown to enhance the carbonation degree of the carbonated slag products.

2.1.2. Wet carbonation

Wet carbonation involves the addition of water to the steel slag during the carbonation process, creating an aqueous environment that facilitates the chemical reactions. Through the wet carbonization device, key factors such as pressure, temperature, gas ratio and moisture content can be accurately controlled, which provides a stable, reliable and efficient reaction environment for the water carbonization reaction of steel slag, and has important significance for realizing the sustainable utilization and water carbonization treatment of steel slag. Fig. 3 shows the installation diagram of wet carbonization. As shown in the picture, steel slag and water are mixed in the rotary kiln, and the pump controls the delivery of water. The gas mixing part regulates the CO_2 and other gases to enter, and the heater maintains the reaction temperature. Under the monitoring of the pressure gauge, the Ca and MgO in the steel slag first reacts with water to dissolve, the CO_2 dissolves and ionizes to produce ions, and finally combines with Ca^{2+} and Mg^{2+} to form carbonate precipitation to realize the carbonization of the steel slag. The general carbonation reaction can be represented as follows:

$$CaO + H_2O + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

$$MgO + H_2O + CO_2 \rightarrow MgCO_3 + H_2O \quad (4)$$

Wet carbonation entails a gas-liquid-solid multiphase reaction, with the corresponding reaction equations shown in Eqs. (5)–(8) (Wei et al., 2024). In the presence of water, the free CaO and MgO in the steel slag can dissolve, forming Ca^{2+} and Mg^{2+} in the aqueous phase. Subsequently, these ions interact with dissolved CO_2, leading to the precipitation of Ca and Mg carbonate minerals.

$$CO_2(g) + H_2O \rightleftharpoons 2H^+ + CO_3^{2-} \quad (5)$$

$$[Ca, Mg]_2SiO_4 + 4H^+ \rightarrow 2[Ca^{2+}, Mg^{2+}] + SiO_2(aq) + 2H_2O \quad (6)$$

$$[Ca^{2+}, Mg^{2+}] + CO_3^{2-} \rightarrow CaCO_3(aq) + MgCO_3(aq) \quad (7)$$

$$[CaCO_3, MgCO_3](aq) \rightarrow [CaCO_3, MgCO_3](s) \quad (8)$$

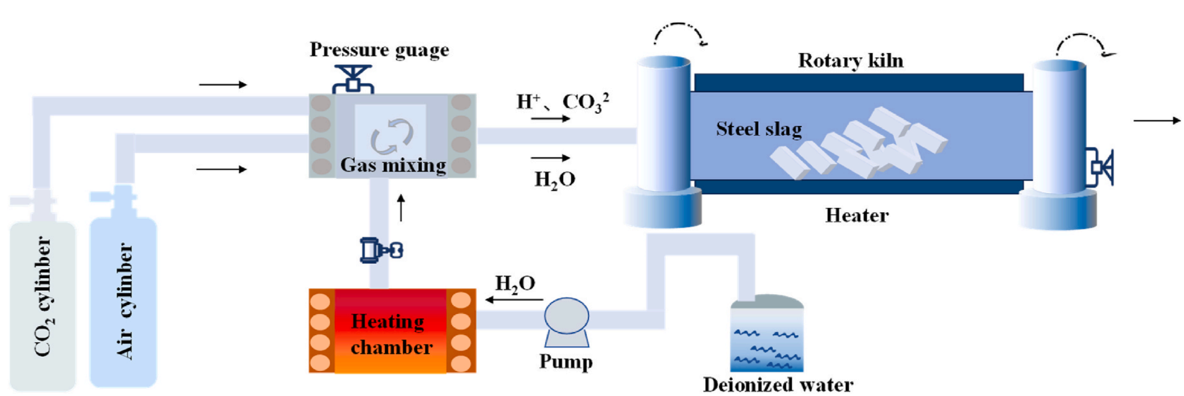


Fig. 3. Schematic diagram of wet carbonization device.

Compared to dry carbonation, the wet carbonation process offers several advantages. Firstly, the aqueous environment promotes the dissolution of the reactive components in the slag, increasing the availability of Ca^{2+} and Mg^{2+} for carbonation (Ragipani et al., 2021). Secondly, the precipitation of carbonate minerals occurs more readily in the liquid phase, leading to higher carbonation efficiency. Lastly, the carbonation products formed in the wet process can act as nucleation sites for the further growth of carbonate minerals, enhancing the overall carbonation degree.

Despite these benefits, wet carbonation also faces some challenges. The low solubility of CO_2 in water can limit the carbonation reaction rate, and the need for water consumption and subsequent dewatering steps can increase the operational complexity and cost. Additionally, the water chemistry and the presence of other ionic species in the system can influence the carbonation kinetics and the characteristics of the final carbonation products.

To address the limitations of wet carbonation, researchers have explored various modifications, such as the use of alkaline additives to increase the pH and promote the dissolution of Ca^{2+} and Mg^{2+}, the application of mechanical agitation or ultrasonic treatment to enhance mass transfer, and the integration of membrane technology to improve CO_2 absorption and carbonation efficiency (Chen et al., 2023). The schematic representation of the direct carbonization reaction, based on the shrinkage kernel model, is illustrated in Fig. 4. In this process, CO_2 dissolves in the aqueous phase to form H_2CO_3, which subsequently ionizes to form H^+ and CO_3^{2-}. Ca^{2+} and Mg^{2+} diffuse from the inner matrix of steel slag to the surface under slightly acidic environment, where they react with CO_3^{2-} in the water boundary layer to form carbonate ($CaCO_3/MgCO_3$). These carbonates either precipitate on the particle surface or remain dissolved within the liquid phase.

2.2. Indirect carbonation (pH swing)

Direct carbonation has many limitations, which can lead to cracking and deformation of steel slag, making the strength effect unstable, and the carbonation reaction rate of direct carbonation is unstable, however, the low carbonation efficiency has led to the development of indirect carbonation method, also known as the pH swing approach. Indirect carbonation includes two steps, leaching reaction and precipitation reaction, that is, first extraction of alkali earth metal ions in raw materials (mainly Ca^{2+}), and then after solid-liquid separation, CO_2 is passed into the filtrate for carbonization reaction (Chiang and Pan, 2017), the two-step process is as follows.

Step 1: Leaching: In the first step, the steel slag is exposed to an acidic solution, such as hydrochloric acid (HCl), to selectively leach out the Ca^{2+} and Mg^{2+} from the slag matrix. This can be represented by the following reaction:

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O \tag{9}$$

$$MgO + 2HCl \rightarrow MgCl_2 + H_2O \tag{10}$$

The purpose of the leaching step is to increase the concentration of Ca^{2+} and Mg^{2+} in the aqueous phase, thus facilitating the subsequent carbonation step.

Step 2: Carbonation: In the second step, the Ca^{2+}/Mg^{2+}-rich solution is exposed to a CO_2-rich environment, typically at a higher pH, to facilitate the precipitation of Ca and Mg carbonate minerals. This can be represented by the following reactions:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{11}$$

$$Mg^{2+} + CO_3^{2-} \rightarrow MgCO_3 \tag{12}$$

The pH swing method presents various advantages compared to direct carbonation techniques. Firstly, the segregation of leaching and carbonation stages enables enhanced regulation of reaction conditions, resulting in improved carbonation efficiency and product quality. Secondly, the leaching phase aids in impurity removal and enhances the purity of carbonation products, rendering them more suitable for specific applications. Luo and He (2021a) investigated the indirect carbonation of steel slag with varying particle sizes using acetic acid at different concentrations. Fig. 5 illustrates the process flow diagram of the two-step leaching indirect carbonation process. Steel slag is first mixed with deionized water and leaching agent to leach metal ions, after filtration, the filtrate is passed into CO_2 for carbonation reaction, and then filtered again to obtain carbonate precipitates.

However, the pH swing method also has its drawbacks. The two-step process is more complex and energy-intensive, requiring additional equipment, reagents, and processing steps compared to direct carbonation. Additionally, the disposal or treatment of the acidic leachate solution can pose environmental and economic challenges (Luo and He, 2021a).

To address these issues, researchers have investigated a range of modifications and optimization techniques for the pH swing method. These adaptations encompass the utilization of gentler leaching agents like ammonium salts or organic acids, the incorporation of membrane

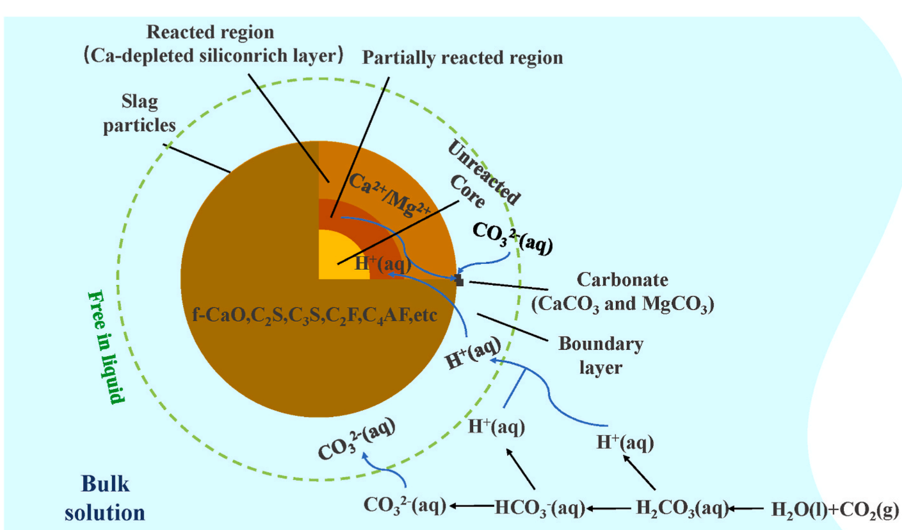


Fig. 4. Mechanism diagram of direct carbonization reaction based on shrinkage kernel model.

