Contents lists available at ScienceDirect

Green Energy and Resources

journal homepage: www.journals.elsevier.com/green-energy-and-resources

Study on preparation technology and properties of calcium based CO_2 absorbent from acid leaching steel slag

Ruiying Wang [a], Tao Qi [a], Hongfeng Ji [a], Gang Du [a], Canhua Li [a,b,*], Shujing Zhu [c], Jiamao Li [b], Chen Zhao [d]

[a] School of Metallurgical Engineering, Anhui University of Technology, Ma'anshan, 243002, China
[b] School of Materials Science and Engineering, Anhui University of Technology, Ma'anshan, 243002, China
[c] School of Resources & Environment Science, Hubei University, Wuhan, 430068, China
[d] School of Materials Science and Engineering, City University of Hong Kong, Hong Kong, 999077, China

ARTICLE INFO

ABSTRACT

Currently, more and more industrial carbon emissions lead to a significant increase in greenhouse gases, which has a significant impact on global climate change. Therefore, the storage and reuse of carbon dioxide is an important issue in modern society. In this paper, calcium based CO_2 absorbent was prepared from converter slag by acetic acid extraction and modification of steel slag. The study investigated the effects of parameters in indirect acetic acid leaching, including acetic acid concentration, leaching time, solid-to-liquid ratio, and temperature, on the elemental content in the adsorbent. It also compared the cyclic adsorbent stability of calcium-based adsorbents with commercial calcium oxide. The results indicated that the optimal technical parameters were: acetic acid concentration 1 mol/L, leaching time 40 min, solid-liquid ratio of 1:10, leaching temperature of 40°C, achieving an extraction rate of 88.05% for calcium elements. Its initial CO_2 adsorbent capacity is 0.51 $g_{CO2}/g_{adsorbent}$, and the CO_2 adsorbent capacity after 20 cycles is 0.202 $g_{CO2}/g_{adsorbent}$, and the inactivation rate is 60.39%. Compared with AR CaO, the adsorbent has more ideal CO_2 capture ability.

1. Introduction

China's crude steel production reached 1.033 billion tons in 2021 (Li et al., 2023), generating 15%–20% steel slag by weight (Sang and Lee, 2017).According to Fig. 1, while some developed nations achieve 85%–90% utilization (Gao et al., 2023), China's rate remains below 30%, with over 1 billion tons stockpiled (White et al., 2010). Current applications include cement/concrete (Costa et al., 2024), construction (Zhu et al., 2025), and agriculture (Wang et al., 2021). The GB175-2023 standard's exclusion of steel slag (GB175-2023, 2024) reduces utilization options, despite national policies promoting waste innovation (National Development and Reform Commission, 2021)

As the world's largest energy consumer, China's energy industry inevitably produces large amounts of CO_2 in industrial production processes, which according to statistics account for over 80% of the increase in atmospheric CO_2. China's emission model (CAEP-CP 1.1) projects CO_2 emissions reaching 10.5 billion tons by 2030 (Cai et al., 2021), potentially causing climate change impacts including glacier melt and the risk of extensive land inundation (Song, 2006; Lasheras et al., 2011; Zhu et al., 2020; Li et al., 2025). The steel industry accounts for 6%–7% of global emissions, with this proportion rising to 15% in China (Pan et al., 2016).

Therefore, reducing CO_2 emissions is imperative. The most effective method to reduce CO_2 currently is to use solid adsorbents to adsorb CO_2, thereby separating it from other gases and obtaining high-purity CO_2. Due to the fact that the main carbon emission processes in industry occur under high temperature conditions, it is necessary to achieve efficient CO_2 adsorbent under such conditions (Chen et al., 2022). Research has shown that at high temperatures, CaO adsorbents can effectively adsorb CO_2 to form $CaCO_3$ at temperatures ranging from 600 to 700°C, with a theoretical adsorbent capacity of up to 0.786 g_{CO2}/g_{CaO}. Subsequently, the adsorbent can be reduced to CaO by heating it to 900°C, thereby releasing CO_2. This cyclic CO_2 adsorbent and desorption form the basis of the "calcium cycle (CaL)" technology. It has the advantages of high selectivity and fast reaction rate, and has been widely used for CO_2 capture after high-temperature combustion (Geng et al., 2021; Guo et al., 2019). At present, the main source of CaO in industry is surface limestone. However, excessive extraction of limestone can cause
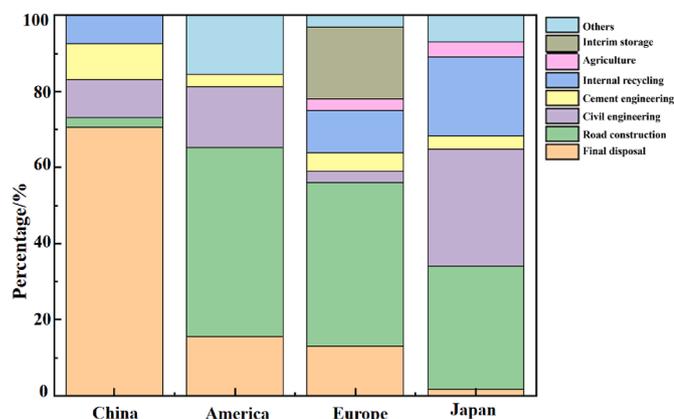

Fig. 1. The utilization of steel slag in different countries.

environmental damage such as land degradation, landslides, and air pollution. Therefore, finding alternative sources of calcium has become an important task. Steel slag can be used as an effective CO_2 capture material because of its high CaO content. At present, the mineral carbonation methods for CO_2 mainly include direct carbonation and indirect carbonation. When the humidity is less than 0.2, direct carbonation can be called gas-solid direct carbonation, and when the humidity is greater than 0.2, direct carbonation can be called aqueous phase carbonation (Liu et al., 2021). Ukwattage et al. (2017) first studied the carbonation reaction mechanism of CO_2 fixation using steel slag as raw material, and the determining factors of CO_2 fixation amount are steel slag particle size and reaction temperature.

