Viser Technology Pte. Ltd.
Research and Application of Materials Science
DOI: 10.33142/rams.v8i1.20147

Research Article Open Access

Direct CO_2 Capture by Carbide Slag: Moisture Regulation, Uptake Performance, and Reaction Kinetics

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Abstract

To evaluate the feasibility of carbide slag as a low-cost calcium-based solid waste for CO_2 mineral capture, direct carbonation experiments were carried out under different moisture contents. The effects of moisture content on CO_2 uptake, carbonation efficiency, phase composition, and morphology were investigated. Five moisture contents of 0%, 5%, 10%, 20%, and 30% were selected, and CO_2 was introduced at ambient temperature and pressure. The results show that the abundant $Ca(OH)_2$ in carbide slag can react with CO_2 to form $CaCO_3$, indicating that carbide slag has potential for direct mineral carbonation of CO_2. As the moisture content increased from 0% to 20%, the CO_2 uptake of carbide slag gradually increased. The best carbonation performance was obtained at 20% moisture content, where the CO_2 uptake reached 4.60 mol/kg after 120 min, corresponding to a CO_2 fixation amount of 0.2024 g/g and a carbonation efficiency of 36.8%. When the moisture content increased further to 30%, the CO_2 uptake decreased to 3.20 mol/kg. TG/DTG, XRD, and FTIR results indicate that $Ca(OH)_2$ was gradually converted into $CaCO_3$ during carbonation. An appropriate amount of moisture promoted $CaCO_3$ formation and deposition, whereas excessive moisture hindered CO_2 diffusion and reduced the carbonation efficiency. These results demonstrate that moisture regulation is an important factor for improving the efficiency of direct CO_2 capture by carbide slag and provide a reference for low-cost CO_2 mineralization using alkaline industrial solid wastes.

Keywords: *carbide slag; CO_2 capture; direct carbonation; moisture content; uptake capacity; reaction kinetics*

1 Introduction

With the continuous increase in CO_2 emissions from industrial production, the development of low-cost and easily implemented CO_2 capture and fixation methods is of great significance. Mineral carbonation is a stable CO_2 fixation route, in which calcium- or magnesium-containing materials react with CO_2 to form carbonate products. Compared with conventional absorption and adsorption methods, mineral carbonation can directly fix CO_2 in solid products, and the subsequent treatment is relatively simple. Therefore, the use of active calcium components in industrial solid wastes for CO_2 mineralization has gradually become an important direction for the synergistic development of solid-waste utilization and carbon-emission reduction[1-4].

Carbide slag is an industrial by-product generated during acetylene production through calcium carbide hydrolysis. Its main component is usually $Ca(OH)_2$, with minor amounts of $CaCO_3$, CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO[1,5-7]. Owing to its strong alkalinity and high moisture content, long-term stockpiling of carbide slag may cause land occupation, dust emission, and alkaline leachate. At the same time, these chemical characteristics make carbide slag a reactive calcium reservoir. $Ca(OH)_2$ can combine with CO_2 to form $CaCO_3$, so carbonation can both immobilize CO_2 and lower the alkalinity of the residue, improving the possibility of subsequent reuse [6,8-14].

In direct carbonation, the role of water is particularly sensitive. A small amount of water can provide a liquid pathway for CO_2 dissolution, $Ca(OH)_2$ dissolution, and Ca^{2+} transport, which accelerates

Received: March 1, 2026; Accepted: April 18, 2026

carbonate precipitation. If the water content is too high, however, a continuous or thick water layer may develop around particles and partly fill the voids between them. Under that condition, the gas path becomes longer and CO_2 diffusion to unreacted $Ca(OH)_2$ is restricted. The carbonation response of carbide slag is therefore expected to depend on the balance between liquid-phase reaction promotion and gas-phase mass-transfer limitation[8,12,15-17].

On this basis, the present study examined carbide slag with controlled moisture contents to clarify how water dosage affects direct CO_2 uptake and reaction progression. Samples were carbonated under identical ambient conditions, and the reaction products were characterized by TG/DTG, XRD, FTIR, and pH testing. The time-dependent uptake data were further used to compare initial reaction rates and final fixation capacities.[8,9,13,15,18]. This study aims to provide an experimental reference for the use of carbide slag in low-cost CO_2 capture.