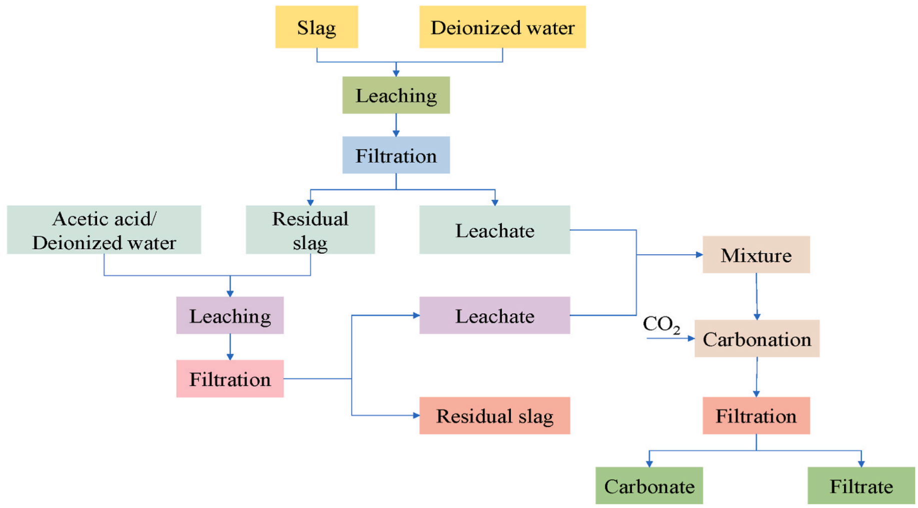


Fig. 5. Indirect carbonization process by two-step leaching.

technologies for selective ion separation and concentration, and the establishment of closed-loop recycling systems to reduce waste production and enhance resource retrieval (Ragipani et al., 2021). Table 1 summarizes the characterizations and suitable conditions of direct and indirect carbonation.

2.3. *Factors influencing conventional carbonation efficiency*

The carbonation efficiency of steel slag, regardless of the specific method employed, is influenced by a range of factors. Understanding and optimizing these parameters is crucial for enhancing the overall performance and viability of the carbonation process.

Table 1
Advantages and disadvantages of direct and indirect carbonation.

Carbonation		Advantages	Disadvantages	Applicable Conditions
Direct	Dry	1 Lower energy consumption 2 Simple operation, low equipment requirements 3 No waste water discharge	1 The reaction rate is slow. 2 The reaction is incomplete and the active ingredients in the slag may not be fully utilized.	1 Steel slag with low water content 2 High requirements on energy consumption
	Wet	1 The reaction rate is fast and the carbon capture efficiency is high. 2 The reaction is relatively complete and the product quality is high.	1 High energy consumption, need to treat a lot of water. 2 Requiring complex water treatment and equipment maintenance.	1 Steel slag with high water content 2 Having high requirements for product quality.
Indirect	Wet	1 Making full use of the active ingredients in steel slag. 2 The reaction conditions of each step can be controlled to produce high purity products 3 Chemical reactions can be optimized at each step.	1 The reaction process is complex and requires multi-step chemical treatment. 2 High energy consumption and cost, need to deal with by-products or liquid waste	1 Steel slag is rich in active ingredients. 2 Suitable for high value-added products

2.3.1. *Temperature*

Temperature is a critical parameter that affects the kinetics and thermodynamics of the carbonation reactions (Li et al., 2012). Moreover, temperature also affects the microscopic morphology and crystal growth rate of carbonized crystals (Brand and Fanijo, 2020). Generally, higher temperatures favor the carbonation process by increasing the reaction rates and improving the solubility of CO_2 in the aqueous phase. However, excessively high temperatures can also lead to the decomposition of the carbonate minerals, reducing the overall carbonation efficiency.

The leaching rate of Ca^{2+} can be increased by heating, thus enhancing the reaction kinetics (Bundur et al., 2015). Ben et al. (2020) systematically studied the kinetic process of carbonation of steel slag. The results showed that the higher the carbonation temperature is, the faster the reaction rate is in a single CO_2 atmosphere. Under different curing temperatures, the compressive strength of steel slag samples will be different. Since the degree of CO_2 absorption is an important index to measure the carbonization capacity of steel slag samples, as shown in Fig. 6, the degree of CO_2 absorption changes with the carbonation time at different curing temperatures (Luo et al., 2021).

Experimental studies have shown that the optimal temperature range for the carbonation of steel slag typically lies between 20 °C and 60 °C, with the highest carbonation degree often observed around 30–40 °C (Zhang, S. et al., 2022). The specific temperature optimum may vary depending on the slag composition, particle size, and other experimental conditions.

2.3.2. *CO_2 concentration and pressure*

The primary factor influencing the rate of carbonation is the diffusion and dissolution rate of CO_2 in steel slag. The rate of the concentration reaction is correspondingly enhanced with increasing CO_2 concentration and pressure. However, when the CO_2 concentration or pressure rises to a certain value, it is not conducive to reducing the degree of carbonization. This is due to the accelerated precipitation rate of carbonate, leading to the formation of a protective carbonate layer on the surface of the steel slag (Song et al., 2021).

The effect of CO_2 gas pressure on steel slag carbonization can be assessed using the pressure drop over time in the system, as shown in Fig. 7. To investigate the influence of pressure on the carbonation process of steel slag, a series of carbonation tests and control experiments were conducted under initial CO_2 pressure of 1MPa, 2MPa, MPa, 4MPa, 5MPa and 6MPa (Ukwattage et al., 2017). As time progresses, the pressure decreases due to carbonation. At each initial pressure level, the

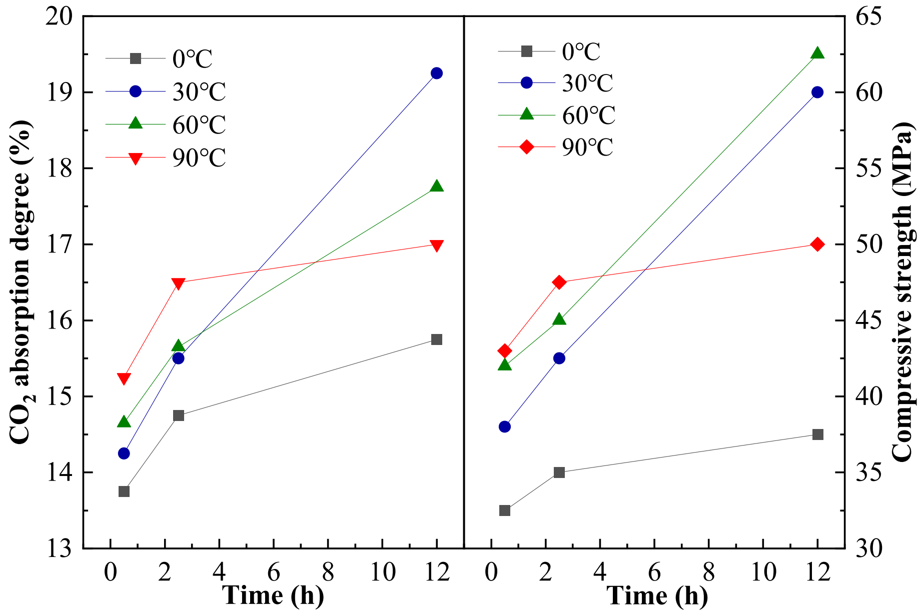


Fig. 6. Compressive strength of steel slag samples and the level of CO_2 absorption at different stages of carbonation under varying curing temperatures.

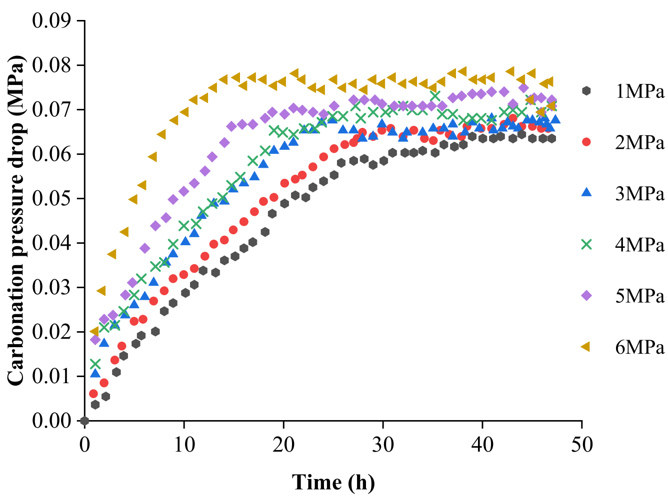


Fig. 7. Effect of CO_2 gas pressure on carbonization of steel slag.

pressure drop during carbonation increases over time as CO_2 is consumed by the carbonation process. After a certain duration, the pressure reduction stabilizes as all available oxides are carbonated and no further sequestration occurs. Fig. 7 illustrates that the reaction time required to achieve complete steel slag carbonation is shorter under increased pressure.

Therefore, the concentration and partial pressure of CO_2 in gas phase are directly related to the driving force of carbonation reaction. Increasing CO_2 concentration or pressure can enhance the dissolution of CO_2 in the aqueous phase, resulting in a reduction in the required carbonization reaction time. For example, Huijgen et al. (2005) conducted carbonization experiments on steel slag and found that the longer the carbonization time, the greater the degree of carbonization, and the carbon fixation reaction was faster in the early stage and gradually stabilized in the later stage. Studies have shown that the carbonation efficiency of steel slag generally increases with higher CO_2 concentrations, with optimal values ranging from 10% to 100% CO_2 in the gas phase (Wang et al., 2023). The use of pure CO_2 or flue gas streams with high CO_2 content can significantly improve the carbonation yield. Similarly, the application of elevated CO_2 pressures, typically in the range of 1–10 bar, has been found to enhance the carbonation rate and degree. Excessive CO_2 dissolution will lead to a decrease in the pH value of the pore solution of steel slag, which is not conducive to the improvement of the carbonation degree of steel slag (Ri-wei et al., 2017).Supercharging can increase the leaching rate of Ca^{2+}, thus enhancing the reaction kinetics (Bundur et al., 2015).

2.3.3. Reaction time

The duration of the carbonation reaction is another critical parameter influencing the degree of carbonation. Extended reaction times typically result in more thorough conversion of the reactive Ca and Mg components in steel slag, resulting in higher levels of carbonation. As the carbonation curing time increases, both the carbonation weight gain rate and compressive strength of the pure steel slag sample exhibit an upward trend. A positive correlation between the carbonation weight gain rate and compressive strength of the sample is observed, indicating that the compressive strength rises in tandem with the increase in the carbonation weight gain rate (Hua-lei et al., 2010), as shown in Fig. 8.

