

Utilization of Steel Slag for Permanent CO₂ Sequestration as CaCO₃: Performance Evaluation of Direct and Indirect Carbonation Pathways

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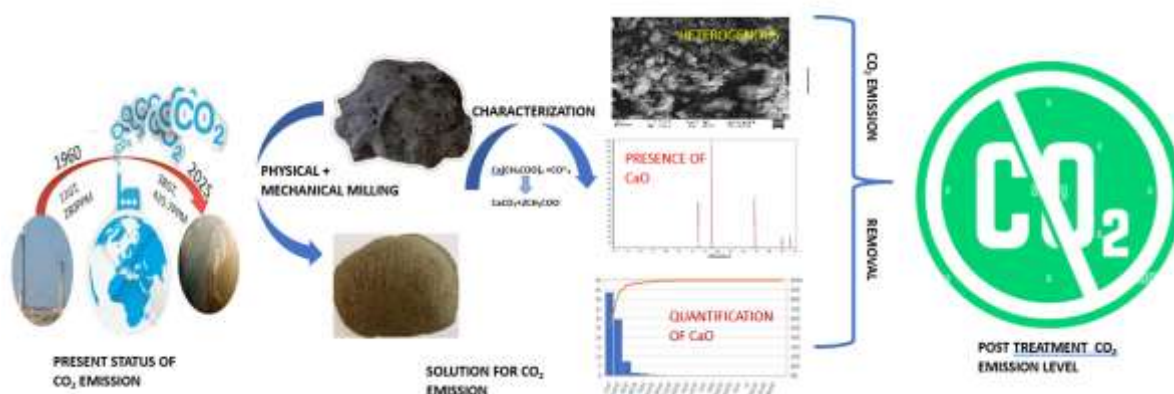
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ABSTRACT



The emission of CO₂ upon fossil fuels combustion has reached 38.1 billion tonnes in 2025, with India contributing 3.22 billion tonnes, this highlights the need for scalable carbon capture as many emissions remain uncontrolled due to high cost and complex infrastructure. To address this, an experimental study explores a low-cost, sustainable method for capture by utilizing calcium-rich waste material, steel slag. Based on a waste-to-resource concept, this work aligns with the United Nations Sustainable Development Goals regarding Climate action (SDG 13), Responsible Consumption and Production (SDG 12). The experimental work was carried out using mineral carbonation under both direct and indirect modes. The processed slag was characterized using fourier transform infrared spectroscopy (FTIR), particle size analysis (PSA), x-ray diffraction (XRD), scanning electron microscopy (SEM) and x-ray flourscence (XRF). The BOF slag derived calcium-rich submicron particles, containing 43.66% CaO, possess heterogeneous surfaces and reactive calcium sites that enhance CO₂ adsorption and subsequent transformation into stable carbonate products. In Direct Carbonation, the effect of particle size was studied under three conditions, for particles size greater than 0.450μm the removal efficiency ranged between 44-45% . When the particle size was reduced to 0.200-0.450μm, the efficiency increased to 50%. The highest efficiency of about 58% was achieved for particles size less than 0.200μm . In Indirect Carbonation, the efficiency was achieved nearly 70% by utilizing the extracted calcium using ammonium acetate, so both methods exhibit promising CO₂ removal potential, with Indirect Carbonation providing marginally higher efficiency under optimized conditions. Overall, this study demonstrates that steel slag waste can be effectively repurposed as low-cost sorbent, offering a practical, circular economy approach to reducing carbon emissions from decentralized biomass sources.

Keywords: sorbent, decentralized, carbonation, circular economy, CO₂ sequestration, steel slag, ammonium acetate.

1. INTRODUCTION

The global economy has developed rapidly, leading to extensive human activity and extensive exploitation of coal and its use for combustion, resulting in large amounts of carbon dioxide being produced and emitted into the atmosphere (Gür, 2022; Yoro & Daramola, 2020). Previously high levels of greenhouse gases have caused the Earth's temperature to continue to rise. The Intergovernmental Panel on Climate Change (IPCC) reports that over the period from 1850 to 1900, the average surface temperature of the Earth has increased by approximately 1 degree Celsius and it is projected

that it will be increased by an additional 4 degrees Celsius by the year 2100 (Yoro & Daramola, 2020). These trends highlight the urgent need for effective strategies to mitigate anthropogenic CO₂ emissions. Many researchers and engineers have been working on various ways to reduce CO₂ emissions and have proposed Carbon Capture Utilization and Storage (CCUS) technologies to do so (Dziejarski et al., 2023; Gür, 2022; Rajabloo et al., 2023). A major part of CCUS technology is the process of mineralizing carbon dioxide. Through this process calcium and magnesium ions (Ca²⁺ and Mg²⁺, respectively) from natural minerals or alkaline solid waste can be converted into stable carbonates (CaCO₃, MgCO₃) and silica gel (Dziejarski et al., 2023; Rashid et al., 2024). The process of mineralization not only stores carbon dioxide in solid form but enhances the consolidation and mechanical strength of waste-based cementitious materials as well (Ibrahim et al., 2019; Wang et al., 2022). The International Energy Agency (IEA) estimates that by 2050, CCS/CCUS will be able to mitigate over 7.6 billion tons of carbon dioxide emissions per year worldwide (Alturki, 2022; Dziejarski et al., 2023).