Dry carbonization is a gas-solid reaction process, in which gaseous CO_2 directly reacts with CaO in slag to form $CaCO_3$ and release heat (Bobicki et al., 2012). The reaction temperature of dry carbonization is generally higher than that of wet carbonization, often in hundreds of degrees Celsius (Polettini et al., 2016). From the composition of steel slag, it has significant advantages in gas-solid reaction carbon fixation. However, the reaction rate of gas-solid reaction for carbon fixation is relatively slow, resulting in a lower amount of carbon fixation (Tian et al., 2013; Gao et al., 2024; Myers et al., 2019). Revathy et al. (2016) found that the carbonization process can spontaneously occur at room temperature. After 1 h of carbonization, the carbon fixation rate of steel slag slows down, and after 3 h, the CO_2 adsorption almost no longer increases. This is mainly due to the formation of a carbonate layer on the surface of steel slag particles during the carbonization process and the residual calcium poor silicate area after the reaction, which hinders the diffusion of CO_2 gas to the unreacted zone at the center of steel slag particles. In the gas-solid reaction carbon fixation process, the initial carbon fixation rate is fast and controlled by the chemical reaction rate; Then, as the new phase product layer forms and grows, the product layer gradually wraps around the central unreacted zone, and the reaction begins to be controlled by diffusion mass transfer. The carbon fixation rate begins to slow down, which also leads to limited carbon fixation by dry carbon fixation (Tu et al., 2015). Due to the important role of temperature in accelerating the reaction rate, increasing the carbonization temperature can accelerate the initial carbonization rate. Therefore, dry carbon fixation of steel slag at high temperatures is more advantageous (Wang et al., 2021).

The wet carbonization process uses water as the medium, and the carbonization process includes three phases of gas liquid solid, which is more complex than the reaction process of dry carbonization. The presence of water provides favorable conditions for the dissolution of CO_2 gas and the leaching of calcium ions from steel slag, which helps to improve the carbonization reaction rate. In addition, it does not require high temperatures like dry carbonization, which is beneficial for longer carbonization reactions (Costa et al., 2007; Thonemann et al., 2022). The increase of temperature will improve the hydration reaction of steel

slag, and more calcium ions are dissolved in water, which can promote the carbonation reaction (Ko et al., 2015). Tian et al. (2016) found through research that acid leaching technology can recover CaO from steel slag in the form of high-purity quicklime, while also recovering iron rich minerals, thereby achieving high-value utilization of steel slag. Sun et al. (2018) prepared CaO based adsorbents using steel slag as raw material and acetic acid. The study found that the adsorbent had the best carbon dioxide capture capacity and stability when the extraction time was 2 h, the extraction temperature was 60°C, the acid concentration was 60°C, the acid concentration was 30%, and the solid-liquid ratio was 1:10. Bilen et al., 2018 found in their study on leaching and indirect carbonization processes of steelmaking slag that acid concentration, liquid-solid ratio, particle size, and reaction temperature have a significant impact on the extraction of calcium from steel slag. Kashiwaya et al. (2020) had studied a kinetic model that can analyze the calcium leaching behavior of steel slag with different particle size distributions. Therefore, the rate control step of Ca leaching will vary with the change of particle size. Rong et al. (2025) obtained calcium based adsorbents by treating three different types of steel slag with acetic acid. Through orthogonal experiments, it was found that the carbon capture performance of the calcium based adsorbent reached its optimum when the acid concentration was 1 mol/L, the ratio of steel slag to acetic acid was 1:15, the acid leaching time was 2 h, and the acid leaching temperature was 60°C. However, due to the stable properties of the silicon calcium phase in steel slag, it is difficult to directly utilize steel slag to absorb CO_2. Therefore, the research on leaching, extracting and recycling calcium from steel slag for capturing CO_2 can not only turn waste into treasure, but also reduce carbon emissions, which has dual significance for environmental protection and resource reuse (Chen et al., 2019; Kong et al., 2019). Meanwhile, the carbon capture performance may vary depending on the leaching conditions set in the experiments (Fang et al., 2021).

Dry carbonization at room temperature has low carbon sequestration capacity and slow rate, and does not have the advantage of carbon sequestration. However, wet carbonization is beneficial for improving the diffusion rate of CO_2. Using steel slag as a raw material for preparing CO_2 adsorbents is not only cost-effective but also often located near CO_2 emission sources, enabling the reduction and resource utilization of bulk solid waste. Therefore, the following discussion mainly focuses on wet carbonization and its influencing factors. To address the limiting factor of extremely low active calcium components available for CO_2 carbonation fixation in steel slag, this study aims to separate and recover calcium from steel slag by using acetic acid for leaching and modification, in order to prepare calcium-based adsorbents. A multi-factor synergistic analysis was conducted to evaluate the efficiency of element extraction, systematically investigating the effects of leaching conditions, including acid leaching time, initial acid concentration, solid-liquid ratio, and leaching temperature. Additionally, the process of acetic acid leaching of steel slag and the regulatory mechanisms of element adjustment in the modified adsorbent were studied. he cyclic CO_2 capture ability of the prepared calcium based adsorbents was studied using a thermogravimetric analyzer.

2. Experimental materials and methods

2.1. Experimental materials

The steel slag used in the experiment came from the converter slag of a steel company in Ma'anshan City, Anhui Province, China. Before the experiment, the steel slag was subjected to pretreatment such as crushing, grinding, drying, screening, and calcination. The chemical composition was analyzed using an ARLAdvant'x360 X-ray fluorescence spectrometer as shown in Table 1. The phases and appearance were analyzed using a Bruker D8 Advance X-ray diffractometer and a JSM-6490LV scanning electron microscope, as shown in Figs. 2 and 3.

Table 1
Main chemical composition of steel slag.

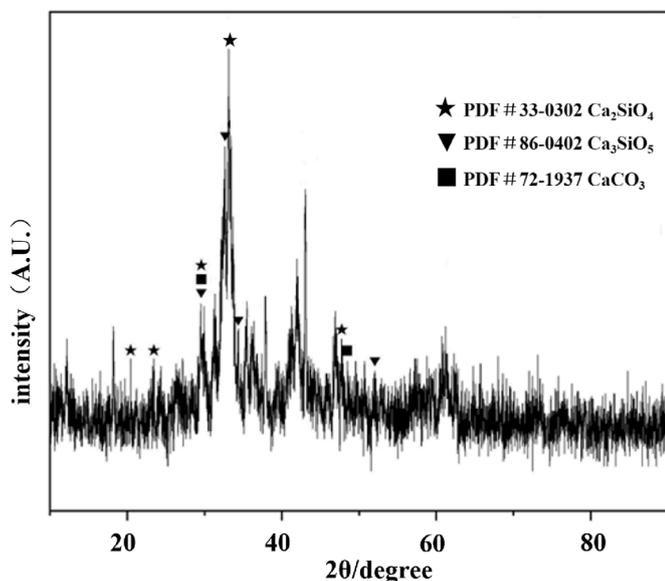| Composition	CaO	SiO$_2$	Fe$_2$O$_3$	Al$_2$O$_3$	MgO	MnO	P$_2$O$_5$	TiO$_2$	SO$_3$	Cr$_2$O$_3$	Others
Mass fraction, wt%	38.290	20.460	16.640	10.030	6.130	2.650	1.530	1.280	1.220	0.477	1.293

Fig. 2. XRD analysis of converter slag.