Experimental studies have reported that the carbonation of steel slag

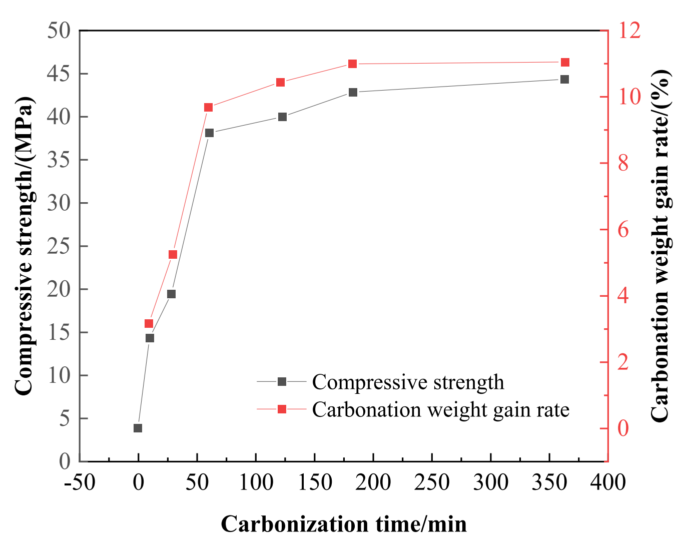


Fig. 8. Carbonation effect of steel slag samples at different carbonation times.

can reach equilibrium within a few hours to a few days, depending on the specific carbonation method and other operating conditions (Gopinath and Mehra, 2016). For dry carbonation, the carbonation degree typically increases rapidly within the first few hours, followed by a gradual approach to the maximum value over the course of several days (Tu et al., 2015). In the case of wet carbonation and pH swing methods, the carbonation reaction can continue for several days to weeks, with the rate of progress slowing down as the reaction progresses.

2.3.4. Liquid-to-solid ratio

The liquid-to-solid (L/S) ratio, defined as the ratio of the volume of the aqueous phase to the mass of the solid slag, is a critical parameter in wet carbonation and pH swing processes. The L/S ratio influences the availability of water for the dissolution of Ca and Mg components, the transport of reactants and products, and the precipitation of carbonates (Luo and He, 2021a). In the experiment of two-step leaching indirect carbonization method, the change of Ca^{2+} carbonization conversion of steel slag with different particle sizes is shown in Fig. 9.

Generally, increasing the L/S ratio enhances the carbonation efficiency by facilitating the dissolution of the steel slag and the subsequent precipitation of carbonate minerals. However, optimal L/S ratios for steel slag carbonation are typically reported in the range of 5–20 (Baras et al., 2023), excessively high L/S ratios can also lead to increased energy consumption and operational costs associated with water handling and treatment. In the process of wet carbonization, increased water consumption enhances the dissolution of Ca^{2+} and CO_2 increases, which improves the carbonization degree of steel slag (Huijgen et al., 2005; Veetil and Hitch, 2020).

Studies have shown that the carbonation reaction is mainly controlled by the leaching rate of Ca^{2+} and the dissolution rate of CO_2 at low L/S ratio (Yanfeng et al., 2023). Increasing the L/S ratio can improve the reaction rate and induction degree. At high L/S ratio, the carbonation reaction is mainly affected by the diffusion rate of CO_2, and increasing the L/S ratio will reduce the reaction speed and reaction degree.

2.3.5. Particle size

The particle size of the steel slag feedstock is another important parameter that influences the carbonation efficiency. Huijgen et al. (2005) found that the carbonization reaction decreased with the increase of particle size. Smaller particle sizes, with larger specific surface areas, provide more reactive sites for the carbonation reaction and improve the mass transfer of CO_2 and other reactants into the slag matrix (Baciocchi et al., 2009; Ko et al., 2015; Polettini et al., 2016). Under certain CO_2 pressure and L/S ratio, the carbonization degree decreases gradually with the increase of steel slag particle size (Takazawa et al., 2016). As shown in Fig. 10, the 24-h experiment under 250 kg/cm^2 CO_2 pressure and water/slag ratio of 5 shows that as the particle size decreases from 3.5-2 mm to 2-1 mm, 1–0.5 mm and ≤0.5 mm, the carbonation degree increases from 16.3% to 27.2%, 46.3% and 71.1%.

Studies have shown that decreasing the particle size of steel slag, typically through mechanical grinding or milling, can significantly enhance the carbonation degree (Liu et al., 2020). For example, carbonation rates have been observed to increase by 2–3 times when the slag particle size is reduced from the millimeter to the micrometer scale. However, the energy consumption and associated costs of fine grinding must be weighed against the potential benefits of improved carbonation performance (Li et al., 2023).

2.3.6. pH value

The pH value of the system plays a critical role in wet carbonation and pH swing processes. The pH influences the solubility of CO_2, the dissolution of Ca and Mg components, and the precipitation of carbonate minerals (Hong et al., 2021).

Alkaline steel slag system is beneficial to capture more CO_2, increase the concentration of CO_3^{2-} in the environment, stimulate the activity of steel slag, and promote the precipitation of $CaCO_3$ (Li et al., 2021). With the extension of carbonization time, the pH value in the system will continue to decrease, the carbonate concentration will decrease, and the Ca^{2+} conversion rate will slow down (Costa et al., 2016).In general, a slightly alkaline pH range (around 8–11) is considered optimal for the carbonation of steel slag, as it promotes the dissolution of the reactive oxides and the subsequent precipitation of Ca and Mg carbonates. Maintaining the appropriate pH throughout the carbonation process is crucial, as changes in pH can affect the reaction kinetics and the characteristics of the final carbonation products (Ragipani et al., 2021).

Various strategies have been employed to control the pH, such as the addition of alkaline reagents (e.g., NaOH, KOH) in the wet carbonation process or the incorporation of a pH swing step in the indirect carbonation approach (Lin et al., 2023). The optimization of pH, along with other parameters, is essential for maximizing the carbonation efficiency and achieving the desired properties of the carbonated steel slag. Table 2 summarizes the influence mechanism of different factors on steel slag carbonization.

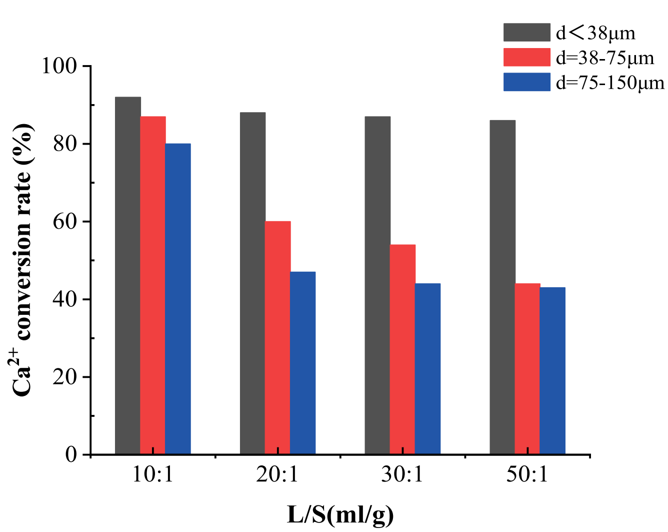


Fig. 9. Variations of Ca^{2+} carbonization conversion of steel slag with different particle sizes.

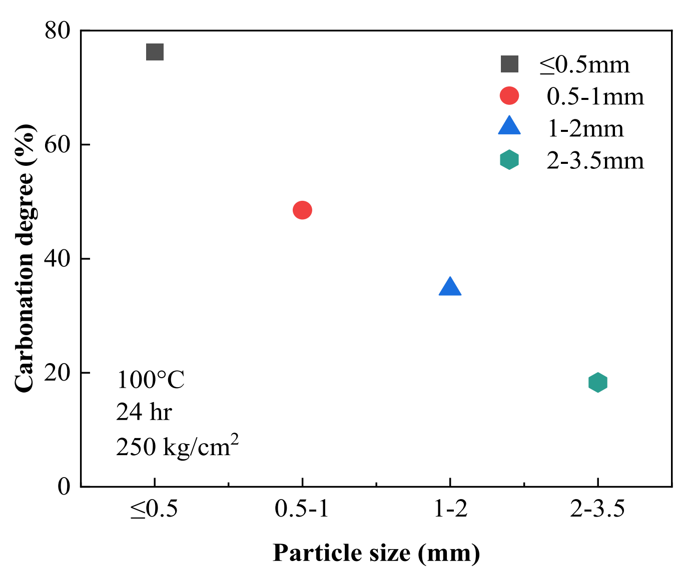


Fig. 10. Relation between particle size and carbonization degree of steel slag.

Table 2
Influence mechanism of different factors on carbonization of steel slag.

Factors	Influencing mechanism	References
Temperature	1 Higher temperature increases the solubility and reaction rate of CO_2 and accelerates the formation of carbonate. 2 Excessive temperature may change the crystal structure of carbonate and affect its stability.	(Baras et al., 2023; Wang et al., 2019)
CO_2 concentration and pressure	1 Higher concentration of CO_2 can improve carbonization efficiency and increase carbonate formation rate, and too high concentration of CO_2 may lead to uneven carbonate deposition. 2 Pressure can improve the solubility and reaction rate of CO_2 and promote carbonization. Too high pressure may affect the structure and formation mode of carbonate.	(Mo et al., 2016; Rostami et al., 2012; Shi et al., 2012)
Reaction time	1 The longer the reaction time, the higher the degree of carbonization. 2 Need to balance reaction efficiency and economy.	Mahoutian and Shao (2016)
Liquid-to-solid ratio	1 Proper moisture helps to dissolve CO_2 and increase the reaction rate 2 Too much water may cause particles to aggregate and reduce the reaction area.	(Ghouleh et al., 2017; Zhan et al., 2019)
Particle size	1 Smaller particle size provides larger specific surface area and promotes carbonization reaction. 2 Larger particle size may lead to uneven carbonization.	(Humbert et al., 2019; Jiang and Ling, 2021)
pH value	1 Higher pH (alkaline) helps CO_2 react with alkaline oxides to form carbonate. 2 pH value affects the activity of microorganisms, which in turn affects the carbonization reaction.	(Han et al., 2020; Zhan et al., 2019)

2.4. Limitations of conventional carbonation methods

Conventional direct and indirect carbonation techniques generate $CaCO_3$ and $MgCO_3$ crystals, which can be integrated with steel slag particles to enhance the density and strength of the material. Fig. 11 illustrates the carbonation reaction of steel slag, highlighting the conversion of f-CaO and Ca^{2+} into $CaCO_3$ crystals. Fig. 11 shows the microstructure changes of steel slag before and after carbonization reaction. Before carbonization, steel slag contains a variety of mineral phases and pores. In the process of carbonization, CO_2 reacts with active components (Ca^{2+}, Mg^{2+}) to form carbonate precipitation. After carbonization, the structure of steel slag changes, the pores are filled, and the carbonate mineral phase affects its performance improvement and application. Despite substantial research and application of these methods, they encounter limitations that impede their widespread implementation for the efficient utilization of steel slag.