A very promising feedstock for CCUS is alkaline industrial waste, including carbide slag, steel slag and waste concrete. Previous studies have demonstrated that metallurgical wastes (i.e., blast furnace slag, steel slag) are not only effective at sequestering CO₂ but they also enhance the mechanical properties of cementitious materials (Wang et al., 2022).

Steel slag is produced in large quantities as a byproduct of the steel-making process and has the potential to be a considerable resource for sequestration of carbon dioxide due to its high calcium content (approximately 44-45% CaO) and alkaline properties (Ibrahim et al., 2019; Meng et al., 2021). In India, CO₂ emissions from the steel sector are significant, with millions of tonnes of steel slag produced on a yearly basis (Ibrahim et al., 2019; Meng et al., 2021; Rajabloo et al., 2023). Many of the traditional methods of disposing of steel slag (stockpiling, landfilling, or direct burial) consume valuable land and pose potential environmental risks due to leachable heavy metals and contamination of soils and water from the alkaline nature of the slag (Hanifa et al., 2023; Ibrahim et al., 2019; Meng et al., 2021). While being intrinsically alkaline, steel slag can also form stable compounds through carbonation reactions with CO₂, such as calcium carbonate (CaCO₃) and magnesium carbonate (MgCO₃). In this process, CO₂ enters the steel slag and is sequestered, while at the same time, steel slag is transformed into an economically useful resource (Meng et al., 2021; Wang et al., 2022).

Carbon dioxide (CO₂) sequestration can occur with steel slag through both direct and indirect carbonation processes. Direct carbonation processes can be further divided into hot and cold carbonation processes. Hot carbonation occurs when preheated waste CO₂ gas is used to speed up the carbonation reaction. The disadvantage of using hot carbonation is that excessive heat can partially decompose the formed CaCO₃ (Alturki, 2022; Ibrahim et al., 2019). Cold carbonation processes can be accomplished in both dry and wet forms and are complicated because they typically do not completely convert CaO and MgO into carbonates and will experience expansion due to hydration during wet slurry processing.

Although direct carbonation may be limited by diffusion resistance and incomplete utilization of reactive phases, its operational simplicity and lower reagent requirements make it attractive for practical applications. Indirect carbonation consists of leaching both calcium and magnesium from steel slag with the aid of chemical reagents and then performing CO₂ mineralization to produce carbonate products of very high purity. Although calcium can be readily leached using strong acids, strong acids are also, by nature, very corrosive, therefore utilising up significant amounts of chemical reagents and producing potentially deleterious side reactions. Therefore, ammonium salts (e.g. ammonium acetate) are considered an ideal choice due to moderate acidity, selective leaching of calcium ions with ease of collection and re-use and low toxicity levels results to give ideal operational characteristics to allow for industrial scale Capture of CO₂ from steel slag, therefore improving the overall efficacy and purity of products produced (Alturki, 2022; Meng et al., 2021).

By utilising steel slag through these two carbonation routes, a sustainable waste-to-resource strategy is in effect, ultimately addressing both challenges of CO₂ reduction and sustainable resource management of metallurgical by-products, in addition to aligning with the principles of a circular economy (Alturki, 2022; Dziejarski et al., 2023; Ibrahim et al., 2019; Rashid et al., 2024). Thus providing a practical solution towards emissions reductions while also generating valuable carbonate materials for use in cement markets, cementitious construction, and many other industrial applications (Ibrahim et al., 2019; Meng et al., 2021; Wang et al., 2022). Furthermore, the use of ammonium acetate in indirect carbonation provides a practical and economically feasible method for CO₂ Sequestration at a large scale within India (Alturki, 2022; Meng et al., 2021).

Despite growing interest in steel slag- based mineral carbonation, comparative studies evaluating both direct and indirect carbonation pathways under similar operating conditions remain limited. In particular, the influence of particle size on direct carbonation efficiency and the enhancement of calcium availability through ammonium acetate-assisted extraction using biomass-derived CO₂ sources have not been extensively investigated. Therefore, the present study aims to comparatively evaluate direct and indirect carbonation of BOF slag, investigate the effects of particle size and calcium extraction on CO₂ sequestration performance, and assess the potential of BOF slag as a sustainable sorbent for decentralized carbon capture applications.

2 MATERIALS AND METHODS

2.1 Experimental Materials:



Fig.1 . Stages of BOF slag refinement: (a) raw slag stone, (b) crushed fragments, (c) ultra-fine