According to Table 1, the calcium oxide content of steel slag is very high, exceeding 38%. It shows that steel slag has high carbonation potential, and provided conditions for subsequent carbon dioxide adsorption experiments.

From X-ray diffraction analysis (refer to Fig. 2), the diffraction peaks of steel slag are irregular, sharp, and highly intense, with numerous miscellaneous peaks, indicating that its composition is highly complex. It can be seen that the calcium containing phases of converter steel slag are mainly calcium silicon oxides (Ca$_2$SiO$_4$, Ca$_3$SiO$_5$), calcium carbonate (CaCO$_3$), etc., which is consistent with the XRF analysis results. The XRD results demonstrate that calcium silicate oxides exhibit stronger diffraction peaks, indicating both higher abundance and superior carbonation activity compared to the weakly detected CaCO$_3$ phase. Therefore, the raw steel slag cannot be directly utilized in calcium-looping systems for high-temperature CO$_2$ capture.

Steel slag possesses a porous structure, indicating its large specific surface area and abundant active adsorbent sites, making it an excellent raw material for adsorbent preparation. From Fig. 3, it can be seen that the steel slag has a dense and hard texture, and contains more irregularly arranged pore. This indicates that steel slag must be pretreated in order to better adsorb carbon dioxide.

2.2. Experimental methods

The experimental setup for this study used a 500 mL three necked round bottom flask to construct the reaction system. The experimental flowchart was shown in Fig. 4. The specific operation process follows the following technical route: (1) Raw material pretreatment: steel slag and 200 mL of known concentration of acetic acid solution are added to a three necked round bottom flask at a certain solid-liquid ratio (1:10, 1:20, 1:30); (2) Magnetic stirring: set the time of 1h and use a magnetic stirrer to stir and mix the slurry; (3) Phase separation: using a vacuum filtration device to perform solid-liquid separation on the mixed liquid; (4) Preparation of precursor: The obtained leachate was placed in a blast drying oven and dried at 105°C for 12 h to obtain the adsorbent precursor; (5) Calcination: The precursor was calcined in a muffle furnace at 850°C for 1 h; (6) Cooling ball milling: After calcination and natural cooling, ball milling treatment was carried out to finally produce steel slag calcium based adsorbent.

It was characterized the cyclic performance of the calcium based adsorbent obtained from the steel slag source using a thermogravimetric analyzer.

The CO$_2$ adsorption capacity of the adsorbent (C_n, g$_{CO2}$/g$_{adsorbent}$) can be calculated by equation (1).

$$C_n = \frac{\Delta m_n}{m} \tag{1}$$

The deactivation rate (L_n, %) of the adsorbent after n cycles was calculated using equation (2).

$$L_n = \frac{C_1 - C_n}{C_1} \times 100\% \tag{2}$$

Where,

the C_1 is the CO$_2$ adsorbtion capacity of the adsorbent after the 1st cycle, g$_{CO2}$/g$_{adsorbent}$;

the C_n is the CO$_2$ adsorption capacity of the adsorbent after the n times cycles, g$_{CO2}$/g$_{adsorbent}$;

the Δm_n is mass change of adsorbent after n times cycles, g;

the m is initial mass of the sample at the beginning of the n times cycles, g.

（a）Magnify 200 times   （b）Magnify 1400 times
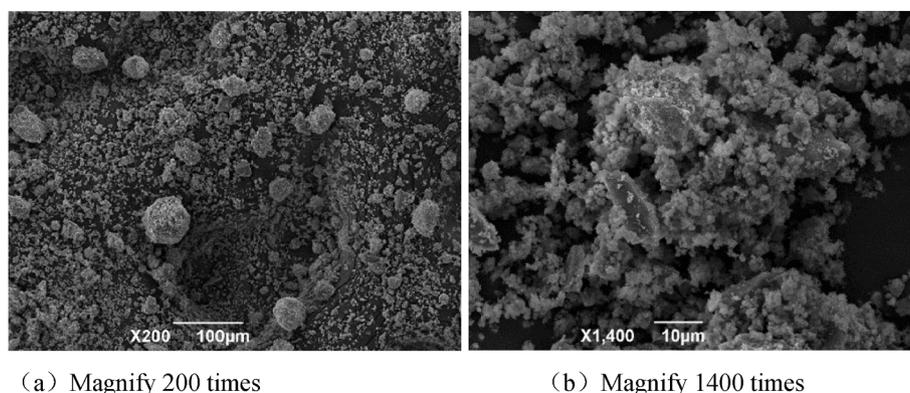
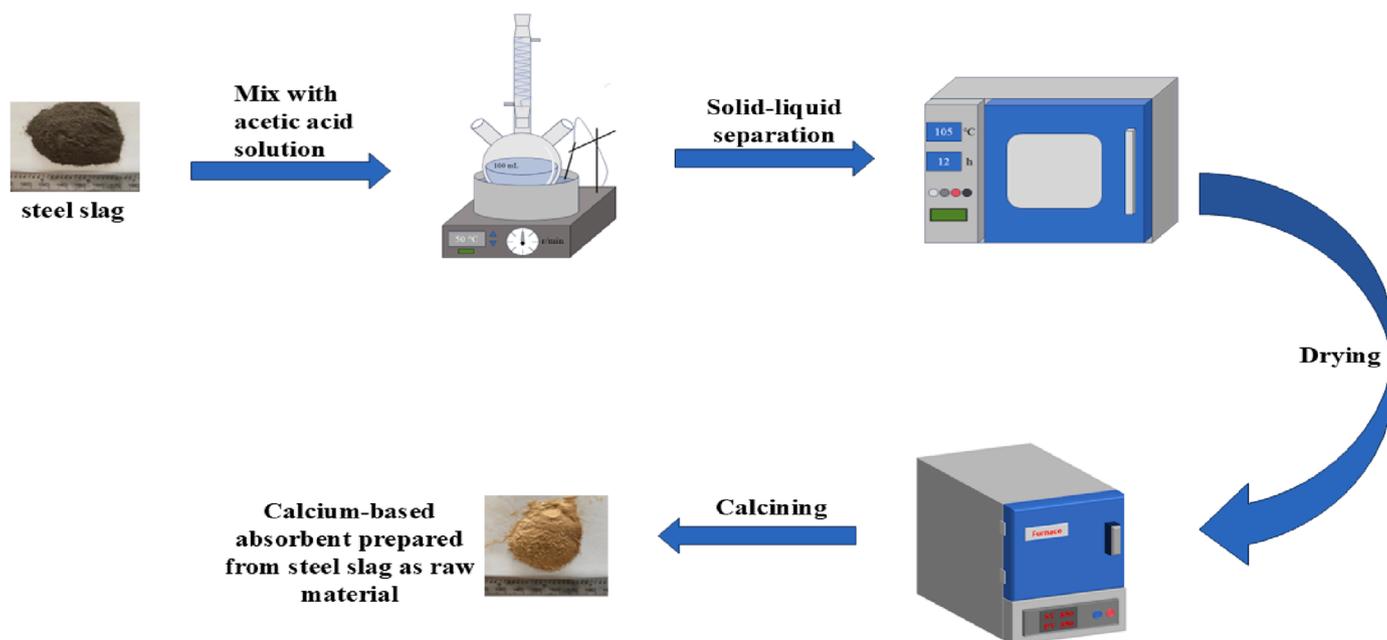**Fig. 3.** Morphology analysis of converter slag.