One of the primary limitations is the relatively low carbonation efficiency, particularly in the case of direct carbonation. The slow kinetics and limited mass transfer of CO_2 into the steel slag particles, as well as the low solubility of CO_2 in water, can result in carbonation degrees typically below 60–70% (Li et al., 2022). This means that a significant portion of the reactive components in the slag remains unreacted, limiting the potential for carbon capture and the overall stabilization of the material.

The complexity of the indirect carbonation (pH swing) method, involving multiple steps and the use of additional reagents, can also pose challenges in terms of operational costs, energy consumption, and environmental impact(Luo and He, 2021b). The disposal or treatment of the acidic leachate solutions generated during the leaching step can be an additional burden. Furthermore, the carbonation products generated through conventional methods may not always exhibit the desired properties, such as optimal particle size, morphology, and mechanical performance, which can limit their suitability for specific applications, particularly in the construction industry.

To address these limitations and further enhance the efficiency and performance of steel slag carbonation, researchers have explored alternative approaches, including the utilization of microorganisms to catalyze the carbonation process. The principles and advantages of MIMC are discussed in the following section.

3. Principles of microbial mineral carbonation

3.1. Overview

MIMC, also known as biocarbonation or bio-mineralization, is an emerging approach that leverages the metabolic activities of microorganisms to catalyze and enhance the carbonation of industrial wastes, such as steel slag. Fig. 12 shows the schematic diagram of the steel slag carbonization process facilitated by microorganisms. This figure shows the process of promoting the carbonization of steel slag by microorganisms. Microorganisms catalyze CO_2 hydration by producing carbonic anhydrase, or metabolize OH^- to improve PH value, promote CO_2 to carbonate ion, and combine with Ca^{2+} and Mg^{2+} in steel slag to form carbonate precipitation, thus achieving efficient carbonation of steel slag and improving the performance of steel slag. This approach offers several advantages over conventional physicochemical carbonation methods, including higher efficiency, milder operating conditions, reduced environmental impact, and the potential for cost savings.

The underlying principle of microbial mineral carbonation is the ability of certain microorganisms to actively participate in and accelerate the carbon sequestration process. Microorganisms can contribute to the carbonation of steel slag through two primary mechanisms.

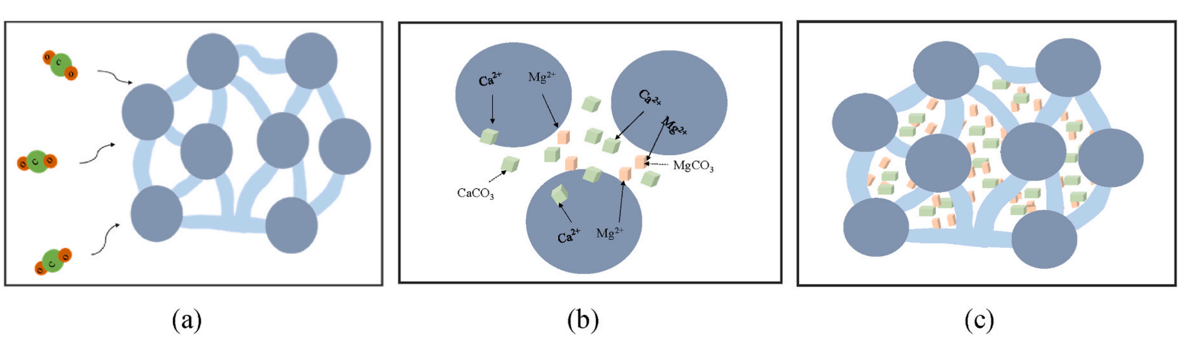


Fig. 11. Schematic diagram of carbonization reaction:(a) Before carbonization; (b) Magnification of carbonization reaction; (c) After carbonization.

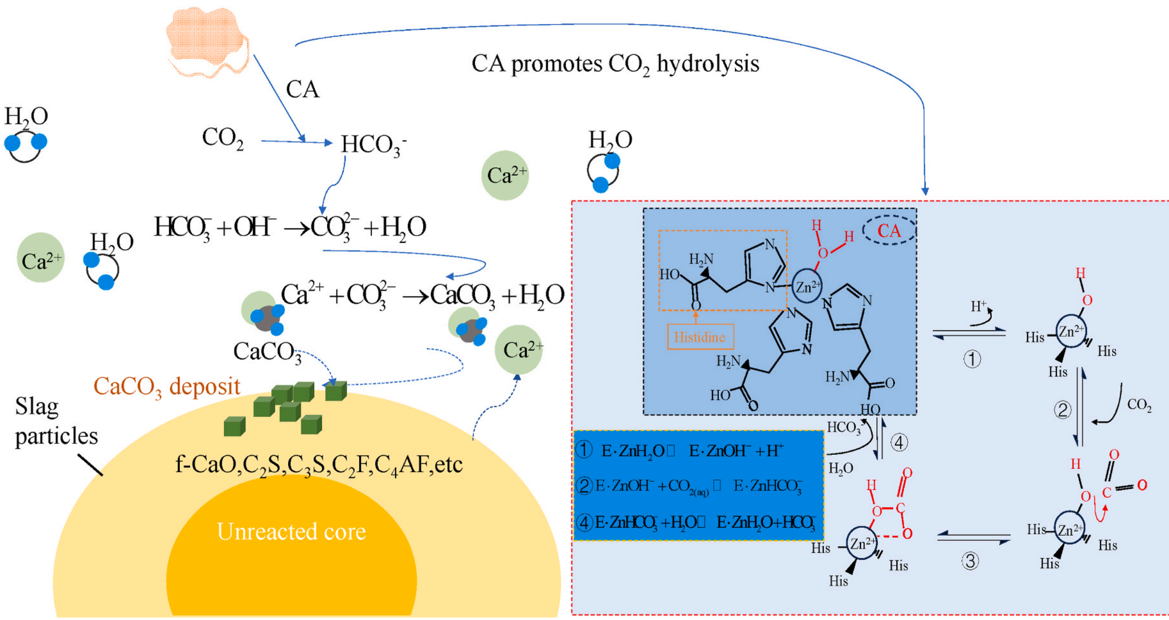


Fig. 12. Schematic diagram of the steel slag carbonation process facilitated by microorganisms.

(1) the production of carbonic anhydrase, an enzyme that catalyzes the hydration of CO_2 to form HCO_3^- and CO_3^{2-} (Yi and Qian, 2018).
(2) the generation of OH^- through metabolic processes, such as the utilization of urea as a carbon and energy source, which can increase the local pH and promote the precipitation of Ca and Mg carbonate minerals (Kaur et al., 2021).

The carbonic anhydrase enzyme plays a crucial role in the microbial carbonation process by facilitating the conversion of CO_2 into its ionic forms, as shown in the following reactions:

$$CO_2 + H_2O \xrightarrow{\text{Carbonic Anhydrase}} HCO_3^- + H^+ \tag{13}$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+ \tag{14}$$

The production of HCO_3^- and CO_3^{2-} by the carbonic anhydrase enzyme increases the availability of these carbonate species, which can then react with the Ca^{2+} and Mg^{2+} released during steel slag dissolution to form stable carbonate minerals (Power et al., 2016). In addition to the carbonic anhydrase-mediated mechanism, certain microorganisms can also contribute to the carbonation process through the generation of OH^- during their metabolic activities. For example, some bacteria that utilize urea as a carbon and energy source can produce ammonia (NH_3), which then reacts with water to form ammonium (NH_4^+) and OH^-, as shown in the following reactions (Bhagat et al., 2018):

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_2 \tag{15}$$

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^- \tag{16}$$

The OH^- produced can then react with the dissolved CO_2 or with Ca^{2+} and Mg^{2+}, leading to the precipitation of Ca and Mg carbonate minerals.

The enzymatic hydration of CO_2 and the pH increase through metabolic processes, allows microorganisms to effectively catalyze the carbonation of steel slag, often achieving higher carbonation efficiencies compared to conventional physicochemical methods.

3.2. Advantages of microbial mineral carbonation

The utilization of microorganisms in the carbonation of steel slag offers several advantages over conventional carbonation methods, making it a promising approach for improving the sustainability and resource efficiency of the steel industry.

3.2.1. Increased carbonation efficiency

One of the primary advantages of microbial mineral carbonation is its ability to enhance the overall carbonation efficiency of steel slag. Microorganisms, through their metabolic activities and the production of carbonic anhydrase, can significantly increase the rate and extent of CO_2 conversion into stable carbonate minerals (Jin et al., 2021). Studies have reported carbonation degrees of up to 90–95% for steel slag when utilizing microbially-induced carbonation, compared to 60–70% for conventional methods (Yi et al., 2022). The higher carbonation efficiency achieved through microbial processes can lead to improved carbon sequestration and the stabilization of a larger fraction of the steel slag, thereby reducing the environmental burden associated with the disposal or stockpiling of this industrial byproduct.

3.2.2. Milder operating conditions

Conventional carbonation methods, particularly direct carbonation, often require harsh operating conditions, such as elevated temperatures, pressures, or the use of strong acids or alkaline reagents. These conditions can lead to higher energy consumption, operational costs, and potential environmental impacts. In contrast, MIMC can be carried out under much milder conditions, typically at room temperature and atmospheric pressure, without the need for intensive chemical pretreatment (Huang et al., 2024; Zhang, X. et al., 2022). The metabolic activities of the microorganisms can drive the carbonation process at relatively low-energy inputs, making the overall process more sustainable and cost-effective.