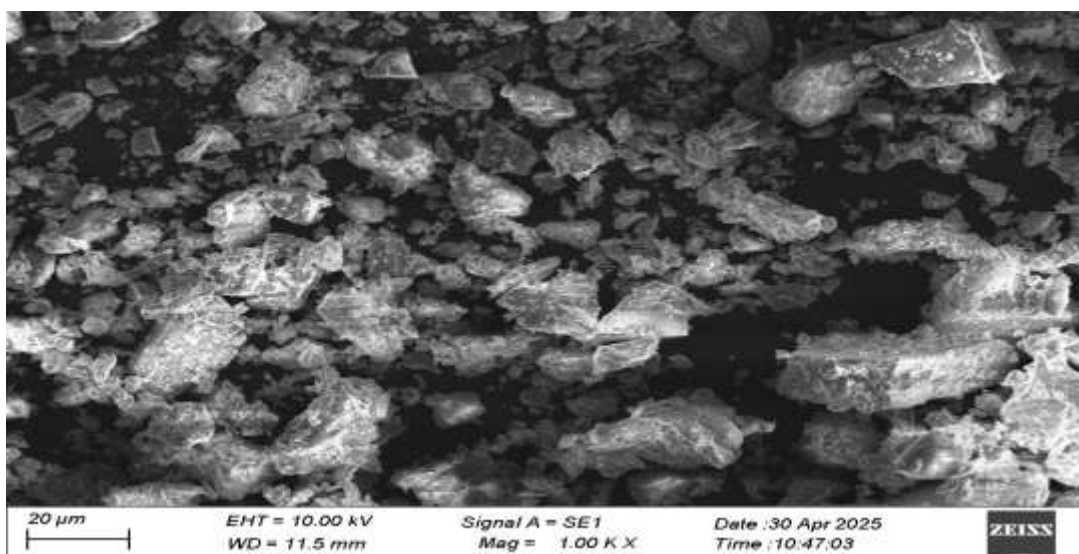


Fig.2 . SEM image of the Milled Steel slag powder

The steel slag was collected from the solid waste of steel production plant in Jamshedpur. The raw material was observed in the form of uneven granules, with particle sizes ranging from approximately 45cm to 2 cm as shown in Fig.1 . For the preparation of modified slag powder, the raw material was initially subjected to physical crushing to reduce its size then it was processes in a planetary ball mill for further size reduction. Following this, the milled powder was sieved using a standard 2500-3000 mesh to obtain finer particles. Following crushing, planetary ball milling, and sieving, the processed BOF slag was subjected to PSA after sonication. The PSA results revealed a multimodal particel size distribution comprising three distinct particle populations. The finest fraction exhibited a particle size of approximately 143.6nm, whereas the overall average particle size was found to be around 415-455nm, indicating the coexistence of ultrafine particles and larger agglomerated fractions within the sample. The morphology of the prepared powder is

illustrated in the figure 2 , which highlights its structural characteristics which is followed by calcium extraction using 2M $\text{CH}_3\text{COONH}_3$. (Gan, 2025).

2.2 Experimental setup and Procedure: The carbon capture experimental setup is illustrated in the Fig.3 and primarily consists of a chimney for CO_2 generation, a flowmeter for regulating gas flow, a motor, a 500 mL double-neck round bottom flask, CO_2 detection sensors, and a pH meter. CO_2 is produced in real time by the combustion of biomass wastes such as dry leaves, branches, and coconut shells.

The experimental study was carried out in two approaches: **Direct CO_2 mineralization** and **indirect CO_2 mineralization**. The operating temperature during the experiments was maintained in the range of 40–50°C.

In the **direct CO_2 mineralization process**, raw steel slag of varying particle sizes was weighed according to experimental requirements and introduced into the round bottom flask. Biomass waste was combusted in the chimney to generate CO_2 , which was drawn into the system and regulated using a flowmeter. The gas was then introduced through one neck of the flask for a duration of 20–25 minutes, corresponding to the complete combustion of the biomass. During this process, CO_2 concentrations at the inlet and outlet were monitored using CO_2 sensors at intervals of 5 minutes and recorded.



Fig.3 . Experimental setup for both Direct and Indirect Carbonation

In the **indirect CO_2 mineralization process**, modified steel slag obtained after treatment with 2 M ammonium acetate ($\text{CH}_3\text{COONH}_4$) was used. The required quantity of the prepared solution was added to the flask. Similar to the direct method, CO_2 generated from biomass combustion was passed into the flask under controlled flow conditions for 20–25 minutes. The pH of the solution was measured during this process and was found to be 9.41, indicating alkaline conditions favorable for CO_2 mineralization. CO_2 levels at the inlet and outlet were recorded at 5-minute intervals using detection sensors. All experiments were conducted in multiple trials to ensure accuracy and reproducibility of the results.

2.3 Characterization Techniques used for BOF Slag:

Raw coarse Basic Oxygen Furnace (BOF) slag was first collected from its source and the size of the slag was reduced manually : grinding stone was used to break the larger fragments of slag, then again the size is reduced with a mortar and pestle until finer slag particles are obtained. This finer slag was then transferred to a laboratory planetary ball mill for further refinement (Y. Sun et al., 2022). In this step, milling jars containing both the slag and grinding media rotate in a high-energy planetary motion each jar spins on its own axis while simultaneously orbiting a central “sun wheel” generating intense centrifugal and coriolis forces that drive effective impact and frictional grinding. The grinding jar is filled and upon milling, it potentially reaches submicron or even nano particles depending on parameters like speed, time and whether wet or dry milling is used. The resulting ultra-fine slag powder was then utilized for characterization studies including Particle Size Analysis (PSA), Fourier-Transform Infrared Spectroscopy (FTIR), Scanning Electron

Microscopy (SEM), X-Ray Diffraction (XRD), and X-Ray Fluorescence (XRF) to investigate its particle-size distribution, chemical structure, morphology, crystalline phases, and elemental composition.