2 Materials and Methods

2.1 Raw materials

The carbide slag used in this study was an industrial by-product generated during acetylene production from calcium carbide hydrolysis. The raw carbide slag was gray-white powder or slurry and showed strong alkalinity. To reduce the influence of the initial moisture content on the experimental results, the raw carbide slag was dried in an oven at 105 ℃ for 24 h before testing. It was then ground and sieved to obtain dry carbide slag powder with a particle size below 75 μm. The dried carbide slag was used as the base sample for subsequent moisture regulation and direct CO_2 carbonation experiments.

To determine the basic properties of carbide slag, X-ray diffraction was used to analyze its main mineral phases, and thermogravimetric analysis was used to identify the thermal decomposition characteristics of $Ca(OH)_2$ and $CaCO_3$. Scanning electron microscopy was used to observe the original particle morphology. In addition, the pH of the leachate of raw carbide slag was measured to evaluate its initial alkalinity. These tests were used to determine the existing forms of active calcium components in carbide slag and to provide a basis for the analysis of subsequent CO_2 carbonation reactions [5,13,18].

2.2 Preparation of carbide slag samples with different moisture contents

To investigate the effect of moisture content on the direct carbonation performance of carbide slag for CO_2 capture, five moisture levels of 0%, 5%, 10%, 20%, and 30% were set based on the dry mass of carbide slag. The moisture content was defined as the ratio of the added water mass to the dry carbide slag mass. Specifically, a certain mass of dried carbide slag was weighed for each group, and the corresponding amount of deionized water was added according to the designed moisture content. After thorough mixing, the samples were sealed and stored for 24 h to allow relatively uniform moisture distribution.

The moisture content was calculated as follows:

$$w = \frac{m_w}{m_s} \times 100\% \quad (1)$$

Where w is the designed moisture content, m_w is the mass of added water, and m_s is the dry mass of carbide slag. No additional water was added to the 0% moisture sample, which represented the dry carbonation condition. The other groups represented carbide slag carbonation systems with different moisture contents. Through this grouping, CO_2 uptake under dry, low-moisture, medium-moisture, and relatively high-moisture conditions could be compared.

2.3 Direct CO_2 carbonation experiment

The direct CO_2 carbonation experiment was conducted at ambient temperature and pressure. The same mass of carbide slag samples with different moisture contents was uniformly spread in the reaction vessel to maintain an approximately consistent sample layer thickness. CO_2 gas was then continuously introduced into the reactor to ensure sufficient contact between the gas and the carbide slag sample and to initiate the carbonation reaction. To ensure comparability among different groups, the sample mass, gas flow rate, reaction temperature, reaction time, and sample spreading method were kept consistent during the experiments[8,9,13,15].

To obtain the variation of CO_2 uptake with reaction time under different moisture contents, four reaction times of 10, 30, 60, and 120 min were set. At each designated reaction time, the sample was removed and immediately sealed to reduce possible errors caused by further reaction with CO_2 or moisture in air. Each experiment was repeated at least three times, and the

average value was used for analysis.

The purpose of this experimental design was to compare the effect of moisture content on the direct carbonation efficiency of carbide slag. The 0% moisture group was used to characterize the CO_2 capture capacity under dry conditions; the 5% and 10% moisture groups were used to analyze the promoting effect of a small amount of water; the 20% moisture group was used to examine the reaction performance under medium moisture conditions; and the 30% moisture group was used to determine whether excessive moisture would inhibit CO_2 diffusion and carbonation. The experimental workflow is shown in Figure 1.

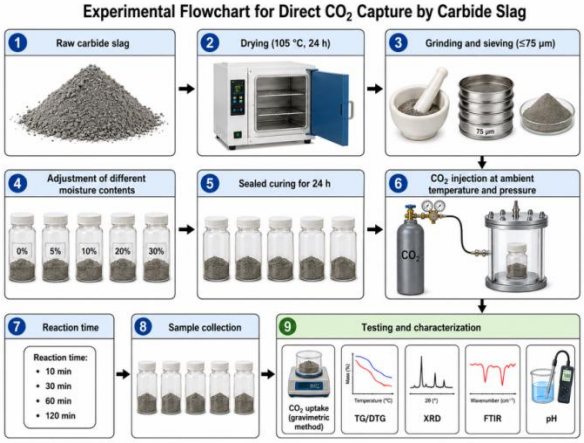

Figure 1 Experimental flowchart for CO_2 capture by direct carbonation of carbide slag

2.4 Testing and characterization methods

X-ray diffraction was used to analyze the phase changes of carbide slag samples before and after carbonation, with particular attention to the characteristic peaks of $Ca(OH)_2$ and $CaCO_3$. By comparing the XRD patterns of samples carbonated under different moisture contents, the effect of moisture content on $Ca(OH)_2$ consumption and $CaCO_3$ formation could be evaluated[5,13,18].