3.2.3. Environmental friendliness and safety

Conventional carbonation methods often involve the use of hazardous chemicals, such as strong acids or bases, which can pose risks to the environment and human health. In contrast, MIMC utilizes microorganisms that are generally harmless and can be cultured using simple, eco-friendly growth media (Perito and Mastromei, 2011). Microbial induced carbonate precipitation technology can change the occurrence form of heavy metal copper into a more stable carbonate bound state, reduce its migration and diffusion potential and bioavailability, and thus reduce its ecotoxicity (Xie et al., 2023). Urinolytic organisms can effectively immobilize toxic metals through precipitation or coprecipitation, and conduct bioremediation of metal pollution in the soil(Kumari et al., 2016). Pb, Cd and Zn can be effectively eliminated by using urine dissolved bacteria for bioprecipitation (Jalilvand et al., 2020). Due to its low energy requirements and ability to conserve carbon at ground level, biomechanical technology can be a possible carbon-negative technology in buildings (Amidi and Wang, 2015).

The carbonation products generated through microbial processes are typically more environmentally benign, as they do not contain residual chemical additives or contaminants. Additionally, the ability of microorganisms to sequester CO_2 and stabilize the steel slag can contribute to the overall reduction of greenhouse gas emissions and the mitigation of environmental pollution associated with the steel industry(Sinkhonde, 2022).

3.2.4. *Potential for cost savings*

Compared to conventional carbonation methods, MIMC can offer potential cost savings due to several factors (Sharma et al., 2020). Firstly, the milder operating conditions and the reduced energy requirements can lead to lower operational costs. Secondly, the utilization of microorganisms as catalysts can be a more economical approach than the use of energy-intensive equipment or expensive chemical reagents. Furthermore, the carbonated steel slag produced through microbial processes may have improved properties, such as enhanced volume stability and mechanical performance, which can translate into cost savings in its downstream applications, particularly in the construction industry.

4. Microbial species for steel slag carbonation

As outlined in the previous sections, the selection of suitable microbial strains plays a crucial role in maximizing the efficiency and performance of MIMC of steel slag. This section analyzes the microbial species that have been explored so far for the carbonization of steel slag, focusing on the bacteria that produce carbonic anhydrase or urease to hydrolyze urea, and also discusses the influencing factors that affect microbial activity. Table 3 shows the properties of urease and carbonic anhydrase (Liu et al., 2023; Nerella et al., 2024; Zhang, Y. et al., 2024).

4.1. *Carbonic anhydrase-producing bacteria*

Carbonic anhydrase is an enzyme that plays a crucial role in the microbial carbonation of steel slag by catalyzing the hydration of CO_2 to form HCO_3^- and CO_3^{2-}. The carbonization depth of steel slag can be significantly improved by carbonated liver enzyme. Several bacterial species have been identified as effective producers of this enzyme, making them suitable candidates for enhancing the carbonation efficiency of steel slag.

4.1.1. *Bacillus cereus*

One of the most extensively studied carbonic anhydrase-producing bacteria is Bacillus cereus. Bacillus cereus is a gram-positive, endospore-forming bacterium widely distributed in soils. It can secrete abundant extracellular carbonic anhydrase, with each enzyme molecule catalyzing the hydration of around 1.4 million CO_2 molecules per second (Perito and Mastromei, 2011). Due to the high carbonation efficiency conferred by carbonic anhydrase, Bacillus cereus is a preferred candidate in many MIMC studies.

Researchers have isolated Bacillus cereus strains from various environments and screened for optimal carbonic anhydrase production. The urease and carbonic anhydrase activities of a Bacillus cereus strain isolated from coal mine soil were higher than those of the standard strain. The precipitation rate of the cell-free extract reached 92% within 3 h under environmental conditions. Further research was carried out to optimize the culture conditions to promote the secretion of enzymes (Xiaodong et al., 2019). In the medium with a pH of 8–9, tryptophan, yeast extract and NaCl were beneficial to the growth of Bacillus cereus and increased the yield of carbonic anhydrase (Xiao-mei et al., 2021). The optimized conditions boosted steel slag carbonation by 36% compared to uncontrolled cultures. The high carbonation efficiency and the ability to tolerate the alkaline conditions typically found in steel slag environments have made Bacillus cereus a widely used microorganism for microbial mineral carbonation applications.

4.1.2. *Sporosarcina pasteurii*

Another notable carbonic anhydrase-producing bacterium is Sporosarcina pasteurii (formerly known as Bacillus pasteurii). It has been isolated from various alkaline environments worldwide. S. pasteurii cell-free extracts demonstrated significant promotion of Ca carbonate precipitation rates compared to cell extracts alone (Dikshit et al., 2022; Guzman et al., 2022).

Multiple studies employed S. pasteurii for MIMC applications with steel slag and other industrial residues. For steel slag carbonation, S. pasteurii showed promising performance under ambient conditions, forming irregular calcite crystals. Its carbonic anhydrase activity proved conducive for accelerated carbonation reactions.

4.1.3. *Other carbonic anhydrase-producing bacteria*

In addition to Bacillus species, other bacterial strains, such as Arthrobacter, Serratia, and Pseudomonas, have also been reported to possess carbonic anhydrase activity. For instance, Pseudomonas aeruginosa and Arthrobacter crystallopoietes enzymatically catalyzed the carbonation of steel slag in aqueous slurries (Biswal et al., 2019; Tamayo-Figueroa et al., 2024). Three genes encoding putative beta-carbonic anhydrases were identified in Pseudomonas aeruginosa, which are active under certain conditions and expressed in cells. In addition, extracellular carbonic anhydrase has also been purified from Pseudomonas fragilis (Lotlikar et al., 2013). At 30 °C, the growth of Bacillus schafferii bacteria was the fastest, and the enzyme activity was the highest at 45 °C. The enzyme activity of bacteria reached the highest when they entered the decay stage. The results of intracellular and extracellular tests showed that the strain produced intracellular carbonated anhydrase (Cai-yan et al., 2022).

Overall, Bacillus and Sporosarcina species remain the predominant carbonic anhydrase producers for MIMC applications based on their robust carbonation performance and tolerance to varied environmental conditions encountered during steel slag processing and usage. Continuous isolation and characterization efforts aim to discover new microbial sources with potential for enhanced carbon capture. Table 4 summarizes the bacterial carbonization characteristics, applicable conditions and application scenarios of several carbonic acid-producing liver enzymes.

4.2. *Urea-hydrolyzing bacteria*

Certain microorganisms can contribute to the carbonation of steel slag through the generation of OH^- during their metabolic processes, particularly the utilization of urea as a carbon and energy source. This is because urease, as a catalyst, can decompose urea into HCO_3^- and NH_4^+, and the hydrolysis rate of carbonate is increased in a highly alkaline

Table 3
Characteristics of urease and carbonic anhydrase.

Catalytic enzyme type	High activity range		Catalytic object	Typical microorganism
	Temperature	PH		
Carbonic anhydrase	35–55 °C	7.0–10.0	CO_2	Bacillus cereus Sporosarcina pasteurii
Urease	30–40 °C	7.0–8.0	Urea	Sporosarcina pasteurii Bacillus sphaericus

Table 4
Summary and comparison of carbonization characteristics of bacteria producing carbonated liver enzymes.

Bacterial category	Advantage	Disadvantage	Applicable condition	Application scenario	Reference
Bacillus cereus	Strong tolerance, can survive in a high alkaline environment.	Toxins may be produced under certain conditions and require strict control.	High alkaline, high temperature conditions	Large-scale industrial waste treatment and carbonation of steel slag	(Jin et al., 2021; Mahapatra et al., 2022)
Sporosarcina pasteurii	Carbonic anhydrase activity is high and can work under mild conditions.	Poor environmental adaptability, strict requirements for growth conditions	Run in a well-controlled laboratory or industrial reactor.	Laboratory research and small-scale industrial applications	Tabatabaei (2000)
Other Carbonic Anhydrase-Producing Bacteria	Various metabolic pathways, adapt to a variety of environmental conditions.	The performance of different strains is different, and the optimal strain should be screened.	Adjust pH value, temperature and so on according to the characteristics of different strains.	Special treatment for different industrial wastes to improve carbonation efficiency	(Kajla et al., 2022; Kaur et al., 2021)

environment, and a large amount of CO_3^{2-} reacts with metal cations leached from steel slag to generate carbonate precipitates (Castro-Alonso et al., 2019; Mwandira et al., 2017). These urea-hydrolyzing bacteria can increase the local pH, which in turn promotes the precipitation of Ca and Mg carbonate minerals.

4.2.1. Sporosarcina pasteurii

One of the most extensively studied urea-hydrolyzing bacteria for steel slag carbonation is Sporosarcina pasteurii (previously mentioned as a carbonic anhydrase producer). This bacterium is known for its ability to hydrolyze urea, producing NH_3 and OH^-, which can then react with dissolved CO_2 or metal ions to form carbonate minerals.

4.2.2. Bacillus sphaericus

Another prominent example of a urea-hydrolyzing bacterium is Bacillus sphaericus. This gram-positive, endospore-forming bacterium has been shown to effectively accelerated the carbonation of concrete specimens impregnated with culture supernatant. For steel slag, certain B. sphaericus strains demonstrated improved mechanical strength and mineralogical transformations in carbonated products compared to abiotic carbonation (Nasser et al., 2022; Saridhe and Selvaraj, 2021).

4.2.3. Other urea-hydrolyzing bacteria

In addition to Bacillus species, other urea-hydrolyzing bacteria, such as Deinococcus, Enterobacter, and Lysinibacillus, have also been investigated for their potential in enhancing the carbonation of mineral materials. However, in-depth characterization is still lacking, and their carbonation efficacy requires further optimization compared to well-documented Bacillus and Sporosarcina strains. Table 5 shows the characteristics, applicable conditions and application scenarios of the above three types of urea hydrolyzing bacteria for steel slag carbonization.

Overall, the metabolic traits of both carbonic anhydrase production and urea hydrolysis confer microbial catalysts the dual abilities to accelerate the carbonation reactions through various mechanisms. Proper selection and optimization of appropriate microbial strains remain pivotal in applying MIMC for enhanced steel slag carbon sequestration.

5. Factors influencing microbial carbonation of steel slag

The efficiency and performance of MIMC applied to steel slag is influenced by a variety of intrinsic and extrinsic factors. The internal factors include the characteristics of microbial strains, the characteristics of steel slag substrate, and the external factors include the conditions of carbonization process. Understanding and optimizing the key influencing parameters is pivotal in developing robust and efficient MIMC systems for steel slag carbonation.

