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Enhanced Carbon Capture through Mineral Carbonation of Steel Slag: A Sustainable Approach to CO2 Sequestration

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The challenge of mitigating the adverse effects of climate change has driven significant research into carbon capture technologies, which aim to reduce the levels of carbon dioxide (CO2) in the atmosphere. One promising approach within this domain is mineral carbonation, a process that involves the chemical reaction of CO2 with naturally occurring minerals to form stable carbonates [1] [3] [5] [8]. This process not only sequesters CO2 but also creates valuable by-products, making it a dual-purpose solution in the fight against global warming. Among the various materials that can be used in mineral carbonation, industrial by-products such as steel slag have gained considerable attention due to their high reactivity and widespread availability [2] [4] [7].

Keywords: Mineral Carbonation, Carbon Capture, Industrial By-Products.

1. Introduction

The challenge of mitigating the adverse effects of climate change has driven significant research into carbon capture technologies, which aim to reduce the levels of carbon dioxide (CO2) in the atmosphere. One promising approach within this domain is mineral carbonation, a process that involves the chemical reaction of CO2 with naturally occurring minerals to form stable carbonates [1] [3] [5] [8]. This process not only sequesters CO2 but also creates valuable by-products, making it a dual-purpose solution in the fight against global warming. Among the various materials that can be used in mineral carbonation, industrial by-products such as steel slag have gained considerable attention due to their high reactivity and widespread availability [2] [4] [7].

Steel slag, a by-product of the steel manufacturing process, is rich in calcium and magnesium oxides, which are key ingredients for effective carbonation [6] [10] [13]. The utilization of steel slag in carbon capture offers a sustainable pathway to manage industrial waste while contributing to the reduction of greenhouse gases. Moreover, the process of mineral carbonation using steel slag can be conducted under ambient conditions, which makes it a more feasible and less energy-intensive method compared to other carbon capture techniques [11] [16] [18].

The potential for enhanced carbon capture through mineral carbonation of steel slag lies in its ability to transform a significant environmental challenge—industrial waste—into a solution for another pressing issue: carbon emissions [12] [17] [20]. By leveraging the reactive properties of steel slag, CO2 can be efficiently sequestered in the form of stable carbonates, which can be used in various applications, such as construction materials, thereby closing the loop in a circular economy model [14] [21] [24].

Recent advancements in this field have focused on optimizing the conditions under which mineral carbonation occurs, including the particle size of the slag, the concentration of CO2, and the presence of additives that can accelerate the carbonation process [19] [22] [26]. These studies have demonstrated that under controlled conditions, steel slag can achieve high levels of carbonation, making it a viable option for large-scale carbon capture initiatives [23] [25] [27].

In addition to the environmental benefits, the economic implications of this technology are also significant. The by-products of mineral carbonation, such as synthetic aggregates, have commercial value, which can offset the costs of the carbon capture process [28] [30] [31]. This economic viability is crucial for the widespread adoption of mineral carbonation as a mainstream carbon capture strategy.

The fundamental principle of mineral carbonation is to replicate the natural weathering process, where magnesium and calcium oxides are converted into magnesium and calcium carbonates [9] [15] [29] [32]. The reaction can be represented as:

(Ca,Mg)O(s)+CO2(g)→(Ca,Mg)CO3(s)(Ca, Mg)O(s) + CO_2(g) \ (Ca, Mg)CO_3(s)(Ca,Mg)O(s)+CO2(g)→(Ca,Mg)CO3(s)

This reaction underscores the interaction between CO2 and metal oxides, predominantly involving calcium and magnesium, to form their respective carbonates [13]. However, since natural mineral carbonation is an inherently slow process, it is insufficient for large-scale CO2 sequestration. Therefore, to make the process viable, it must be significantly accelerated. One promising approach to expedite mineral carbonation is the aqueous carbonation method. In this process, CO2 is bubbled through a slurry of calcium and magnesium-rich raw materials [1] [2].