Thermogravimetric analysis was used to measure mass loss during heating. Combined with DTG curves, the characteristic temperature ranges corresponding to $Ca(OH)_2$ dehydration and $CaCO_3$ decomposition with CO_2 release were identified. The CO_2 fixation amount and carbonation efficiency of carbide slag were calculated from the variation in $CaCO_3$ content before and after carbonation. Compared with the direct weighing method, the thermogravimetric method can reduce the influence of adsorbed water and free water on the calculation of CO_2 fixation amount[5,13,18].

Fourier transform infrared spectroscopy was used to analyze functional group changes in the carbonation products, with a focus on the characteristic absorption peaks of carbonate ions to further confirm $CaCO_3$ formation. pH tests were conducted to analyze the change in alkalinity before and after carbonation and to evaluate the alkalinity reduction effect of CO_2 carbonation on carbide slag[6,18,19].

2.5 Calculation of CO_2 fixation amount and carbonation efficiency

In this study, the CO_2 fixation amount during carbide slag carbonation was calculated using thermogravimetric results. $CaCO_3$ in the sample decomposes and releases CO_2 in the high-temperature range; therefore, the CO_2 fixation amount can be calculated from the increase in $CaCO_3$ content after carbonation. The CO_2 fixation amount was expressed as the mass of CO_2 fixed per unit mass of dry carbide slag, with the unit of g CO_2/g carbide slag.

The CO_2 fixation amount was calculated as follows:

$$Uco_2 = \frac{m_{co_2}}{m_s} \tag{2}$$

Where Uco_2 is the CO_2 fixation amount, m_{co_2} is the mass of CO_2 fixed after carbonation, and m_s is the dry mass of carbide slag.

The carbonation efficiency was used to evaluate the relationship between the actual CO_2 fixation amount and the theoretical maximum CO_2 fixation amount. It was calculated as follows:

$$\eta = \frac{Uco_2}{Uco_2, max} \times 100\% \tag{3}$$

Where η is the carbonation efficiency, Uco_2 is the actual CO_2 fixation amount, and Uco_2, max,theo is the theoretical maximum CO_2 fixation amount calculated from the reactive $Ca(OH)_2$ content in carbide slag.

To further analyze the carbonation rate under different moisture contents, CO_2 uptake curves were plotted based on the CO_2 fixation amount at different reaction times. By comparing the CO_2 uptake of each group at 10, 30, 60, and 120 min, the effect of moisture content on the initial carbonation rate and final uptake capacity could be analyzed.

3 Results and Discussion

3.1 Effect of moisture content on CO_2 uptake

The variation of CO_2 uptake with reaction time

under different moisture contents is shown in Figure 2. Overall, the CO_2 uptake of all samples increased gradually with reaction time, but obvious differences were observed among samples with different moisture contents. The dry sample, namely the 0% moisture sample, showed the lowest CO_2 uptake throughout the reaction. Its CO_2 uptake was only 0.23 mol/kg at 10 min and increased to 0.90 mol/kg after 120 min. This indicates that, without additional moisture, carbide slag can still undergo a certain degree of carbonation with CO_2, but both the reaction rate and final uptake are relatively low.

As the moisture content increased, the CO_2 capture capacity of carbide slag improved markedly. At 5% moisture content, the CO_2 uptake increased to 1.80 mol/kg after 120 min. At 10% moisture content, the CO_2 uptake further increased to 2.90 mol/kg. Compared with the dry sample, the CO_2 uptake values of the 5% and 10% moisture samples increased by approximately 100.0% and 222.2%, respectively. This suggests that an appropriate amount of moisture can improve the carbonation conditions of carbide slag and facilitate the participation of CO_2 in the carbonation reaction of $Ca(OH)_2$.