5.1. Microbial characteristics

5.1.1. Microbial type and strain selection

With the increase of microbial content, the compressive strength and carbonization rate are increased. Bacteria can accelerate the rate of carbon sequestration during mineralization. The microbially induced products will fill the pores of the steel slag cementitious material, forming an integrated dense structure and producing greater strength. And because different microorganisms show differences in enzyme activity and metabolic characteristics related to carbonation catalysis, it is necessary to select suitable microbial species and strains (Yi and Qian, 2018). For example, in different microbes, carbonic anhydrase-producing and ureolytic bacteria have gained particular research attention due to their abilities to accelerate CO_2 hydration and pH elevation, respectively. At present, the known microbial mineralizing bacteria mainly include sulfur producing bacteria, sulfate reducing bacteria, denitrifying bacteria, oxidizing bacteria and so on. The type of bacteria affects the crystal morphology, morphology and deposition rate of $CaCO_3$ (Ivanov et al., 2014). Among the many types of enzyme-breaking bacteria, Bacillus and Bacillus sporoides were the most selected bacteria in the study. These two bacteria have many advantages: they are adaptable to the environment, do not easily aggregate between cells, have a high specific surface area of the cells, and can use urea as a source of energy and nitrogen during metabolic processes.

Table 5
Summary and comparison of carbonization of steel slag by three types of urea hydrolyzing bacteria.

Bacterial category	Advantage	Disadvantage	Applicable condition	Application scenario	Reference
Sporosarcina pasteurii	High urease activity can effectively accelerate calcium carbonate precipitation.	The requirements for nutrition and environmental conditions are high and need to be well controlled.	Neutral to weakly alkaline environment Adequate source of urea and calcium	Microbial induced calcium carbonate precipitation is used for soil reinforcement and crack repair.	(Achal et al., 2011; Chu et al., 2012)
Bacillus sphaericus	It is well tolerated and has urease activity in a variety of environments.	Urease activity is relatively low and precipitation efficiency may not be as good as Sporosarcina pasteurii.	A variety of environmental conditions, including highly alkaline and nutrient-poor environments	Environmental remediation, alternative calcium carbonate precipitating microorganisms	(Ramachandran et al., 2001; Sharma and Ramkrishnan, 2016)
Other Urea-Hydrolyzing Bacteria	High diversity, adaptable to different environmental conditions.	Urease activity varied greatly, and the effect of different strains was significantly different.	Extreme environmental conditions, diverse waste disposal	Specific applications such as calcium carbonate precipitation and pollutant treatment in extreme environments	Ivanov and Chu (2008)

Under the condition of adding Ca^{2+} salt solution, it can be converted to CO_3^{2-} and quickly deposited $CaCO_3$. The two bacteria are mainly used in MICP experiments and application projects due to the advantages of Bacillus's fast production of $CaCO_3$, high yield, bacterial mineralization and cementation process (De Muynck et al., 2010).

Beyond physiochemical properties, certain phenotypic attributes, such as stress tolerance, growth kinetics, and secretion profiles, must also be evaluated during strain isolation and screening. Given the typically alkaline nature of steel slag, alkali-tolerant or haloalkaliphilic microbial strains adapted to extreme pH conditions may prove more suitable than neutrophilic or acidophilic variants.

5.1.2. Culture conditions and growth phase

The cultivation conditions applied to activate the microbial candidates, including temperature, pH, nutrient sources and concentrations, can impact both cell number/metabolic activity and the expression of carbonation-enhancing enzymes or metabolites (Lopez-Vazquez et al., 2009; Parmar and Sindhu, 2013). The difference in the precipitation form of $CaCO_3$ is related to the calcium salt used. Adding different calcium sources ($CaCl_2$, CaO, $Ca(CH_3COO)_2$ and $Ca(NO_3)_2$), the test results showed that $CaCl_2$ has higher urease activity and higher calcite yield, and is a good calcium source for microbial treatment technology (Achal and Pan, 2014). The concentration of cementing fluid plays an important role in the design and implementation of cementing fluid. Compared with the high concentration of cementing liquid, the crystals produced by the low concentration of cementing fluid are more uniform and stronger (Al Qabany et al., 2012; Qabany and Soga, 2014). The change of ambient temperature will directly affect the growth and metabolic activities of bacteria, thus changing the deposition rate and yield of $CaCO_3$, and changing the type and morphology of crystals. Studies have shown that urease has the strongest catalytic activity at 20–37 °C (Okwadha and Li, 2010). PH value plays an important role in bacterial metabolic activity and $CaCO_3$ deposition, and most urease bacteria commonly used in microbial mineralization are suitable for growth in alkaline environment.

Moreover, the carbonation efficiencies displayed by microbial strains often vary with culture age/physiological state. Taking some urea-metabolizing bacteria as an example, their enzyme expression patterns were different in different culture stages. In exponential or fixed growth stages, the expression of enzymes made these bacteria show higher carbonization activity than in lagging or dead stages. This means that the preparation of inoculations must be carefully controlled and optimized to ensure that microbial strains play a more stable and efficient role in the carbonization process of steel slag, fully reflecting the characteristics of their carbonization efficiency changes with the culture stage.

5.2. Steel slag substrate properties

5.2.1. Chemical composition

Generally speaking, based on the different steelmaking equipment that produces steel slag, most steel slag can be divided into three categories: electric furnace steel slag, open furnace steel slag and converter steel slag, of which converter steel slag production is the largest, is currently the most studied type of steel slag, the main components of steel slag for CaO, SiO_2, Al_2O_3, MgO, Fe_2O_3, also contains a small amount of MnO and P_2O_5 (Brand and Fanijo, 2020; Jiang et al., 2018; Yildirim and Prezzi, 2011).

A large amount of f-CaO and f-MgO in steel slag cause serious stability problems. Therefore, there are many obvious expansion cracking phenomena in building structures using steel slag admixture several years after completion (Haihe, 2020). Table 6 shows the chemical composition of steel slag (Yanfeng et al., 2023). Fig. 13 shows that the content of f-CaO in different steel slag samples decreased after carbonization treatment (Ma et al., 2023; Wang et al., 2024), so carbonization treatment can effectively reduce the expansion cracking degree of building structures. The mineralogical makeup of steel slag directly impacts its carbonation potential and reactivity. Carbonatable fractions like f-CaO and f-MgO, along with Ca-silicate and Mg-silicate minerals, serve as the primary reactive sites during CO_2 mineralization. Compositional variability arising from differences in steelmaking feedstocks and processes influences overall carbonatability.

5.2.2. Particle size and specific surface area

Smaller particle sizes and higher specific surface areas enhance slag permeability, CO_2/ion diffusion rates within pores, and overall carbonation extents. Microbial colonization and metabolite/enzyme access may also benefit from increased surface availability on finer slag powders. However, excessive fineness comes with issues concerning material flowability and handling. When the particle size of steel slag is over-refined, its specific surface area increases significantly. According to the characteristics of the powder material, the larger the specific surface area, the larger the contact area between the particles and the water, resulting in an increase in water demand (Hui-qun et al., 2012). Most pastes containing ultrafine steel slag have a longer setting time, and the compressive strength of most mortars is reduced when they contain ultrafine steel slag (Pang et al., 2022).

5.2.3. Pore structure characteristics

Studies have shown that the rate of carbonization reaction is mainly determined by the rate and degree of Ca^{2+} diffusion from the interior of steel slag to the surface (Lackner et al., 1995).The pore network topology and interconnectivity within steel slag grains determines mass transport pathways for microbial infiltration and carbonation reactions. Compared with carbonized samples, the structure of microbial

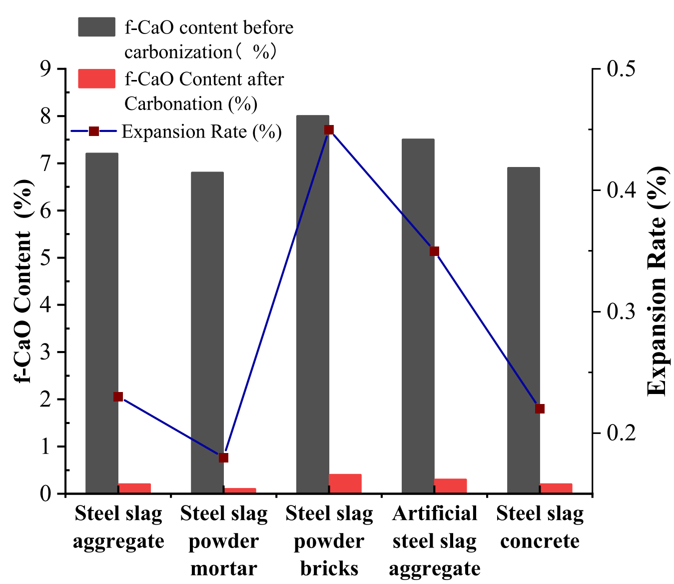


Fig. 13. Changes of f-CaO content in different steel slag samples after carbonization.

Table 6
Chemical compositions of steel slag.

Raw material	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	MnO	CrO_2	TiO_2	P_2O_5	SO_3
Steel slag (%)	36.4	14.8	25.2	5.0	12.6	1.0	0.6	0.7	2.0	0.3

mineralized samples is more dense, and the porosity at different depths of the experimental group without adding microorganisms is higher than that of the experimental group with adding microorganisms (Haihe, 2020). More open, permeable structures with larger cumulative pore volumes and narrower pore throat radiuses tend to correlate with superior reaction kinetics. However, excessive porosity impacts material strength.

5.3. Carbonation process conditions

5.3.1. Temperature and pH

Temperature plays a crucial role in microbial physiology, CO_2 solubility, and the solubility/stability of carbonate minerals within the process (Zhu and Dittrich, 2016). Likewise, solution pH affects microbial activity, CO_2 hydration/speciation, metal ion solubility, and carbonate precipitation. Both variables necessitate systematic optimization tailored to the specific microbial strains and substrates employed.

5.3.2. CO_2 concentration and pressure

Baciocchi et al. (2016) analyzed the influence of CO_2 partial pressure and L/S ratio on the carbonation reaction process of converter slag, and the results showed that when the CO_2 partial pressure increased from 0.1 to 1, the maximum carbon sequester of converter slag increased from 8% to 40.3%. Higher CO_2 partial pressures and gas phase concentrations translate to elevated driving forces for mineral carbonation, higher dissolved CO_2/bicarbonate availability, and increased overall carbonation rates and extent. However, excessive CO_2 levels may inhibit microbial activity or shift carbonation product polymorphs. The injection of CO_2 into the cement slurry, if limited to a shorter injection time, can increase the compressive strength of the carbonized paste (up to 18%) (Davolio et al., 2025).