Industrial wastes, such as steel slag, are particularly suitable for this process due to their high content of calcium and magnesium oxides and their alkaline nature [5] [10] [12]. The proximity of steel slag to major CO2 emission sources and its composition makes it an ideal feedstock for mineral carbonation. Additionally, utilizing steel slag for CO2 sequestration offers the dual benefit of capturing carbon emissions while potentially reclaiming some of the CO2 generated during the manufacturing process [8] [19] [24].

In summary, the mineral carbonation of steel slag represents a promising intersection of waste management and carbon capture technology [7] [16]. By turning an industrial by-product into a tool for CO2 sequestration, this approach not only addresses the issue of industrial waste but also contributes to the broader goal of reducing atmospheric CO2 levels [23] [28]. As research in this area continues to evolve, the potential for enhanced carbon capture through steel slag carbonation could play a pivotal role in global efforts to combat climate change [3] [30] [31].

2. Experimental Procedures

2.1 Chemical Analysis of Steel Slag

Steel slag is a byproduct generated during the steelmaking process, specifically during the separation of molten steel from impurities. Initially, this slag is in a molten state, but as it cools and solidifies, it forms a complex mixture of silicates and oxides. Chemically, steel slag typically contains 30 to 40% calcium oxide (CaO) and 5 to 10% magnesium oxide (MgO) [1] [2] [6]. Due to its high content of these oxides and its natural alkalinity, with a pH ranging from 8 to 10, steel slag is considered a promising candidate for use as a feedstock in mineral carbon sequestration processes [8] [13] [17].

For this study, the steel slag used was sourced from FOSROC Pvt. Ltd. The material obtained had a particle size that passed through a 4.75 mm sieve. The slag was then analyzed for its CaO and MgO content according to the standards outlined in IS-4032:1985 [5] [12] [19].

2.2 Mineral Carbonation of Steel Slag

The carbonation experiments were conducted in a reactor where various parameters were systematically altered, one at a time, while keeping the other conditions constant [3] [4]. A sample of 10 grams of steel slag, with particles smaller than 90 microns and free of moisture, was mixed with distilled water to achieve a pre-determined liquid-to-solid ratio. This mixture was stirred to form a slurry, which was then introduced into the reactor [7] [10].

Once inside the reactor, the lid was securely fastened to ensure an airtight environment. The reactor was then heated to the target temperature. Upon reaching this temperature, carbon dioxide was bubbled through the slurry for a specified duration to facilitate the carbonation reaction [2] [9]. Throughout the experiment, the temperature and pressure within the reactor were meticulously controlled using appropriate regulating valves to maintain the desired conditions [12] [18]. The experimental setup, including the reactor used for the carbonation process, is depicted in Figure 1 [16].

Fig.1. Reactor for mineral carbonation

After the designated reaction time had elapsed, the reactor was gradually depressurized by opening the exhaust valve [5] [8]. Subsequently, the reactor was cooled down to 30°C by circulating cold water through the cooling system. Once the reactor reached the desired temperature, the lid was removed, and the resulting slurry was filtered using a No. 42 Whatman filter paper [11] [15]. The carbonated material collected on the filter paper was then dried in a hot air oven at 50°C overnight. The dried carbonated sample was stored in airtight containers until it was analyzed to determine the extent of carbonation [6] [17] [22].

2.3 Analysis of the Extent of Carbonation

Thermogravimetric Analysis (TGA) for Enhanced Carbon Capture via Mineral Carbonation of Steel Slag

1. Preparation of Steel Slag Sample

- Sample Collection: Begin by obtaining a representative sample of steel slag from a steel production facility. The slag should be fresh to ensure that no pre-existing carbonation has occurred, which could affect the analysis.

- Crushing and Grinding: Crush the steel slag into smaller fragments to facilitate easier handling and processing. Afterward, grind the crushed slag to a fine powder using a mechanical grinder. The particle size should be uniform, ideally within the range of 50 to 150 microns, to maximize the surface area available for the carbonation reaction.