When the moisture content increased to 20%, the sample exhibited the highest CO_2 capture capacity. The CO_2 uptake, CO_2 fixation amount, carbonation efficiency and pH values of the samples after 120 min carbonation are summarized in Table 1.

The highest uptake was obtained at 20% moisture. As summarized in Table 1, this group fixed 4.60 mol/kg after 120 min, equivalent to 0.2024 g CO_2/g carbide slag and a carbonation efficiency of 36.8%. The increase relative to the dry sample was approximately 411.1%. At this moisture level, water apparently supplied enough liquid phase for CO_2 dissolution and Ca^{2+} transport while still preserving gas pathways through the particle bed.

The positive effect of water did not continue at 30% moisture. At this higher dosage, the 120 min uptake fell to 3.20 mol/kg, below the value obtained at 20%. This decrease suggests that excess water began to dominate the transport process by thickening the surface water film and occupying interparticle voids. The resulting diffusion resistance reduced the contact between incoming CO_2 and unreacted internal $Ca(OH)_2$. Within the range examined here, 20% moisture therefore represented the most favorable balance between reaction promotion and mass transfer.

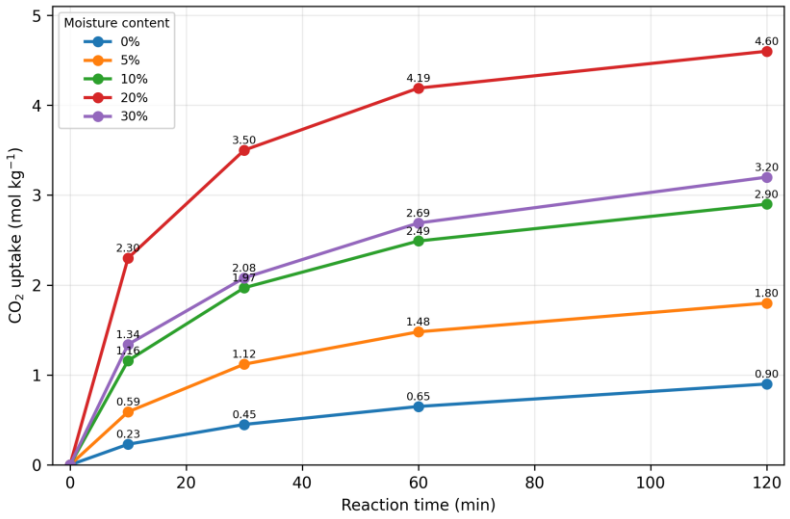

Figure 2 Variation of CO_2 uptake with reaction time under different moisture contents

Table 1 CO_2 capture results of carbide slag after 120 min carbonation under different moisture contents

Moisture content/%	CO_2 uptake/(mol·kg^{-1})	CO_2 fixation/(g·g^{-1})	Carbonation efficiency/%	pH
0	0.90	0.0396	7.3	12.15
5	1.80	0.0792	14.4	11.75
10	2.90	0.1276	23.2	11.25
20	4.60	0.2024	36.8	10.55
30	3.20	0.1408	26.1	10.95

3.2 Variation of CO_2 uptake with reaction time

The CO_2 uptake values of the samples at 10, 30, 60 and 120 min are listed in Table 2 and plotted in Figure 2. As shown in Table 2 and Figure 2, the CO_2 uptake of all samples increased rapidly at the early stage and then gradually approached a plateau. For the 20% moisture sample, the CO_2 uptake reached 2.30 mol/kg at 10 min, accounting for 50.0% of the final uptake at 120 min. At 60 min, the uptake reached 4.19 mol/kg, accounting for 91.1% of the final value. This indicates that the carbonation reaction of carbide slag mainly occurred rapidly in the early stage, and the increase in CO_2 uptake gradually decreased as the reaction proceeded.

This trend is related to the carbonation process of carbide slag. In the initial reaction stage, a large amount of unreacted $Ca(OH)_2$ existed on the sample surface, and CO_2 could easily contact the active calcium component; thus, the reaction rate was high. As carbonation proceeded, $CaCO_3$ gradually formed and deposited on particle surfaces, partially covering the unreacted $Ca(OH)_2$ and increasing the resistance for CO_2 diffusion into the particle interior. Therefore, the CO_2 uptake rate decreased in the later stage, and the curve gradually approached a plateau. Similar product-layer diffusion resistance and late-stage rate reduction have also been reported in the mineral carbonation of carbide slag and other alkaline solid wastes[20].