2.3.1 Particle Size Analysis (PSA). Particle size distribution of BOF slag was found using a Zeta sizer Nano ZS90 (Malvern Instruments Ltd., UK). Before finding the PSA the particles were subjected to sonication in an hydroalcoholic medium (ethanol:water, 1:1) then the sample is subjected for PSA analysis with the refractive index of 1.52, a two peak distribution was found at 1.678 μm (54.3%) and 0.230 μm (45.7%) where the average diameter was 0.416 μm with a PDI of 0.492.

2.3.2 Fourier Transform Infrared Spectroscopy (FTIR). Functional group was found using a PerkinElmer Spectrum 2 were KBr-mixed pellets revealed absorption bands at 2391 and 915 cm^{-1} which correspond to surface hydroxylation, silicate bonding, and partial carbonation.

2.3.3 X-ray Diffraction (XRD). The Phase analysis was found with a Panalytical X'Pert Pro Diffractometer, where multiple crystalline phases like CaO, CaSiO₃, Fe₂O₃, Fe₃O₄, CaFe₂O₄ and SiO₂ and moreover it was interpreted with High Score software, which confirms the presence of these multiple phases this multiphase reflects its complex mineralogy and crystalline stability(B. K. A. M. S. C. A. S. K. C. Ragunath N, 2019; R. S. R. R. C. A.S. Balaganesh, 2018).

2.3.4 Scanning Electron Microscopy (SEM): The morphology analysis was done using the Zeiss instrument which confirms the irregular shapes, angular particles with rough and porous surfaces in nature and also indicated the evidence of agglomeration, so this heterogeneous microstructure increases the slag's reactivity by enhancing its surface area.

2.3.5 X-ray Fluorescence (XRF). The Chemical Composition of BOF slag was found by using the Epsilon Bench top, shows the major composition of CaO dominated by 43.66 wt% and followed by Fe₂O₃ and SiO₂. The presence of CaO plays an important role in Neutralization applications.

3. RESULTS AND DICUSSION

3.1 PARTICLE SIZE DISTRIBUTION

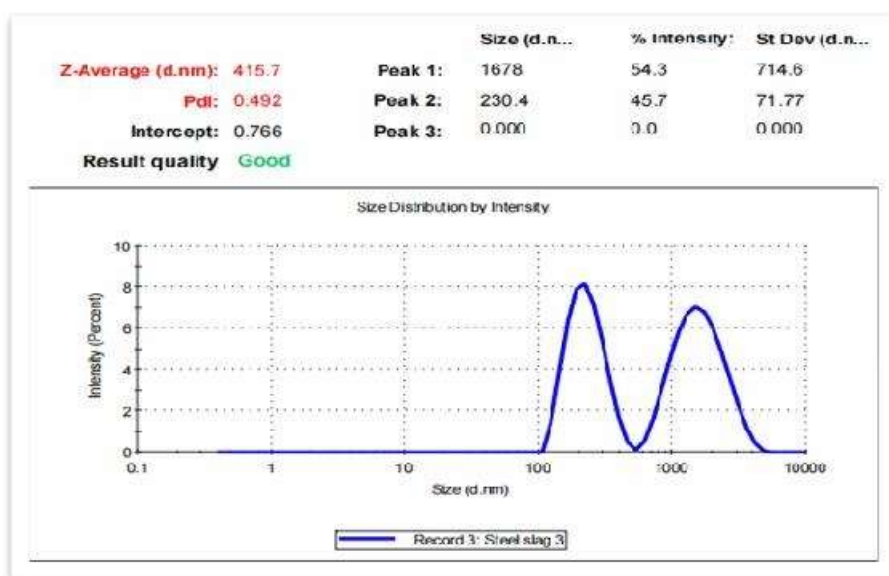


Fig. 4. PSA for BOF slag

The particle size distribution of the processed BOF slag was determined using the Malvern particle size analyzer, which plays an important role for further characterization analysis like XRD, FTIR, XRF, SEM. After sonication, PSA was done and the results are presented in Fig.4 where it shows a Poly dispersity Index (PDI) of 0.492, which indicates moderately broad size distribution that comprises of both fine and coarse particles. The obtained intensity distribution curve revealed a two peak distribution where peaks at 1.678 μm and 0.230 μm . The final result quality shows it was "Good" confirming the reliability and supporting interpretation of slag's behaviour.