5.3.3. Liquid-solid ratio and reaction time

The L/S ratio governs the accessibility of water (and nutrients) required to support microbial activity as well as dissolution of Ca/Mg species from the slag (Huang et al., 2024). However, excess water may dilute reactants or physically block mass transfer. Sufficient reaction time must be provided to allow carbonation reactions and product deposition to proceed to completion.

5.3.4. Agitation and aeration conditions

Vigorous agitation enhances mass transfer and mixing, distributing reactants and metabolic secretions more uniformly during MIMC (Faridi and Satyanarayana, 2015). Adequate aeration replenishes oxygen demands of respiring microbes and strips off gaseous/volatile byproducts.

In the process of steel slag carbonization, stirring and aeration conditions have important effects on the reaction. Proper stirring can promote the full contact between steel slag particles and carbon dioxide, and increase the reaction rate. The aeration directly supplies the carbon dioxide gas needed for the carbonization reaction.

The efficiency of microbial carbonization of steel slag is affected by many factors. Microbial characteristics such as species, strains and culture conditions play a key role, substrate characteristics including chemical composition, particle size and pore structure affect the reaction, carbonization process conditions such as temperature and humidity, gas concentration, L/S ratio are also crucial. These factors are interrelated and jointly determine the carbonization effect, which also provides a basis for subsequent performance improvement and application research.

6. Performance enhancement of microbial carbonated steel slag

The applications of microbial carbonation have shown promise to address steel slag utilization challenges through enhanced product properties and environmental compatibility compared to conventional carbonation alone. However, further research is still required to fully quantify performance enhancements achieved through specific microbial catalysis and optimize carbonated slag materials for practical end-uses. This section evaluates how microbial involvement during steel slag carbonation processing influences resultant properties central to target applications, covering key areas such as mineralogy and microstructure, physical and mechanical properties, and environmental behavior. All areas are closely linked and interact with each other to determine the potential and value of microbial steel slag carbonization in practical applications.

6.1. Mineralogy and microstructure

Microbial activity induces intricacies to the carbonation-derived mineralogy and microstructure of steel slag, impacting resultant attributes.

(1) Carbonate mineral polymorphism

Certain bacteria, like Bacillus cereus and Sporosarcina pasteurii, have been observed to promote the formation of $CaCO_3$ and hydromagnesite ($4MgCO_3 \cdot Mg(OH)_2 \cdot 4H_2O$) in addition to the common calcite and magnesite. The varied carbonate polymorphs exhibit distinct crystal morphologies, stabilities, and mechanical properties. For example, Li et al. (2018) observed Pseudomonas bacteria preferentially promoted vaterite and aragonite over calcite in concrete, altering strength development. Additionally, certain enzymes or metabolites can nucleate metastable crystal forms.

(2) Secondary phase precipitation

Beyond the primary carbonate minerals, the carbonation of steel slag can also lead to the precipitation of other secondary mineral phases, such as SiO_2, gehlenite ($2CaO \cdot Al_2O_3 \cdot SiO_2$), and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$). The formation and distribution of these phases depend on the chemical composition of the slag as well as the carbonation conditions. For example, Pan et al. (2015) observed ettringite precipitation within calcite shells upon microbial carbonation, which increased strength.

(3) Pore structure modification

The porous nature and pore structure characteristics of carbonated steel slag, such as pore size distribution, interconnectivity, and total pore volume, significantly impact material performance. Increased porosity can enhance water absorption, gas permeability, and ion exchange properties, benefiting applications like concrete admixtures, filters, and adsorbents. Conversely, excessive porosity may compromise the mechanical strength and durability of the carbonated slag.

Microbial activities redistribute insoluble precipitates, impacting the pore network. Confocal microscopy by Su et al. (2023) revealed denser microstructures and finer pores upon microbial carbonation, attributed to nucleation sites from cells. However, organic residues can occlude voids if over-secreted.

(4) Phase/Particle Interactions

Microbial mediation may chemically bond carbonates to slag phases or each other. SEM-EDS by Yang et al. (2022) identified C-S-H gels binding $CaCO_3$ nodules within carbonated slag. Such interactions may stabilize carbonate polymorphs with inferior thermodynamic stabilities.

Overall, harnessing microbial effects on carbonation-induced mineralogical transformations represents untapped potential for tailored slag material design. Systematic comparisons of abiotic versus microbial carbonation pathways can illuminate underlying mechanisms.

6.2. Physical and mechanical properties

The influence of microorganisms on the internal physical and mechanical properties of steel carbide slag products is closely related to the change of mineralogy and microstructure of steel carbide slag, and further extends to its performance in practical applications.

(1) Density, porosity and strength

Microbial secretion of carbonates occupying voids or binding mineral phases densifies carbonated slag matrices. Microbial carbonation has been observed to increase the compressive strength of slag-based cementitious composites compared to non-microbial carbonation (Rui and Qian, 2022).This is attributed to the formation of a denser, more uniform carbonate mineral matrix and the precipitation of secondary strengthening phases like ettringite. Microbial modified steel slag usually exhibits higher compressive strength. Microbial metabolism can lead to chemical changes on the surface of steel slag particles, forming cementing substances, thereby increasing the adhesion between particles. In addition, microbial modification also affects the particle distribution and size of steel slag particles, thus affecting the uniformity of compressive strength (Bohao et al., 2022). These changes in microstructure are directly translated into the enhancement of material strength at the macro level, which makes microbial carbonized steel slag have greater application potential in the field of building materials.

(2) Permeability and transport behavior

Pore structure tailoring through preferential carbonate nucleation spatially regulates permeability. Li and Qu (2012) reported permeability reductions despite porosity increases upon yeast-mediated carbonation. Transport behaviors directly impact applications like gas separation and water remediation. At 0.3MPa pressure, the carbon sequestration efficiency of microbial-carbonized steel slag technology can reach 16.65%, and the carbonized products can fill the internal pores of steel slag, significantly increasing the fractal dimension of penetration holes and transition holes (Zhang, X. et al., 2024).

(3) Durability and resistance properties

The mechanical properties and long-term durability of carbonated steel slag are critical performance attributes, especially when the material is utilized as a construction or building material. Microbial-mediated carbonation can potentially enhance these performance aspects compared to abiotic carbonation through tailored mineral precipitation and microstructural engineering.

Dense microstructures lend resilience against external stresses. Joshi et al. (2023) observed resistance enhancements to sulfate attack, thermal cycling and wetting-drying upon microbial carbonation ascribed to micro-refinements(Li et al., 2024; Yin et al., 2024). Metabolite surface coatings may impart resistance boosts.

6.3. Environmental behavior

Microbial activity in the process of steel slag carbonization has an important impact on the distribution of elements and leaching property, which has a beneficial effect on the environmental compatibility and health of steel slag, and reflects the importance of microbial carbonization of steel slag in the broader environmental level.

(1) Heavy metal speciation and mobility

Steel slag often contains elevated levels of heavy metal contaminants, such as Pb, Cr, and Cd, which can pose environmental and health risks if not properly managed. The carbonation of steel slag, especially through microbial-mediated pathways, can effectively immobilize these hazardous species by incorporating them into the stable carbonate mineral matrix or through adsorption on the slag surface. The leaching metal concentration increases with the increase of the steel slag content, and gradually decreases after reaching the peak concentration. The low leaching rate of metal is caused by the carbonate generated by the precipitation process of $CaCO_3$ induced by microorganisms (Zhang et al., 2021).

Microbes influence metal oxidation states and coordinative environments. Bai et al. (2021) observed Pb immobilization as Pb-EPS complexes upon bacterial carbonation. Conversely, reductive dissolution facilitated by Fe (II)-oxidizing bacteria mobilized certain metals.

(2) Carbon capture and sequestration

The primary motivation for the development of microbial carbonation technologies for steel slag is the opportunity to capture and sequester anthropogenic carbon dioxide emissions (Huang et al., 2024). The ability of microorganisms to catalyze the conversion of CO_2 into solid carbonate minerals represents a promising approach for the steel industry to mitigate its carbon footprint. By fixing carbon dioxide in steel slag, it not only reduces the concentration of greenhouse gases in the atmosphere, but also realizes the resource utilization of industrial waste, which has important environmental and economic significance.

(3) Energy and resource efficiency

Compared to conventional thermal or chemical approaches for steel slag carbonation, microbial-based strategies can potentially offer energy and resource efficiency advantages. Microbial catalysts operate under ambient or moderate temperature and pressure conditions, reducing the energy input required (Qian et al., 2022). Additionally, the use of renewable and recyclable microbial resources may further enhance the environmental and economic sustainability of the process.

In general, the interaction between mineralogy, microstructure, stability and environmental behavior requires a deeper understanding of the mechanism, so that it is important to further optimize microbial carbonization technology, expand its application areas, and achieve sustainable use of steel slag.

7. Practical application of MIMC steel slag

MIMC steel slag can effectively improve the performance of steel slag through microbial metabolic activities, and make it more suitable for the special requirements of subgrade and pavement engineering. It is necessary to discuss the application potential, practical effect and challenges of MIMC steel slag in construction industry.

7.1. Performance advantage of MIMC steel slag application

The addition of microorganisms can obviously improve the dissolution of Ca^{2+} in the steel slag phase, so that the f-CaO and f-MgO phases in the steel slag phase can be leached in a short time, and promote the leaching reaction of calcium magnesium silicate phase in the steel slag. Under a certain carbon dioxide pressure curing condition, microorganisms can promote the conversion of carbon dioxide into carbonate, and the Ca^{2+} leached in the system to form Ca carbonate, so that the strength of steel slag gelled material building materials has been significantly improved (Jin et al., 2021). Through the action of microorganisms, the dissolution and transformation of f-CaO and other minerals in steel slag can be accelerated, so as to reduce the content of f-CaO in steel slag and improve the volume stability of steel slag (Qian et al., 2021). The permeable property of porous brick can be improved by using microbe-steel slag to prepare such products. The microbial-steel slag carbon permeable brick prepared by a specific method has a high permeable coefficient (Wang et al., 2021). The use of steel slag in subgrade and pavement engineering can reduce land occupation and environmental pollution, stimulate the economic development of the surrounding area, improve social benefits and reduce construction costs, especially in large-scale use of economic benefits are more significant; The technology can also reduce the exploitation of natural resources, reduce the amount of ore mined, explosion risk and noise pollution, relieve road pressure, and contribute to environmental benefits.