Moisture content also changed the initial reaction rate. At 10 min, the uptake of the dry group was only 0.23 mol/kg, whereas the 20% group reached 2.30 mol/kg. The difference indicates that suitable moisture increased not only the final capacity but also the early availability of reactive calcium. Although the 30% group remained higher than the 0%, 5%, and 10% groups throughout the test, it was consistently below the 20% group, confirming that excessive water imposed a mass-transfer penalty.

Table 2 CO_2 uptake of samples with different moisture contents at different reaction times (mol CO_2/kg dry carbide slag)

Moisture content/%	10 min	30 min	60 min	120 min
0	0.23	0.45	0.65	0.90
5	0.59	1.12	1.48	1.80
10	1.16	1.97	2.49	2.90
20	2.30	3.50	4.19	4.60
30	1.34	2.08	2.69	3.20

3.3 TG/DTG analysis

The TG/DTG curves of raw carbide slag and the samples carbonated under different moisture contents are shown in Figure 3. During heating, the carbide slag samples mainly showed two obvious mass-loss regions. The first region appeared at approximately 350-500 ℃, which mainly corresponded to the dehydration decomposition of $Ca(OH)_2$. The second region appeared at approximately 650-850 ℃, which mainly corresponded to the decomposition of $CaCO_3$ and the release of CO_2. Therefore, TG/DTG results can be used to evaluate $Ca(OH)_2$ consumption and $CaCO_3$ formation before and after carbonation.

Raw carbide slag showed an obvious mass-loss peak in the range of 350-500 ℃, indicating that the sample contained a large amount of $Ca(OH)_2$. After carbonation, the mass loss in this temperature range decreased for all samples, indicating that $Ca(OH)_2$ was gradually consumed during carbonation. Meanwhile, the mass loss in the range of 650-850 ℃ increased significantly after carbonation, indicating that the $CaCO_3$ content increased and CO_2 was fixed as carbonate products.

The phase contents calculated from the TG results are given in Table 3. Before carbonation, the slag contained about 4.0 wt.% $CaCO_3$ and 92.0 wt.% $Ca(OH)_2$. After carbonation, $CaCO_3$ content increased to 12.5, 20.4, 29.3, 41.6, and 31.6 wt.% for the 0%, 5%, 10%, 20%, and 30% groups, respectively. The 20% group therefore had the highest $CaCO_3$ content and the lowest residual $Ca(OH)_2$ content, 48.2 wt.%, indicating the greatest degree of conversion. The lower $CaCO_3$ content at 30% moisture supports the uptake results and shows that excessive moisture reduced the effective carbonation extent.

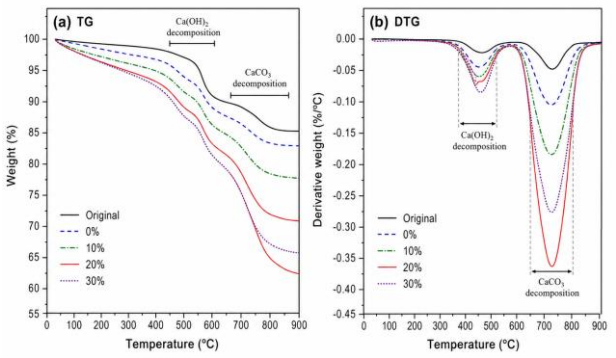

Figure 3 TG/DTG curves of carbide slag samples before and after carbonation

Table 3 $CaCO_3$ content and residual $Ca(OH)_2$ content of carbonated samples with different moisture contents

Sample	$CaCO_3$ content/wt.%	Residual $Ca(OH)_2$/wt.%
Raw carbide slag	4.0	92.0
0%	12.5	82.1
5%	20.4	72.9
10%	29.3	62.5
20%	41.6	48.2
30%	31.6	59.9

3.4 XRD analysis

The XRD patterns of different samples are shown in Figure 4. The raw carbide slag showed strong characteristic peaks of $Ca(OH)_2$, indicating that $Ca(OH)_2$ was the main reactive phase in carbide slag. Weak $CaCO_3$ peaks were also observed in the raw sample, which may be related to natural carbonation during storage.