Fig. 4. Flow chart of the experimental equipment for steel slag leaching.

Table 2
Factors and levels of acidizing parameters of steel slag
Factors: A leaching time (min) B, acetic acid concentration (mol/L) C, solid-liquid ratio (g: mL) D, leaching temperature (°C).

level	factors			
	A	B	C	D
Level 1	20	1	10:1	30
Level 2	60	3	20:1	45
Level 3	120	5	30:1	50

3. Experimental research

3.1. The influence of different acid leaching conditions on the content of absorbent elements

In this study, acetic acid was used as a leaching agent to extract valuable elements from steel slag. Consider these factors: Temperature directly affects reaction rate and mineral decomposition efficiency; acid concentration determines the driving force of chemical reactions; leaching duration controls reaction completeness; while solid-liquid ratio influences mass transfer effectiveness and product concentration. These parameters collectively govern the thermodynamic and kinetic characteristics of the leaching process, and systematic optimization can significantly improve the recovery rate of target elements. A four-factor, three-level orthogonal experiment was designed to investigate the

effects of different parameters on the leaching efficiency of the target elements. The four factors were leaching time (factor A), acetic acid concentration (factor B), solid-liquid ratio (factor C), and leaching temperature (factor D). The four acid leaching factors and their corresponding levels were listed in Table 2. According to the principle of orthogonal experiment, there were a total of 9 experimental groups. The orthogonal experiment table and the elemental composition of the absorbent were listed in Table 3.

The main factors affecting the leaching efficiency of each element were determined using the range analysis value R, and the calculation formula was shown in equation (3).

$$R = \text{Max}(K_{avg}) - \text{Min}(K_{avg}) \tag{3}$$

K_{avg} was the average value of the sum of experimental data at a certain factor and level. The R value can reflect the significance of influencing factors, and the larger the R value, the greater the impact of this level on the experimental results. On the contrary, it indicated that the level has a smaller impact on the experimental results.

According to the range analysis results in Fig. 5, the main factor affecting calcium content was the initial acid concentration, followed by leaching time, and then the solid-liquid ratio. The leaching temperature had the smallest impact on calcium content. It can be seen that in order to increase the content of calcium element in the modified adsorbent, significant effects can be achieved by controlling the leaching time and acetic acid concentration. By using a lower initial acid concentration and a shorter leaching time, a higher leaching rate of calcium elements can

Table 3
Main element contents of precursors.