3.2 FOURIER TRANSFORM INFRARED SPECTROSCOPY

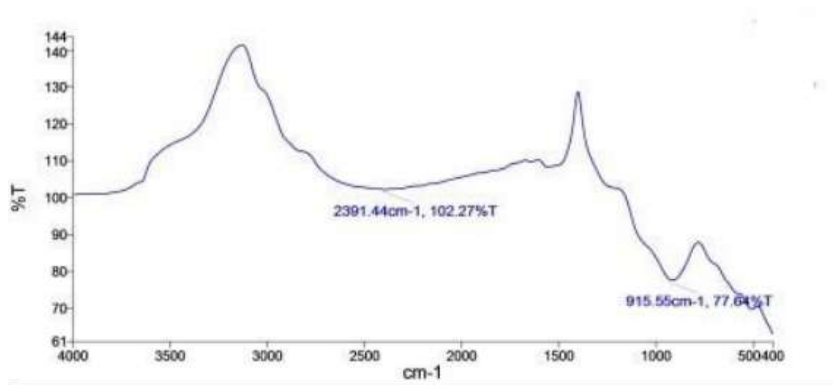


Fig. 5. FTIR Peaks for BOF slag

FTIR is a vital technique for analyzing the molecular structure and decomposition of different materials. The study examines the FTIR spectrum of steel slag and its relationship with BOF slag, highlighting the presence of CaO and its conversion to CaCO_3 . The FTIR spectrum obtained from Fig.5 shows distinct absorption bands that reveal the presence of particular functional groups within the steel slag sample. Covalent bonds typically exhibit IR absorption between 600 and 4000 cm^{-1} , confirming the presence of covalent interactions in the material.(S. R. S. T.Sowmiya, 2004)

TABLE 1 : FTIR Absorption Peaks of BOF slag

SL.NO	WAVENUMBER CM^{-1}	FUNCTIONAL GROUP	ABSORPTION INTENSITY
1	2391.44	Carbonate	Strong
2	915.55	Silicate	Medium

FTIR analysis of BOF slag was performed using a PerkinElmer Spectrum 2 with KBr pellet preparation. The spectrum showed key absorption bands as summarized in Table I, at 2391 cm^{-1} , indicating surface carbonation (likely from CaO reacting with atmospheric CO_2 to form CaCO_3), and at 915 cm^{-1} , characteristic of crystalline calcium silicate phases (S. R. S. T.Sowmiya, 2004)(e.g., dicalcium silicate). These features confirm both carbonation and Ca–Si–O bonding in the slag.

3.3 X-RAY POWDER DIFFRACTION:

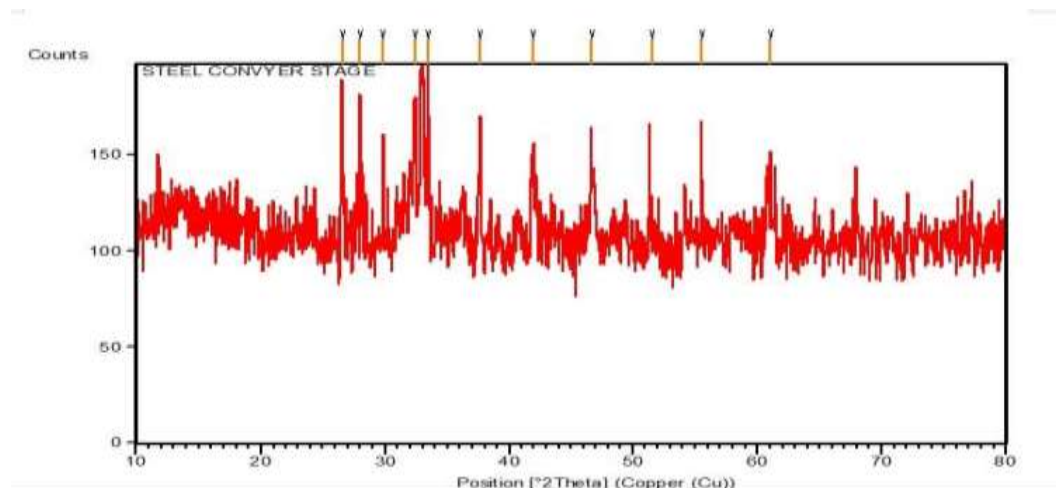


Fig. 6. XRD Analysis of BOF slag

From Fig.6, the diffraction peaks were found at 2θ positions of 26.56° , 28.01° , 29.82° , 32.41° , 33.45° , 37.62° , 41.95° , 46.72° , 51.51° , 55.53° , and 61.05° , confirming that the material is crystalline in nature. Of these, the most intense peak was observed at $2\theta = 33.45^\circ$, with a relative intensity of 100%. This peak, along with those at 29.82° and 32.41° , are indicative of the presence of Ca- and Fe-containing phases, as commonly reported in converter (BOF) slag XRD profiles.

TABLE 2 :Identified XRD Peaks

S.No	2θ ($^\circ$)	d-spacing ($\text{\AA}$)	FWHM M ($^\circ$)	Relative Intensity (%)	Height (cts)
1	26.56	3.356	0.1574	61.42	52.99
2	28.01	3.185	0.1181	84.01	72.48
3	29.82	2.997	0.1181	62.69	54.09
4	32.41	2.763	0.1968	76.85	66.30
5	33.45	2.679	0.1968	100.00	86.28
6	37.62	2.391	0.2362	61.80	53.32
7	41.95	2.154	0.2362	56.70	48.92
8	46.72	1.944	0.3149	46.04	39.72
9	51.51	1.774	0.4723	27.33	23.58
10	55.53	1.655	0.1181	76.06	65.63
11	61.05	1.518	0.6298	33.52	28.92

The X-ray diffraction (XRD) analysis of the BOF slag revealed the presence of multiple phases with calcium phases and Iron phases as dominant components. The observed XRD peaks from Table II for the CaO includes, 28.01° , 32.22° , 37.35° , 55.53° , 64.09° and 67.34° so corresponding to the (111),(200),(220),(222),(400) planes of the cubic CaO structure. These matched well with the JCPDS Card No. 37.1497. The observed Intense and sharp peaks suggest that the slag sample is highly crystalline in nature (R. S. R. R. C. A.S. Balaganesh, 2018). The presence of Calcium rich compounds is important for various future applications including environmental remediation (Konar & Chattopadhyay, 2019) which concludes that not only the presence of CaO is important but also the presence of calcium ferrite (CaFe_2O_4) is important, and the peaks which are observed in slag after XRD analysis for calcium Iron Oxide includes 33.45° , 41.95° , 46.7° , 61.05° which gives certain planes as this phase aligns with JCPDS Card No. 74-2136, from which it confirms the orthorhombic structure (B. K. A. M. S. C. A. S. K. C. Ragunath N, 2019).