After carbonation, the characteristic peaks of $Ca(OH)_2$ decreased significantly, whereas those of $CaCO_3$ increased, indicating that CO_2 reacted with $Ca(OH)_2$ in carbide slag to form $CaCO_3$. As the moisture content increased from 0% to 20%, the $CaCO_3$ peak intensity gradually increased and the $Ca(OH)_2$ peak intensity gradually decreased. The 20% moisture sample exhibited the strongest $CaCO_3$ peaks, indicating that it had the highest carbonate formation, which is consistent with the TG and CO_2 uptake results.

When the moisture content increased to 30%, the $CaCO_3$ peak intensity was lower than that of the 20% sample, and a relatively obvious residual $Ca(OH)_2$ peak was still observed. This suggests that carbide slag was not fully carbonated under the higher moisture condition. Therefore, the XRD results further demonstrate that an appropriate amount of moisture promotes the conversion of $Ca(OH)_2$ to $CaCO_3$, while excessive moisture limits the continued carbonation reaction.

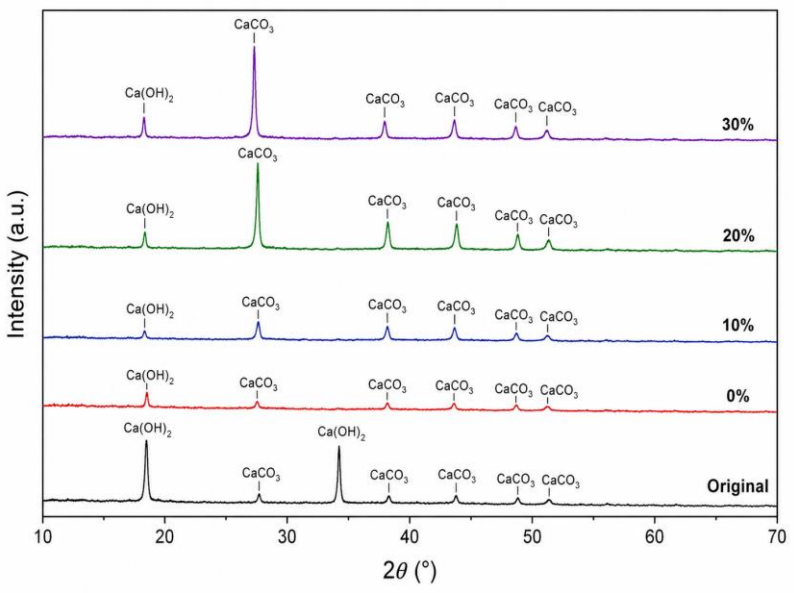

Figure 4 XRD patterns of carbide slag samples before and after carbonation

3.5 FTIR analysis

Figure 5 shows the FTIR spectra of raw carbide slag and the samples carbonated under different moisture contents. An absorption peak related to -OH can be observed in the raw carbide slag, indicating the presence of $Ca(OH)_2$. After carbonation, the characteristic absorption peaks related to CO_3^{2-} were significantly enhanced, indicating that $CaCO_3$ was formed during carbonation.

Specifically, the absorption peak near 1400–1500 cm^{-1} was enhanced in the carbonated samples, which is mainly associated with the asymmetric stretching vibration of CO_3^{2-}. In addition, characteristic absorption peaks of calcium carbonate appeared or increased near 875 cm^{-1} and 712 cm^{-1}. As the moisture content increased from 0% to 20%, the carbonate-related peaks gradually strengthened, indicating increased $CaCO_3$ formation. The carbonate peaks of the 30% moisture sample were weaker than those of the 20% sample, which is consistent with the CO_2 uptake, TG, and XRD results.

As an auxiliary characterization method, FTIR further confirms that CO_2 was fixed as carbonate products during the direct carbonation of carbide slag. Combined with XRD and TG results, the main product of the carbonation reaction can be identified as $CaCO_3$.