- Sieving: Use a sieve to ensure that the ground steel slag is consistent in particle size. This uniformity is crucial for achieving accurate and reproducible TGA results.

- Drying: Place the sieved steel slag in an oven at 105°C for at least 24 hours to remove any residual moisture. The presence of moisture can interfere with the accuracy of the thermogravimetric analysis.

2. Carbonation Process Setup

- Reactor Setup: Prepare a carbonation reactor or chamber capable of controlling environmental conditions such as temperature, pressure, and CO2 concentration. The reactor should be designed to allow uniform exposure of the slag sample to CO2 gas.

- Sample Placement: Evenly distribute the dried steel slag sample within the reactor chamber to ensure consistent contact with CO2 during the carbonation process.

- Environmental Conditions: Set the reactor to the desired temperature (typically between 25°C and 70°C) and pressure and introduce CO2 gas at a concentration ranging from 10% to 100%. These conditions should be selected based on prior research or experimental goals to optimize the carbonation reaction.

3. Initiation and Monitoring of Carbonation

- CO2 Introduction: Begin the carbonation process by introducing CO2 gas into the reactor at a controlled flow rate. The duration of exposure can vary but typically ranges from several hours to days, depending on the desired extent of carbonation.

- Monitoring Conditions: Continuously monitor the reactor's temperature, pressure, and CO2 concentration throughout the carbonation process. Automated systems can be used to log these parameters, ensuring that they remain within the desired range.

4. Thermogravimetric Analysis (TGA) Setup

- TGA Instrument Preparation: Prepare the thermogravimetric analysis (TGA) instrument by calibrating it according to the manufacturer's guidelines. Ensure that the instrument is capable of measuring small changes in mass with high precision.

- Sample Loading: After the carbonation process is complete, carefully retrieve the steel slag sample from the reactor. Place a small, accurately weighed portion of the carbonated slag into the TGA sample holder. The sample size should be appropriate for the TGA instrument, typically ranging from a few milligrams to several grams.

5. Thermogravimetric Analysis Process

- Heating Program: Begin the TGA analysis by heating the sample at a controlled rate, typically 10°C per minute, from ambient temperature up to 1000°C or higher. The exact temperature range should be selected based on the specific carbonates formed in the slag, which decompose at characteristic temperatures.

- Mass Change Monitoring: As the temperature increases, monitor the mass of the sample continuously. The TGA instrument will record the mass loss at different temperatures, which corresponds to the decomposition of carbonates and the release of CO2.

- Data Collection: The TGA instrument will generate a thermogram, a plot of mass change (in percentage) versus temperature. Key features of the thermogram, such as the onset temperature, peak temperature, and total mass loss, provide information on the extent of carbonation.

6. Post-Analysis Data Interpretation

- Identifying Carbonates: Analyze the thermogram to identify the temperature ranges where significant mass loss occurs. These ranges correspond to the decomposition of different carbonates, such as calcium carbonate (CaCO3), which decomposes around 600-800°C.

- Calculating Extent of Carbonation: Calculate the extent of carbonation by determining the total mass loss attributed to the decomposition of carbonates. This can be expressed as a percentage of the initial sample mass or as the amount of CO2 sequestered per unit mass of steel slag.

- Comparative Analysis: Compare the thermogram with reference thermograms of pure carbonates to confirm the identity of the carbonates formed during the carbonation process. This comparison helps in verifying the accuracy of the TGA results.

7. Structural and Morphological Analysis

- Complementary Techniques: To enhance the understanding of the carbonation process, complement TGA results with other analytical techniques. For example:

o X-Ray Diffraction (XRD): Perform XRD analysis to confirm the presence and crystalline nature of the carbonates identified in the TGA thermogram.