The presence of Calcium is important especially the free CaO and other Calcium rich phases as they play an important role in environmental remediation applications which are quantified under XRD and valuated by JCPDS.

3.4 SCANNING ELECTRON MICROSCOPE:

The morphology of a particle can be analyzed using SEM, Unlike optical microscopy, SEM provides high-resolution, three-dimensional imaging, which allows us to analyze surface features, particle shape, texture, porosity, and agglomeration behavior.

The SEM analysis of BOF slag from Fig.7 shows distinct microstructural characteristics, affecting steel slag (18). By examining particle distribution, surface area, and reactivity, SEM helps determine whether slag can effectively bind and absorb pollutants such as CO_2 , SO_2 from industrial emissions (Yildirim & Prezzi, 2011). The required Potential applications in environmental protection and industrial processing,

Particle Shape: The slag exhibits mostly irregular, angular shapes rather than smooth or round structures. This morphology allows better interaction with pollutants by enhancing its reactivity.

Surface Texture: To improve the adsorption properties, higher surface area is required where the surfaces should appear rough, with cracks, sharp edges and uneven formations and upon SEM analysis the BOF slag also revealed the same.

Porosity: Presence of small pores or voids are observed which indicates possible internal spaces for gas or pollutant capture which plays a critical role for sorption mechanisms.

Agglomeration: The finer slag particles cluster together to form dense groups which in turn affects mechanical stability and chemical interactions in material applications.