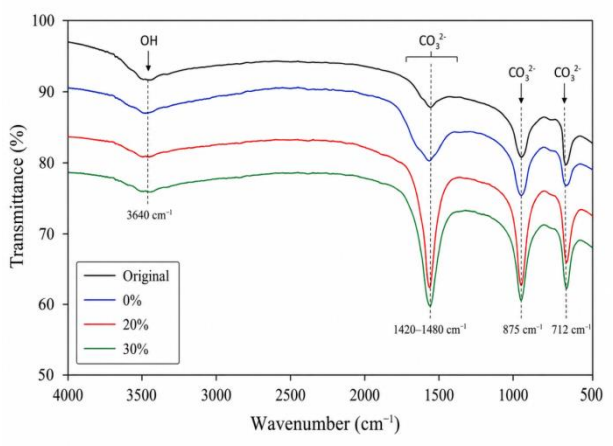

Figure 5 FTIR spectra of carbide slag samples before and after carbonation

3.6 Mechanism of moisture-assisted direct carbonation of carbide slag

The combined uptake, TG/DTG, XRD, and FTIR results indicate that the effect of moisture is governed by the competition between chemical facilitation and mass-transfer resistance. Under dry conditions, the reaction is largely restricted to $Ca(OH)_2$ sites that are directly accessible to gaseous CO_2. Without a liquid phase, CO_2 dissolution is limited and Ca^{2+} transport is weak, so the uptake remains low. This behavior is typical of gas-solid carbonation systems in which the reaction interface and diffusion path constrain the overall rate[8,9,21].

When limited moisture is introduced, a thin water film can form on particle surfaces and within contact zones. This film enhances CO_2 dissolution and supports the dissolution of $Ca(OH)_2$, producing Ca^{2+} that can react with carbonate species to precipitate $CaCO_3$. The increases observed for the 5%, 10%, and especially 20% groups reflect this moisture-assisted pathway. The 20% condition appears to provide enough liquid phase for ion migration without blocking most of the gas channels in the particle bed.

At excessive moisture content, the controlling factor shifts toward gas transport. Additional water can thicken the surface film and occupy interparticle pores, which increases the resistance for CO_2 to penetrate into the sample and reach unreacted $Ca(OH)_2$. Although ion migration remains favorable in the water-rich environment, the supply of CO_2 to internal reactive sites becomes insufficient. Consequently, direct carbonation of carbide slag has an optimum moisture window rather than a simple positive dependence on water content.

Overall, carbide slag fixed CO_2 directly at ambient temperature and pressure, and its performance depended strongly on moisture regulation. The uptake increased from the dry condition to 20% moisture and then declined at 30%. The best result, 4.60 mol/kg after 120 min with 0.2024 g CO_2/g carbide slag and 36.8% carbonation efficiency, was obtained when gas diffusion and liquid-phase reaction were balanced. This finding identifies moisture control as a key operating parameter for improving carbide slag carbonation.

4 Conclusions

This study investigated the direct carbonation behavior of carbide slag for CO_2 capture under different moisture contents. The results show that the abundant $Ca(OH)_2$ in carbide slag can react with CO_2 to form $CaCO_3$ at ambient temperature and pressure, indicating its potential as a low-cost calcium source for CO_2 mineral capture. Moisture content significantly affected the carbonation performance of carbide slag, and the CO_2 uptake first increased and then decreased with increasing moisture content. The 20% moisture sample exhibited the best carbonation performance, with a CO_2 uptake of 4.60 mol/kg, a CO_2 fixation amount of 0.2024 g/g, and a carbonation efficiency of 36.8% after 120 min. When the moisture content increased to 30%, the CO_2 uptake decreased to 3.20 mol/kg.

TG/DTG, XRD, and FTIR analyses show that $Ca(OH)_2$ was gradually converted into $CaCO_3$ during carbonation, and the highest $CaCO_3$ formation occurred under the 20% moisture condition. Mechanistically, moderate moisture promoted CO_2 dissolution, $Ca(OH)_2$ dissolution, and Ca^{2+} migration, whereas excessive moisture increased CO_2 diffusion resistance by thickening the water film and filling pore spaces. A suitable moisture range is therefore essential for efficient direct CO_2 capture by carbide slag. These results provide an experimental basis for carbonation-based utilization of alkaline industrial residues.

Funding: This work was supported by the Shaanxi Qinchuangyuan “Scientists and Engineers” Team Building Program (No. 2023KXJ-242), the Youth

Innovation Team Project of Shaanxi Universities (2023—2026), and the Key Scientific and Technological Innovation Team Project of Shaanxi Province.

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