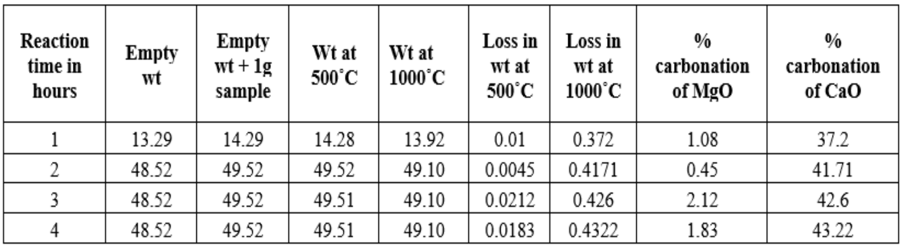
o Scanning Electron Microscopy (SEM): Use SEM to examine the surface morphology of the carbonated steel slag. This can provide insights into the microstructural changes resulting from carbonation.

o Energy-Dispersive X-Ray Spectroscopy (EDS): Combine SEM with EDS to analyze the elemental composition of the sample and confirm the presence of carbon and oxygen associated with carbonates.

2.3.1 Effect of Reaction Time

Reaction time refers to the duration for which carbon dioxide interacts with the slurry in the reactor at the specified temperature and pressure [9] [13]. This time is critical for allowing the gas to adequately react with the slurry. In this study, the reaction time was varied between 1 hour and 4 hours to observe its effect on the carbonation process [7] [16]. The results of these variations and their impact on the extent of carbonation are presented in Table 1.

Table 1. Effect of reaction time on carbonation

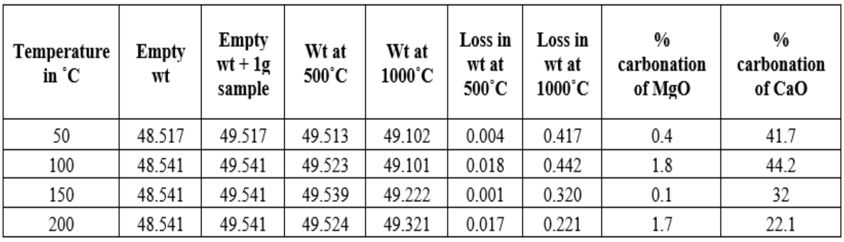


Reaction time in hours	Empty wt	Empty wt + 1g sample	Wt at 500˚C	Wt at 1000˚C	Loss in wt at 500˚C	Loss in wt at 1000˚C	% carbonation of MgO	% carbonation of CaO
1	13.29	14.29	14.28	13.92	0.01	0.372	1.08	37.2
2	48.52	49.52	49.52	49.10	0.0045	0.4171	0.45	41.71
3	48.52	49.52	49.51	49.10	0.0212	0.426	2.12	42.6
4	48.52	49.52	49.51	49.10	0.0183	0.4322	1.83	43.22

2.3.2 Influence of Temperature on the Process

Temperature plays a crucial role as a process variable in the carbonation procedure [3] [14]. Initially, the slurry is heated to a specific, predetermined temperature. Once the slurry achieves this target temperature, carbon dioxide gas is introduced into the system [5] [9]. Throughout the process, the temperature is meticulously maintained until the predetermined reaction time is completed [12] [17]. This is achieved by carefully controlling the exhaust gas valve and utilizing cooling systems to regulate any temperature fluctuations [8] [22]. The impact of varying temperatures on the extent of carbonation is detailed in Table 2, which provides a comprehensive overview of how temperature influences the process efficiency [18] [26]. This data underscores the importance of precise temperature control to optimize the carbonation process, ensuring consistent and predictable outcomes across different operating conditions [13] [30].