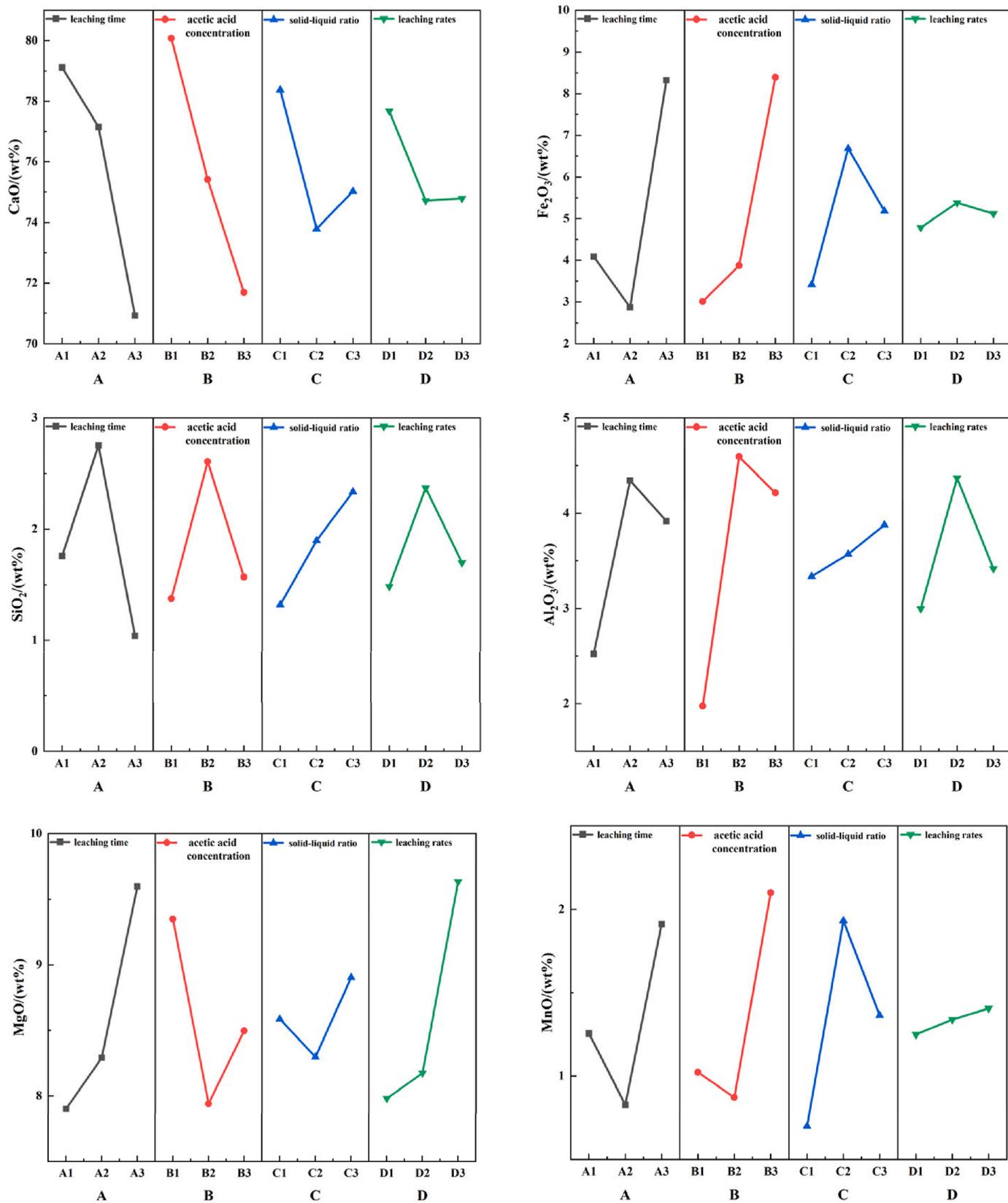| factor/level experimental sequence	factor				(wt%)					
	A	B	C	D	CaO	Fe$_2$O$_3$	SiO$_2$	Al$_2$O$_3$	MgO	MnO
1	1	1	1	1	88.05	0.0216	0.382	0.0472	8.03	0.232
2	1	2	3	2	77.09	3.24	3.520	4.58	7.13	0.838
3	1	3	2	3	72.20	9.00	1.370	2.94	8.54	2.700
4	2	1	3	3	79.87	0.899	2.610	2.83	10.39	0.626
5	2	2	2	1	76.84	2.93	3.190	4.72	6.72	0.886
6	2	3	1	2	74.75	4.78	2.460	5.48	7.76	0.970
7	3	1	2	2	72.32	8.12	1.130	3.05	9.63	2.210
8	3	2	1	3	72.32	5.45	1.110	4.48	9.97	0.894
9	3	3	3	1	68.12	11.40	0.877	4.22	9.19	2.630

Fig. 5. Effects of leaching time, acetic acid concentration, solid-liquid ratio and leaching temperature on leaching rates of Ca, Fe, Si, Al, Mn and Mg elements.

be achieved. This is because the calcium in steel slag primarily exists in the form of $CaCO_3$ or calcium silicate, which reacts with acetic acid to form calcium acetate. At lower acetic acid concentrations, $CaCO_3$ is predominantly dissolved. Since silicic acid is much weaker than acetic acid and calcium silicate has significantly lower solubility than calcium carbonate, the reaction is difficult to occur. Therefore, leaching Si requires higher acid concentrations and longer durations. However, excessive acid concentration and prolonged leaching time may lead to the re-precipitation of Ca^{2+} as calcium acetate. Compared to the process parameters used by Sun et al. (2018), which employed 60% acetic acid concentration, a leaching time of 2 h, and a temperature of 60°C, this study achieved a calcium leaching rate of 88.05% under milder conditions: lower acetic acid concentration (1 mol/L, approximately 6%), shorter leaching time (40 min), and lower temperature (40°C), significantly improving process economics. In contrast to the solid-liquid ratio of 1:15 in the study by Rong et al. (2025), this study optimized the ratio to 1:10, reducing acid consumption while achieving higher calcium leaching efficiency.

In addition, the main factors affecting the content of Fe, Al, and Mg were also the initial acid concentration and leaching time. But for Fe element, the effect of leaching time was greater than the initial acid concentration. Fe element exists as Fe_2O_3 in the steel slag, which exhibits slow leaching kinetics with acetic acid. Therefore, prolonged leaching time serves as the critical factor to overcome kinetic limitations in iron extraction. For Al element, the initial acid concentration had a significant impact. Al^{3+} hydrolysis under low pH conditions significantly inhibits leaching efficiency. Precise control of acid concentration is essential to prevent the formation of $Al(OH)_3$ precipitates that would otherwise compromise extraction yields. For the content of Mg element, the main influencing factors were leaching time, followed by leaching temperature, and then initial acid concentration, with the solid-liquid ratio having the least impact While MgO's dissolution mechanism resembles that of Ca, the reaction kinetics are considerably slower. Elevated temperatures facilitate Mg^{2+} release from the silicate matrix through thermal activation. For Mn element, the concentration of acetic acid and solid-liquid ratio were the main influencing factors, while the effect of leaching temperature was relatively small. Mn element exists mainly as MnO, where increasing H^+ concentration enhances Mn^{2+} solubility. Implementing lower solid-to-liquid ratios effectively minimizes Mn^{2+} re-adsorbent onto residual slag particles.

3.2. Performance of modified absorbent for cyclic absorption of CO_2

Through orthogonal experiments, it can be concluded that the optimal leaching effect is achieved when the leaching time is 20 min, the initial acetic acid concentration is 1 mol/L, the solid-liquid ratio is 1:10, and the leaching temperature is 30°C. The adsorption capacity of the best steel slag source calcium based adsorbent were prepared with the original steel slag compared with AR CaO in experiments. From Fig. 6, it can be seen that the CO_2 adsorption capacity of the original steel slag remained at a relatively low level of less than 0.1 $g_{CO2}/g_{adsorbent}$ during 20 cycles. Compared to the original steel slag, the CO_2 adsorbent capacity of AR CaO and calcium based adsorbents derived from steel slag had significantly increased. After the initial cycle, the CO_2 adsorption capacity of the two reached 0.52 $g_{CO2}/g_{adsorbent}$ and 0.51 $g_{CO2}/g_{adsorbent}$, respectively. However, the rate of decline in the cyclic capture performance of AR CaO was much greater than that of calcium based adsorbents derived from steel slag sources. After 20 cycles, the CO_2 adsorption capacity of AR CaO rapidly decreased to a lower level of 0.16 $g_{CO2}/g_{adsorbent}$, while the CO_2 adsorption capacity of the steel slag source calcium based adsorbent remained as high as 0.202 $g_{CO2}/g_{adsorbent}$.