7.2. Application practice in roadbed and pavement engineering

Carbonization of steel slag can significantly improve the volume stability of cement mortar. Steel slag is used to replace natural sand to make cement mortar according to a certain content, and compressive strength test and expansion performance test are carried out. The results showed that the compressive strength of uncarbonized steel slag cement mortar specimens decrease with the increase of the content, while the compressive strength of carbonized steel slag cement mortar specimens first increases and then decreases with the increase of the content (Pengfei et al., 2024). When steel slag is applied to the water-stabilized layer, there will be uneven distribution of steel slag, resulting in the phenomenon of expansion and cracking of the sample. Therefore, carbonization of steel slag based cementitious materials is required. With the increase of carbonization time and temperature, the self - infiltration expansion rate of pre-carbonized steel slag based cementitious materials gradually decreases, and the activity increases first and then decreases (Zhenwei et al., 2024). Self - infiltration expansion rate is the rate of volume expansion of steel slag under certain conditions, which is of great significance to evaluate the volume stability of steel slag in engineering applications. The volume stability of steel slag can be effectively improved by using Bacillus pasteurellae, and the modified steel slag is used to prepare the road base material. When the cement content is 6%, the 7d unconfined compressive strength of the expressway and the first-level highway base, the second-level and lower-level highway base, and the second-level and lower-level highway base is increased compared with that before the modification (Liu et al., 2024). Through the action of microorganisms, the bond between the steel slag particles is firmer, forming a tighter structure, thus improving the bearing capacity of the roadbed. In addition, microbial modified steel slag also shows superior water resistance in the subgrade strengthening. The involvement of microorganisms makes the pore structure of steel slag more complicated, slows down the rate of water penetration, and reduces the water sensitivity of roadbed. This provides additional advantages for road construction in wet environments or during the rainy season. The mechanical properties and anti-aging properties of asphalt mixture can be adjusted by using novel pavement structure instead of traditional pavement (Jiang et al., 2024), or by introducing microbial modified steel slag into asphalt mixture in the application of road surface materials. Microbial modified steel slag provides better adhesion and gelling properties, thereby enhancing the adhesion of asphalt mixture, reducing the stripping of asphalt and aggregate, and improving the weathering resistance of road surface. The use of microbial modified steel slag in road surface material also improves its cracking resistance. Through the intervention of microorganisms, the particle structure and internal organization of steel slag are more uniform and dense, which makes the road surface material more stable under traffic load and deformation pressure, and slows down the formation and expansion of cracks (Zhihua et al., 2024). Pulverized steel slag, fly ash and cement were used to prepare porous aggregate. With the increase of temperature and carbonization time, the performance of steel slag aggregate increased gradually, and the crushing rate, expansion rate and crushing value decreased gradually (Jian et al., 2023). The results of the study on the effect of curing conditions on the mechanical properties of steel slag cement cementitious materials under high temperature carbonization showed that carbonization can effectively prevent the corrosion of cementitious materials, improve the durability of cementitious materials and improve the compactness of cementitious materials (Pan et al., 2017; Zhan et al., 2014).

Although carbonized steel slag is used in roadbed and pavement engineering, it faces the problem of compatibility with existing construction technology and materials. Its particle shape, size distribution and surface properties may be different from conventional aggregates, affecting the working performance and mechanical properties of concrete or asphalt mixtures. Through material pretreatment and modification of microbial carbonized steel slag, optimization of mix ratio, development of suitable new construction technology, and establishment of long-term performance monitoring and feedback mechanism, the compatibility problem between microbial carbonized steel slag and existing construction technology and materials in roadbed and pavement application is solved.

8. Future prospect of MIMC steel slag technology

This section explores the fundamental reaction mechanisms of microbial carbonation and the assessment of environmental impacts and sustainability, and outlines future research directions.

8.1. Fundamental reaction mechanisms

A deeper mechanistic understanding of the multi-faceted biogeochemical pathways underpinning microbial carbonation is crucial for streamlining process design and optimizing product outcomes. Existing knowledge, although growing, remains fragmented across disciplines, the specific action mechanism of microorganisms in the process of steel slag carbonization remains to be further explored.

(1) Microbial carbonic anhydrase activity. The role of carbonic anhydrase enzymes secreted by certain microbes in catalyzing CO_2 hydration and bicarbonate formation is well-established. However, the specific contributions of this activity versus other metabolic pathways like ureolysis in accelerating slag carbonation kinetics require quantitative elucidation. Mapping how expression levels, activity rates, and stability of these enzymes vary across diverse microorganisms can facilitate targeted strain engineering.
(2) Biofilm development and pore network analysis. The influence of microbial biofilm development, cell adhesion, and extracellular polymeric secretions on the morphology of carbonated steel slag pores poses an unanswered query. Monitoring these biotic-abiotic interactions over space and time using sophisticated in-situ characterization methods can help achieve the desired effect of pore structures within steel slags.
(3) Diverse microbial community effects. A microbiome is a collection of microorganisms that interact with each other in a particular environment and work together to influence the functions and processes of an ecosystem, either synergistically or competitively. The impacts of multispecies microbial consortia, versus monocultures, on carbonation reaction kinetics, product qualities, and environmental compatibility are not well elucidated. Understanding microbial community assembly, metabolic interactions, and succession patterns can inform optimal consortium design for enhanced and reliable performance.

8.2. Environmental impact and sustainability

MIMC steel slag technology faces many challenges in terms of environmental impact and sustainability. For microbial carbonation technologies to gain widespread acceptance, their environmental compatibility, resource efficiency, and economic viability must be comprehensively validated through quantitative assessments.

(1) Life cycle assessment and carbon footprint. Rigorous life cycle analyses quantifying energy consumption, greenhouse gas emissions, and other environmental impacts of microbial carbonation,

relative to conventional abiotic approaches, are crucial for assessing process sustainability.

(2) Wastewater treatment and effluent management. The water, nutrient, and potentially toxic chemical demands of microbial cultivation and carbonation processes, as well as the composition and treatability of effluent streams, must be thoroughly characterized. Developing integrated wastewater treatment strategies is essential for minimizing resource footprints and environmental risks.

(3) Integrated waste valorization frameworks. Conceptualizing microbial carbonation as part of holistic industrial symbiosis networks, where carbonated slag is employed as a resource within broader applications like construction, can maximize the circularity and economic viability of the overall system. Life cycle thinking is essential for identifying such synergistic opportunities.

8.3. Outlook and future directions

The promising yet complex nature of microbial carbonation for steel slag valorization underscores the need for continued, concerted efforts across multiple frontiers to fully harness its potential. Key future research directions include.

(1) Elucidating fundamental biogeochemical reaction mechanisms underlying microbial influences on carbonation kinetics, mineralogical transformations, and microstructural development through multi-scale characterization and modeling. The atomic scale changes of steel slag during microbial carbonization were studied by synchrotron X-ray diffraction (XRD), X-ray absorption spectroscopy (XAS) and transmission electron microscopy (TEM). Develop multi-scale models that integrate the physical, chemical and biological processes involved in carbonation reactions. These models will be verified according to experimental data obtained from different scales, and can accurately predict the behavior of microbial carbonization process of steel slag under different conditions, providing a theoretical basis for process optimization.

(2) Establishing rational design frameworks for engineering multifunctional carbonated steel slag materials tailored to diverse end-use applications, by systematically correlating process conditions, microbial strains, and performance attributes. Establish the relationship between process parameters (such as temperature, CO_2 concentration, reaction time, L/S ratio), different microbial strains and the strength, permeability, durability and other properties of carbonized steel slag. Artificial neural network, support vector machine and other machine learning algorithms are used to build the prediction model of material properties.

(3) Conducting comprehensive environmental life cycle assessments, techno-economic analyses, and stakeholder engagement to validate the sustainability and commercial viability of microbial carbonation technologies at scale. A hybrid approach combining process-based modeling and input-output analysis is used to explain all phases of the technology life cycle, from raw material extraction to end-of-life processing. Contribute to a comprehensive assessment of its carbon footprint, energy consumption and potential environmental impact.

(4) Developing integrated process designs, incorporating novel reactor configurations, advanced monitoring and control, and systems-level optimization, to translate lab-scale advances into robust, industrially-relevant carbonation solutions. Scaling microbial carbonization from laboratory to industrial Settings requires the development of integrated and efficient process designs that can be designed with modular reactor concepts that allow for easy customization and scalability. Each module is equipped with advanced sensors and an automated control system based on internet of things technology to ensure accurate real-time monitoring and control of key process parameters.

Overcoming these critical frontiers can elevate microbial carbonation as a mainstream approach for sustainable steel slag valorization, carbon management, and advanced materials development, with far-reaching environmental and societal benefits.

9. Conclusions

This review provided a comprehensive overview of the current state of research on MIMC as a promising approach for improving carbon sequestration and performance of steel slag. The findings highlight the significant advantages of MIMC over conventional physicochemical carbonation methods.

Compared to direct and indirect carbonation techniques, MIMC has demonstrated superior carbonation efficiency, with reported degrees of up to for steel slag. This enhanced performance can be attributed to the ability of microorganisms to catalyze the conversion of CO_2 into carbonate ions through the production of carbonic anhydrase, as well as their capacity to increase the local pH through metabolic processes, further promoting the precipitation of stable Ca and Mg carbonate minerals.

The utilization of microorganisms also allows for milder operating conditions, such as room temperature and atmospheric pressure, in contrast to the harsh requirements often associated with conventional carbonation methods. This results in lower energy consumption, reduced operational costs, and a more environmentally friendly process.

The review also discussed the various microbial species that have been explored for the carbonation of steel slag, highlighting their unique metabolic capabilities and the factors that influence their carbonation efficiency. The optimization of parameters such as temperature, CO_2 concentration, reaction time, and liquid-to-solid ratio has been shown to be crucial for maximizing the carbon sequestration and stabilization potential of the carbonated steel slag.

Overall, the insights provided in this review suggest that MIMC holds great promise as a sustainable and economically viable solution for enhancing the utilization of steel slag, a valuable industrial byproduct, in various applications. Further research and development in this field can help unlock the full potential of microbial carbonation for the steel industry's transition towards a more circular and environmentally responsible future.

CRediT authorship contribution statement

Jue Li: Writing – review & editing, Writing – original draft, Funding acquisition, Data curation. **Qingmeng Hou:** Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Xinqiang Zhang:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Data curation. **Xiaobin Zhang:** Writing – original draft, Resources, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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