Table 2. Effect of temperature on carbonation

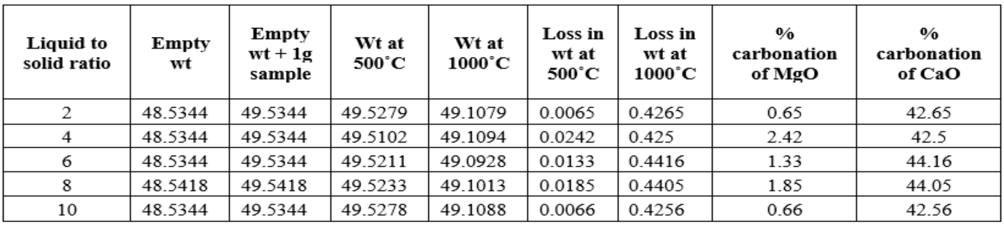


Temperature in ˚C	Empty wt	Empty wt + 1g sample	Wt at 500˚C	Wt at 1000˚C	Loss in wt at 500˚C	Loss in wt at 1000˚C	% carbonation of MgO	% carbonation of CaO
50	48.517	49.517	49.513	49.102	0.004	0.417	0.4	41.7
100	48.541	49.541	49.523	49.101	0.018	0.442	1.8	44.2
150	48.541	49.541	49.539	49.222	0.001	0.320	0.1	32
200	48.541	49.541	49.524	49.321	0.017	0.221	1.7	22.1

2.3.3 Impact of Liquid to Solid Ratio

The liquid to solid ratio, defined as the proportion of water to slag, is a critical parameter in the aqueous mineral carbonation process [6] [11]. In this process, water serves as the medium that facilitates the dissolution of calcium oxide and magnesium oxide, enabling them to react with carbon dioxide effectively [4] [9]. When the liquid to solid ratio is too low, inadequate mixing occurs, leading to inefficient carbon dioxide sequestration [10] [15]. To investigate this effect, the liquid to solid ratio was varied within the range of 2 to 10. The resulting data, summarized in Table 3, illustrates how different ratios influence the effectiveness of the carbonation process [17] [23]. This analysis highlights the necessity of optimizing the liquid to solid ratio to achieve efficient and thorough carbon dioxide sequestration, ensuring maximum reaction efficiency and improved overall process performance [19] [29].

Table 3. Effect of liquid to solid ratio on carbonation



Liquid to solid ratio	Empty wt	Empty wt + 1g sample	Wt at 500˚C	Wt at 1000˚C	Loss in wt at 500˚C	Loss in wt at 1000˚C	% carbonation of MgO	% carbonation of CaO
2	48.5344	49.5344	49.5279	49.1079	0.0065	0.4265	0.65	42.65
4	48.5344	49.5344	49.5102	49.1094	0.0242	0.425	2.42	42.5
6	48.5344	49.5344	49.5211	49.0928	0.0133	0.4416	1.33	44.16
8	48.5418	49.5418	49.5233	49.1013	0.0185	0.4405	1.85	44.05
10	48.5344	49.5344	49.5278	49.1088	0.0066	0.4256	0.66	42.56

2.3.4 Influence of Pressure on the Carbonation Process

Pressure, in this context, refers to the internal pressure of carbon dioxide within the reactor during the carbonation process [7] [14]. The reactor's pressure is carefully controlled by adjusting the inlet and exhaust gas valves to maintain the desired pressure throughout the reaction time [12] [18]. It is essential that the pressure remains constant to ensure the effectiveness of the carbonation process [6] [16].

At lower temperatures, the pressure of carbon dioxide within the reactor does not play a significant role. However, as the temperature increases, the dissolution of carbon dioxide in water becomes more challenging, necessitating higher pressures to maintain effective carbonation [9] [21]. In general, higher pressures are preferred in the mineral carbonation process to enhance the reaction rate and overall efficiency [19] [25].

The experiment involved varying the carbon dioxide pressure within a range of 4 Kg/cm² to 10 Kg/cm² to study its effect on the extent of carbonation [8] [13]. The results, detailed in Table 4, illustrate how different pressures influence the carbonation process. This data provides valuable insights into optimizing reactor pressure to achieve the desired level of carbonation, particularly under varying temperature conditions [11] [27].