The deactivation rates of two materials were shown in Table 4. After 20 cycles, the deactivation rate of AR CaO reached as high as 79.15%. In contrast, the calcium based adsorbent derived from steel slag was only 60.39%. The reason why this adsorbent had superior cyclic adsorption performance was because of its relatively loose pore structure. This
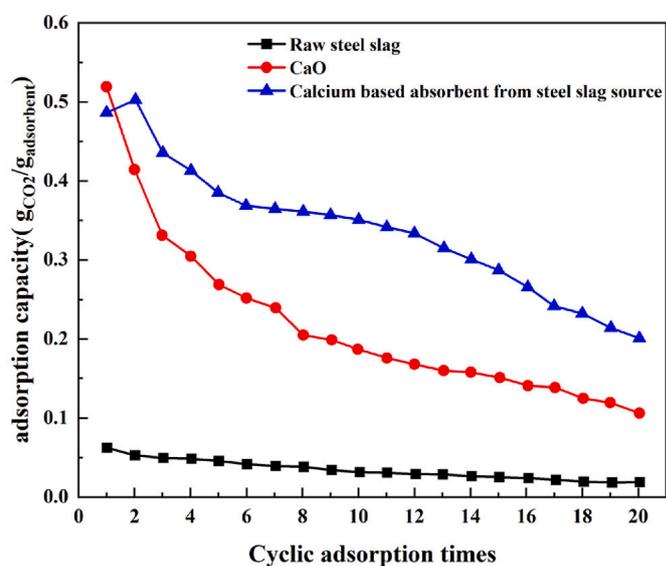

Fig. 6. Capacity of original steel slag, AR and steel slag absorbent for 20 cycles.

Table 4
Inactivation rates of calcium based adsorbent and AR CaO from steel slag source.

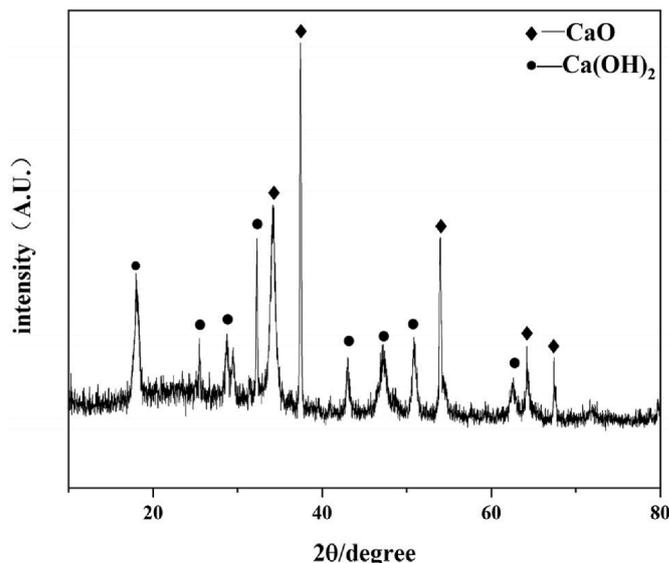| adsorbent	$C_1(g_{CO2}/g_{adsorbent})$	$C_{20}(g_{CO2}/g_{adsorbent})$	L_{20} (%)
AR CaO	0.52	0.106	79.15
calcium based adsorbent	0.51	0.202	60.39

Fig. 7. XRD of calcium based absorbent from steel slag source.

study effectively suppressed the sintering-induced deactivation of CaO particles during high-temperature cycling by regulating the acid leaching parameters to form a rough and porous microstructure, thereby providing a novel pathway for the industrial application of steel slag-based sorbents.

3.3. Mechanism of acid leaching modified steel slag calcium based CO_2 absorbent

The XRD pattern of the prepared steel slag source calcium based adsorbent was shown in Fig. 7. It can be seen that the main phase in the
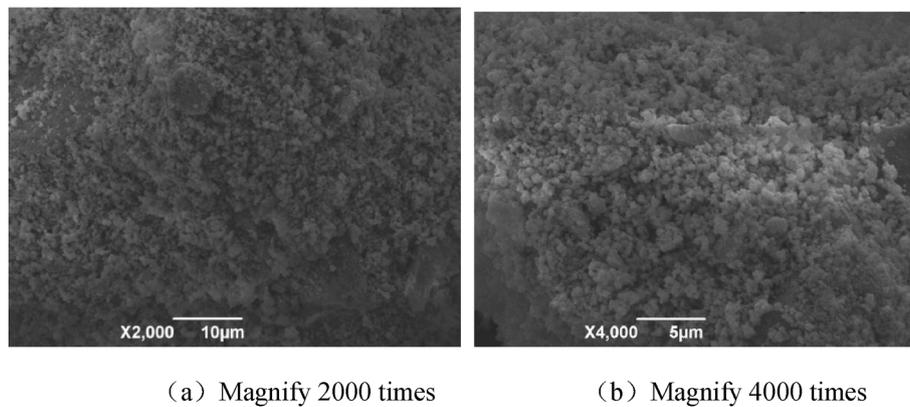
（a）Magnify 2000 times　　　（b）Magnify 4000 times

Fig. 8. SEM diagram of calcium based adsorbent from steel slag source.

Table 5
Pore structure of steel slag calcium based absorbent.

material	specific surface area/(m^2/g)	pore volume/ (cm^3/g)	average pore size/(nm)
calcium based adsorbent	13.32	0.105	27.325

modified adsorbent is CaO, and Ca(OH)$_2$ component was also detected in the sample. This was because some of the calcium oxide in the calcium based absorbent was exposed to air for a long time and formed Ca(OH)$_2$ with the moisture in the air. This was consistent with XRF detection.

The SEM images of the calcium based adsorbent derived from steel slag were shown in Fig. 8. As shown in Fig. 8, the surface of the calcium based adsorbent derived from steel slag was rough, distributed in fine particles, and had a good pore structure. The pore structure parameters of calcium based materials are shown in Table 5. According to Table 5, the specific surface area was 13.32 m^2/g, the pore volume was 0.105 cm^3/g, and the average pore size was 27.325 nm.This was because with the addition of acetic acid, a large number of acetic acid molecules and water molecules were filled in the pores of the material. Therefore, it can be known that at higher acid concentrations and liquid-solid ratios, after high-temperature heat treatment at 850°C, the acetic acid molecules rich in the precursor of calcium based CO$_2$ absorbent undergo thermal decomposition and release with water. This volatilization process significantly enhanced the pore forming effect of the material, thereby improving the pore forming ability and pore structure of the calcium CO$_2$ absorbent (Gao et al., 2024).