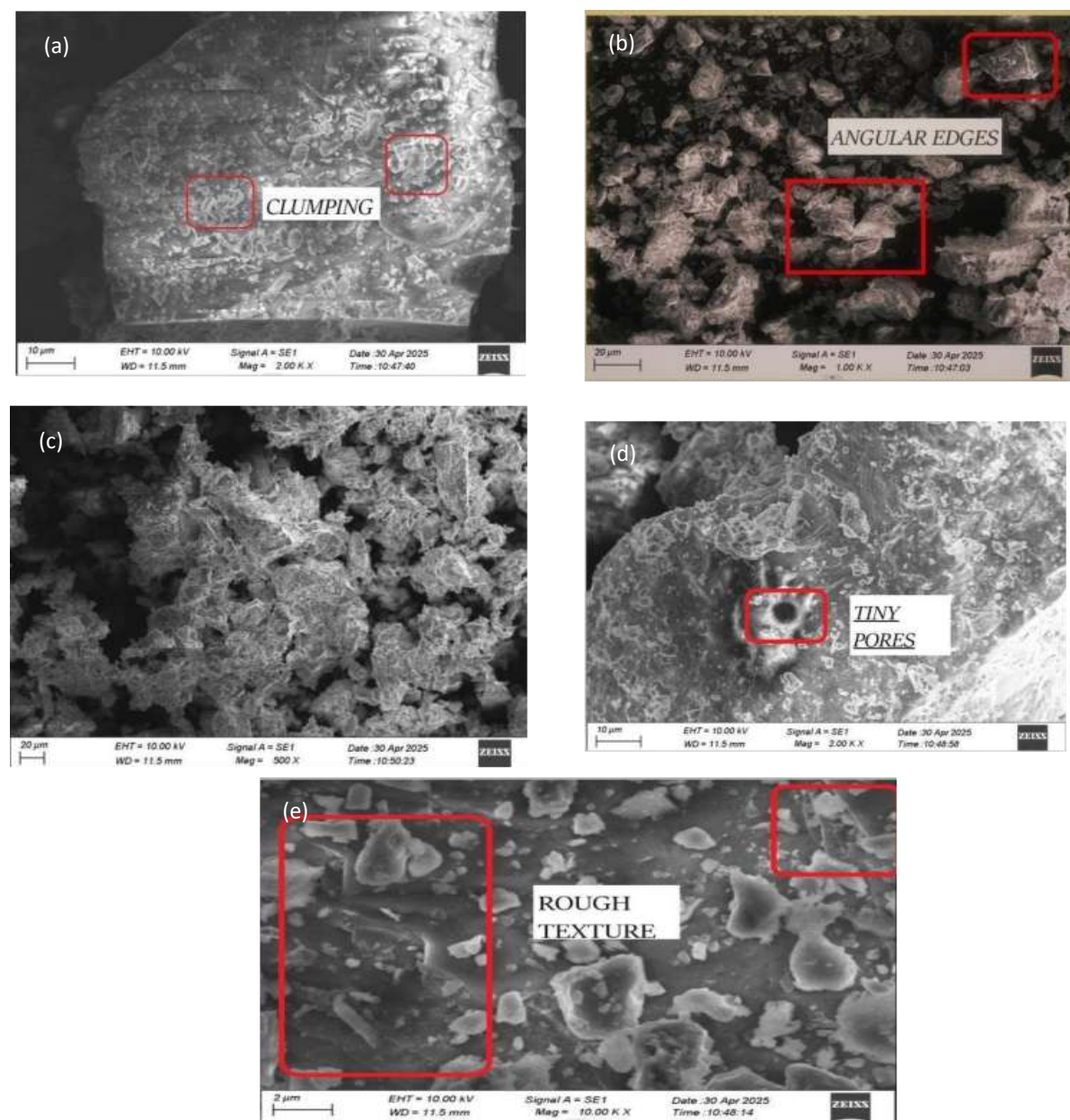


Fig. 7. Heterogeneous Crystalline Nature of BOF slag (a)Clumping, (b)Angular edges, (c)Heterogeneous, (d)Tiny pores,(e)Rough Texture

Heterogeneous Morphology: Slag exhibits an inconsistent texture due to its diverse particle sizes and shapes which makes it suitable for different applications like pollutant capture and reaction processes, the properties obtained through SEM analysis suggest that the BOF slag has the potential in neutralizing the acidic gases like SO_2 , CO_2 (Ma et al., 2025; Z. Sun et al., 2019).

Presence of CaO: To neutralize the acidic gases like SO_2 , CO_2 the presence of CaO is important as it forms a stable compounds like CaSO_4 through adsorption process

So the overall Heterogeneous Morphology of slag concludes that its has the ability to bind SO_2 , CO_2 and other airborne pollutants, slag could serve as an eco-friendly solution for mitigating industrial emissions (Ma et al., 2025; Mercado-Borrayo et al., 2020).

3.5 X-RAY FLOURESCENCE

The chemical composition of BOF slag was found by XRF as illustrated in Table III where the CaO dominated by 43.66 wt% in total, this CaO plays an important role in mitigating CO_2 , SO_2 by neutralizing it. From Fig.8, the amount of Calcium was found to be 51.96% which again confirms the dominating CaO presence.

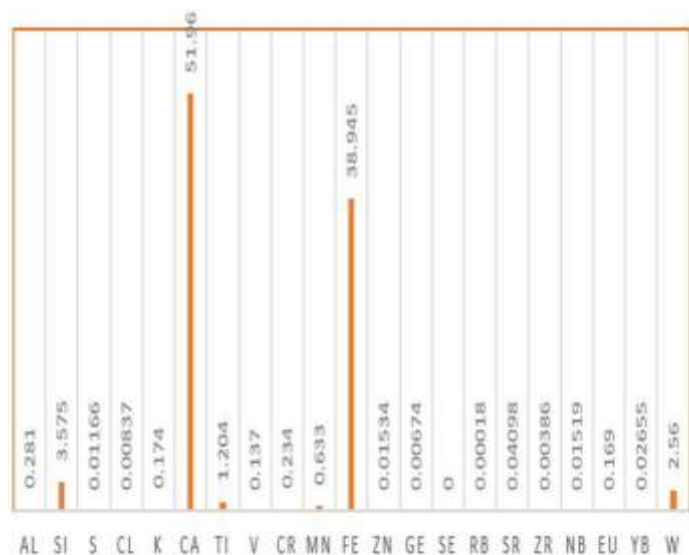


Fig. 8. Elemental Composition of BOF slag

TABLE 3: Chemical Composition of BOF Slag

COMPOSITION	CONCENTRATION
Al_2O_3	0.63
SiO_2	7.494
SO_3	0.02224
Cl	0.00621
K_2O	0.132
CaO	43.662
TiO_2	1.129
V_2O_5	0.16
Cr_2O_3	0.19
MnO	0.44
Fe_2O_3	29.664
ZnO	0.00968
Others	<2

Minor sulfate content: Initially the sulfur trioxide (SO_3) was found to be very little of 0.022 wt% so CaO plays a large reactive role in capturing SO_2 , the obtained composition of BOF slag was in the range similar to other researchers (Chaurand et al., 2007; Das et al., 2007; Liu et al., 2021; Tossavainen et al., 2007).

Importance of High CaO Concentration:

High alkalinity and basicity: The dominating CaO content determines the slag's basicity, which is required for neutralizing acidic gases.

$$\text{Basicity} = 43.66 / 7.49 \approx 5.83$$

Environmental and Industrial Relevance: Operating with BOF slag as a sorbent for CO_2 , SO_2 not only reduces harmful emissions but also provides a circular material utilization for steel production byproducts. This valorisation aligns with circular economy principles and mitigates disposal issues related to steel slag (Konar & Chattopadhyay, 2019).