Table 4. Effect of pressure on carbonation

Pressure	**Empty wt**	**Empty wt + 1g sample**	**Wt at 500˚C**	**Wt at 1000˚C**	**Loss in wt at 500˚C**	**Loss in wt at 1000˚C**	**% carbonation of MgO**	**% carbonation of CaO**
4	48.5315	49.5315	49.5297	49.5012	0.0018	0.0303	0.18	3.03
6	48.5312	49.5312	49.531	49.3959	0.0002	0.1353	0.02	13.53
8	48.5314	49.5314	49.5302	49.3002	0.0012	0.2312	0.12	23.12
10	48.5315	49.5315	49.5311	49.0885	0.0004	0.443	0.04	44.3

4. Results and Discussion

The study on the mineral carbonation of steel slag as a method for carbon dioxide (CO2) sequestration yielded significant insights into the process's efficiency under various controlled conditions. The experiments demonstrated that steel slag, with its high calcium and magnesium oxide content, is a highly reactive material suitable for CO2 sequestration, particularly when subjected to specific process parameters.

Influence of Reaction Time

The research explored the impact of reaction time on the extent of carbonation, varying the duration from 1 to 4 hours. The results showed that carbonation efficiency increased with longer reaction times, with the maximum carbonation achieved at 44.45% for a 4-hour duration. This suggests that extended exposure allows for more thorough interaction between CO2 and the metal oxides in the slag, leading to higher carbonation rates. However, the difference in carbonation between 3 and 4 hours was minimal, indicating that a plateau is reached after a certain period, beyond which additional reaction time yields diminishing returns.

Temperature's Role in Carbonation

Temperature was found to be a critical factor influencing carbonation efficiency. The study tested temperatures ranging from 50°C to 200°C. The data revealed that carbonation efficiency increased with temperature up to 100°C, where the maximum carbonation rate of 45.43% was observed. Beyond this temperature, the efficiency decreased, which can be attributed to the reduced solubility of CO2 in water at higher temperatures. This finding underscores the need for precise temperature control to optimize the carbonation process, as excessively high temperatures may hinder rather than enhance CO2 sequestration.

Liquid-to-Solid Ratio Optimization

The liquid-to-solid ratio, which defines the proportion of water to slag, was another crucial parameter. The study varied the ratio from 2:1 to 10:1. The optimal ratio was found to be 6:1, resulting in a carbonation efficiency of 45.39%. Ratios below this led to inadequate mixing and lower carbonation rates, while higher ratios did not significantly improve the efficiency, indicating that excessive water may dilute the reactants, reducing the effectiveness of the carbonation process.

Pressure's Impact on Carbonation

The pressure of CO2 within the reactor, tested at levels between 4 Kg/cm² and 10 Kg/cm², was also a significant determinant of carbonation efficiency. The highest carbonation efficiency, 45.53%, was achieved at 10 Kg/cm². The results indicate that higher pressures facilitate better dissolution of CO2 into the water, enhancing its interaction with the metal oxides in the slag. However, at lower temperatures, pressure had a less pronounced effect, highlighting the interplay between temperature and pressure in the carbonation process.

5. Conclusion

The study concludes that mineral carbonation of steel slag is a viable and effective method for CO2 sequestration. The optimal conditions identified—100°C temperature, 10 Kg/cm² pressure, a liquid-to-solid ratio of 6:1, and a reaction time of 2 hours—resulted in the highest carbonation efficiency of 45.53%. These findings provide a strong basis for further development of this technology, particularly in industrial settings where steel slag is readily available as a waste product. The research also highlights the potential for this method to contribute significantly to reducing industrial CO2 emissions while repurposing waste materials, aligning with sustainable practices and circular economy principles. Future work should focus on scaling up the process and improving reactor designs to handle higher pressures and optimize carbonation efficiency further.

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