4. Conclusion

Using steel slag as the main raw material and acetic acid as the leaching agent, orthogonal experimental range analysis was used to investigate the main parameters affecting the elemental composition of the modified adsorbent. A thermogravimetric analyzer was used to investigate the cyclic CO$_2$ adsorption performance of the modified steel slag source calcium based adsorbent. The specific conclusion was as follows.

(1) The significant degree of influence on the content of calcium oxide in calcium based materials, from highest to lowest, was as follows: acetic acid concentration, leaching time, solid-liquid ratio, and leaching temperature. The optimal process parameters for the experiment were: acetic acid concentration of 1 mol/ L, leaching time of 40 min, solid-liquid ratio of 1:10, and leaching temperature of 40°C. Under these conditions, the leaching rate of calcium element was as high as 88.05%.

(2) The surface structure of the calcium based adsorbent derived from steel slag after acetic acid leaching was loose and has abundant pores, which provides a good microstructure for the adsorption of the adsorbent. The initial CO$_2$ adsorption capacity of the steel slag source calcium based adsorbent was as high as 0.51 g$_{CO2}$/g$_{adsorbent}$. After 20 cycles, the CO$_2$ adsorption capacity was 0.202 g$_{CO2}$/g$_{adsorbent}$, with a deactivation rate of only 60.39%. Its CO$_2$ adsorption capacity and cycling stability were superior to AR CaO.

(3) This experiment utilized steel slag to produce absorbents with high calcium content and better adsorption performance than limestone, laying a necessary foundation for the subsequent coating modification of the obtained absorbents to prepare high-performance CO$_2$ absorbing materials.

CRediT authorship contribution statement

Ruiying Wang: Writing – original draft. **Tao Qi:** Formal analysis. **Hongfeng Ji:** Data curation. **Gang Du:** Data curation. **Canhua Li:** Funding acquisition. **Shujing Zhu:** Writing – review & editing, Data curation. **Jiamao Li:** Data curation. **Chen Zhao:** Data curation.

Funding

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.

References

Bilen, M., Altiner, M., Yildirim, M., 2018. Evaluation of steelmaking slag for CO$_2$ fixation by leaching-carbonation process. Part. Sci. Technol. 36 (3), 368–377. https://doi.org/10.1080/02726351.2016.1267285.
Bobicki, E.R., Liu, Q.X., Xu, Z.H., et al., 2012. Carbon capture and storage using alkaline industrial wastes. Prog. Energy Combust. Sci. 38 (2), 302–320. https://doi.org/10.1016/j.pecs.2011.11.002.
Cai, B., Cao, L., Lei, Y., et al., 2021. China's carbon emission pathway under the carbon neutrality target. China Popul. Resour. Environ. 31 (1), 7–14. https://doi.org/10.12062/cpre.20210101.
Chen, R., Wu, G.X., Li, L.L., et al., 2019. Carbonation reaction of slag from steel refining for CO$_2$ sequestration in the absence and presence of water vapor. Sci. Adv. Mater. 11 (5), 749–755. https://doi.org/10.1166/sam.2019.3495.
Chen, S., Dai, J., Qin, C., et al., 2022. Adsorption and desorption equilibrium of Li$_4$SiO$_4$-based sorbents for high-temperature CO$_2$ capture. Chem. Eng. J. 429, 132236–132240. https://doi.org/10.1016/j.cej.2021.132236.

Costa, G., Baciocchi, R., Polettini, A., et al., 2007. Current status and perspectives of accelerated carbonation processes on municipal waste combustion residues. Environ. Monit. Assess. 135 (1/2/3), 55–75. https://doi.org/10.1007/s10661-007-9704-4.

Costa, L.C.B., Carvalho, V.R., Ferreira, L.C., et al., 2024. Utilizing steel slag to prolong the durability of reinforced concrete: corrosion resistance mechanisms. J. Build. Eng. 98, 111505. https://doi.org/10.1016/j.jobe.2024.111505.

Fang, D., Zhang, L., Zou, L., et al., 2021. Effect of leaching parameters on the composition of adsorbents derived from steel slag and their CO_2 capture characteristics. Greenhouse Gases: Sci. Technol. 11 (5), 924–938. https://doi.org/10.1002/ghg.2103.

Gao, W., Zhou, W., Yux, L., et al., 2023. Comprehensive utilization of steel slag: a review. Powder Technol. 422, 118449. https://doi.org/10.1016/j.powtec.2023.118449.

Gao, Z., Zhao, Q., Tao, M., et al., 2024. Recent research progress on the direct carbon capture of steel slag to prepare building materials. Green Smart Mining Eng. 1 (4), 387–395. https://doi.org/10.1016/j.gsme.2024.11.003.

Geng, Y.Q., Guo, Y.X., Fan, B., et al., 2021. Research progress of calcium-based adsorbents for CO_2 capture and anti-sintering modification. J. Fuel Chem. Technol. 49 (7), 998–1013. https://doi.org/10.1016/S1872-5813(21)60040-3.

Guo, H., Nan, Y., Kou, X., et al., 2019. Research on doping modification and morphology control of calcium-based CO_2 sorbents. Chem. Ind. Eng. Prog. 38 (1), 457–466. https://doi.org/10.16085/j.issn.1000-6613.2018-1340.

GB175-2023, 2024. "General Portland Cement" is released. Res. Appl. Build. Mater. 2024 (1), 7. https://doi.org/10.3969/j.issn.1009-9441.2024.01.003 (2024).

Kashiwaya, Y., Tauchi, S., Nomura, T., et al., 2020. Kinetic analysis considering particle size distribution on Ca elution from slags in CaO-SiO_2-MgO-Al_2O_3-Fe_2O_3 system. ISIJ Int. 60 (12), 2859–2869. https://doi.org/10.2355/isijinternational.ISIJINT-2020-265.

Ko, M.S., Chen, Y.L., Jiang, J.H., 2015. Accelerated carbonation of basic oxygen furnace slag and the effects on its mechanical properties. Constr. Build. Mater. 98, 286–293. https://doi.org/10.1016/j.conbuildmat.2015.08.051.

Kong, X., Chen, R., Li, L., et al., 2019. Study on CO_2 adsorption reaction of converter slag. Steelmaking 35 (2), 5–11.

Lasheras, A., StrHle, J., Galloy, A., et al., 2011. Carbonate looping process simulation using a 1D fluidized bed model for the carbonator. Int. J. Greenh. Gas Control 5 (4), 686–693. https://doi.org/10.1016/j.ijggc.2011.01.005.

Li, C., Zhang, Y., Zhang, K., et al., 2023. Research on resource utilization of CO_2 in steel industry. Materials Reports 37 (S2), 468–473.

Li, Q., Wang, J., She, X., et al., 2025. Feasibility and comprehensive evaluation of the application of different low-carbon technologies in the iron and steel industry. Fuel 381, 133434. https://doi.org/10.1016/j.fuel.2024.133434.

Liu, W., Teng, L., Rohani, S., et al., 2021. CO_2 mineral carbonation using industrial solid wastes: a review of recent developments. Chem. Eng. J. 416, 129093. https://doi.org/10.1016/j.cej.2021.129093.

Myers, C.A., Nakagaki, T., Akutsu, K., 2019. Quantification of the CO_2 mineralization potential of ironmaking and steelmaking slags under direct gas-solid reactions in flue gas. Int. J. Greenh. Gas Control 87, 100–111. https://doi.org/10.1016/j.ijggc.2019.05.021.

National Development and Reform Commission, 2021. Guiding opinions on the comprehensive utilization of bulk solid waste during the 14th five year plan period. Gold Sci. Technol. 29 (2), 286-286.

Pan, S.Y., Adhikari, R., Chen, Y.H., et al., 2016. Integrated and innovative steel slag utilization for iron reclamation, green material production and CO_2 fixation via accelerated carbonation. J. Clean. Prod. 137, 617–631. https://doi.org/10.1016/j.jclepro.2016.07.112.

Polettini, A., Pomi, R., Stramazzo, A., 2016. CO_2 sequestration through aqueous accelerated carbonation of BOF slag: a factorial study of parameters effects. J. Environ. Manag. 167, 185–195. https://doi.org/10.1016/j.jenvman.2015.11.042.

Revathy, T.D.R., Palanivelu, K., Ramachandran, A., et al., 2016. Direct mineral carbonation of steelmaking slag for CO_2 sequestration at room temperature. Environ. Sci. Pollut. Control Ser. 23 (8), 7349–7359. https://doi.org/10.1007/s11356-015-5893-5.

Rong, N., Shi, X., Wang, S., et al., 2025. Optimized acid leaching synthesis and steam regeneration of the steel slag-derived calcium-based sorbent for enhanced CO_2 capture. J. Clean. Prod. 488, 144673. https://doi.org/10.1016/j.jclepro.2025.144673.

Sang, M., Lee, J., 2017. Calcium extraction from steelmaking slag and production of precipitated calcium carbonate from calcium oxide for carbon dioxide fixation. J. Ind. Eng. Chem. 112 (10), 165–771. https://doi.org/10.1016/j.jiec.2017.04.030.

Song, C., 2006. Global challenges and strategies for control, conversion and utilization of CO_2 for sustainable development involving energy, catalysis, adsorption and chemical processing. Catal. Today 115 (1–4), 2–32. https://doi.org/10.1016/j.cattod.2006.02.029.

Sun, J., Liu, W., Hu, Y., et al., 2018. Acidification optimization and granulation of a steel-slag-derived sorbent for CO_2 capture. Chem. Eng. Technol. 41 (10), 2077–2086. https://doi.org/10.1002/ceat.201700573.

Thonemann, N., Zacharopoulos, L., Fromme, F., et al., 2022. Environmental impacts of carbon capture and utilization by mineral carbonation: a systematic literature review and meta life cycle assessment. J. Clean. Prod. 332, 130067. https://doi.org/10.1016/j.jclepro.2021.130067.

Tian, S.C., Jiang, J.G., Chen, X.J., et al., 2013. Direct gas-solid carbonation kinetics of steel slag and the contribution to in situ sequestration of flue gas CO_2 in steel-making plants. ChemSusChem 6 (12), 2348–2355. https://doi.org/10.1002/cssc.201300436.

Tian, S., Jiang, J., Yan, F., et al., 2016. Highly efficient CO_2 capture with simultaneous iron and CaO recycling for the iron and steel industry. Green Chem. 18 (14), 4022–4031. https://doi.org/10.1039/c6gc00400h.

Tu, M., Zhao, H., Lei, Z., et al., 2015. Aqueous carbonation of steel slag: a kinetics study. ISIJ Int. 55 (11), 2509–2514. https://doi.org/10.2355/isijinternational.ISIJINT-2015-142.

Ukwattage, N.L., Ranjith, P.G., Li, X., 2017. Steel-making slag for mineral sequestration of carbon dioxide by accelerated carbonation. Measurement 97, 15–22. https://doi.org/10.1016/j.measurement.2016.10.057.

Wang, J.Y., Zhong, M., Wu, P.F., et al., 2021. A review of the application of steel slag in CO_2 fixation. ChemBioEng Rev. 8 (3), 189–199. https://doi.org/10.1002/cben.202000021.

Wang, Z., Yu, Q., Li, C., et al., 2021. Preparation, structure and performance of steel slag-manganese slag compound fertilizer. China Metallurgy 31 (1), 75–80. https://doi.org/10.13228/j.boyuan.issn1006-9356.20200336.

White, A., Cannell, M., Friend, A.D., 2010. CO_2 stabilization, climate change and the terrestrial carbon sink. Glob. Change Biol. 6 (7), 817–833. https://doi.org/10.1046/j.1365-2486.2000.00358.x.

Zhu, B., Zhou, J., Lv, X., et al., 2020. Effect of ZnO on reaction of coke with CO_2. J. Iron Steel Res. 32 (4), 273–280. https://doi.org/10.13228/j.boyuan.issn1001-0963.20190180.

Zhu, X., Lei, G., Hou, L., et al., 2025. Experimental and numerical study of steel tubes filled with steel slag-based artificial aggregate (SA-CFST) under lateral impact load. Constr. Build. Mater. 458, 139532. https://doi.org/10.1016/j.conbuildmat.2024.139532.