3.6 pH Change Before and After Slurry CO_2 Mineralization Reaction

The variation in pH of the modified steel slag slurry provides significant insight into the progression of the CO_2 mineralization process. Initially, the slurry exhibited an alkaline pH of 9.41, which is primarily attributed to the hydration of calcium oxide (CaO) present in the slag, forming calcium hydroxide, as shown in eq 1:



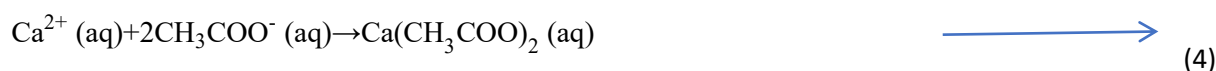
Calcium hydroxide further dissociates in the aqueous medium to release hydroxide ions, increasing (1) the alkalinity of the solution (eq 2):



In addition, ammonium acetate ($\text{CH}_3\text{COONH}_4$) dissociates into ammonium and acetate ions (eq 3), which facilitates the extraction of calcium into the solution:



The released calcium ions further interact with acetate ions to form soluble calcium acetate, enhancing calcium availability in the aqueous phase (eq 4):

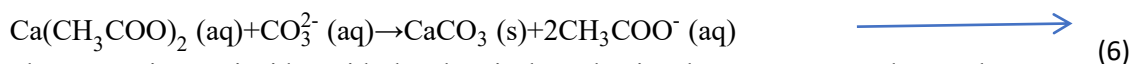


Upon introduction of CO_2 into the slurry, it dissolves in the aqueous medium and undergoes stepwise conversion to form carbonate ions (eq 5):



These reactions generate hydrogen ions (H^+), which neutralize the hydroxide ions present in the system, leading to a progressive decrease in pH. During the initial stages of the reaction (first 5–10 minutes), a rapid drop in pH is observed due to the fast consumption of OH^- ions. As the reaction proceeds up to 30 minutes, the pH stabilizes in the near-neutral range of approximately **6.5–7.0**, indicating a balance between hydroxide ion generation and CO_2 absorption.

Simultaneously, calcium ions react with carbonate ions to form calcium carbonate precipitate, while acetate ions are regenerated back into the solution (eq 6):



The above reactions coincide with the chemical mechanism between CaO and NH_4Cl as stated. The formation of a white precipitate confirms the production of calcium carbonate, while continuous bubbling indicates steady CO_2 flow through the system. A slight color change was also observed during the reaction. The process was carried out at a controlled temperature of **40–50°C** with continuous stirring using a motor, ensuring uniform mixing and enhanced gas–liquid interaction.

Overall, the decrease in pH from alkaline to near-neutral conditions confirms the effective consumption of hydroxide ions and successful conversion of CO_2 into stable carbonate products. The acetate ions act as a recyclable complexing agent, facilitating calcium extraction and remaining in solution at the end of the reaction.

3.7 CO_2 Capture and Mineralization Performance of Modified Steel Slag

This study used steel slag (an industrial byproduct and calcium source) as a substrate for the evaluation of CO_2 sequestration efficiencies through both direct and indirect carbonation pathways. In the initial phase of testing (0–5 min), there were still fairly low total efficiencies (15–42%) due to limited contact between gaseous CO_2 and the available acidic sites on the neomorphic surface of the steel slag. However, the considerably higher amounts of CO_2 removed (up to ~58%) in the second phase of testing (5–10 min) suggested that there was now better diffusion of CO_2 through the steel slag and/or additional access to the active calcium components of this substrate material. Maximum CO_2 removal efficiencies (63–65%) occurred in the third phase of testing (10–15 min), which supports the continued trend of maximum contact time between gaseous CO_2 and the reactive components of steel slag (e.g. CaO) being optimal. Maximum performance from the carbonated substrate material occurred at 15–20 min, after which there was a reduction in performance from this maximum rate during the 20–25 min period, with the rates falling to 14–30% from their maximum. The loss in performance was likely due to active site saturation and the creation of carbonate (CaCO_3) layers over the top of those sites, making it more difficult for CO_2 to diffuse into the internal structure of the material.

Longer periods of time result in a decrease in mass transfer efficiency, which slows down the degree at which CO_2 gets removed from the atmosphere by establishing chemical reactions with iron oxide. In total 4 trials were done under each

condition and the major results are shown in Table IV where 60.31% is the highest removal efficiency in Direct carbonation and 69.73% is the highest removal efficiency in Indirect carbonation.

TABLE 4: DIRECT CARBONATION AND INDIRECT CARBONATION TRIALS

METHOD	CONTACT TIME (mins)	FLOW RATE	INITIAL CONCENTRATION	FINAL CONCENTRATION	C/CO	% REMOVAL
DIRECT CARBONATION OF $X > 0.450 \mu\text{m}$	0-5	0.5	11692	9866	0.843	5.62
	5-10	0.5	9900	6267	0.633	36.69
	10-15	0.5	7500	4150	0.553	44.66
	15-20	0.5	6012	4229	0.703	29.65
	20-25	0.5	4900	4195	0.85	14.4
DIRECT CARBONATION OF $0.200-0.450 \mu\text{m}$	0-5	0.5	11945	9765	0.817	18.2
	5-10	0.5	9700	6378	0.657	34.24
	10-15	0.5	7748	3758	0.485	51.59
	15-20	0.5	6100	4195	0.687	31.22
	20-25	0.5	4878	3992	0.818	18.16
DIRECT CARBONATION OF $X < 0.200 \mu\text{m}$ TRIAL 1	0-5	0.5	11848	9652	0.814	18.5
	5-10	0.5	9800	4108	0.42	58
	10-15	0.5	7428	5248	0.7065	29.35
	15-20	0.5	5946	4209	0.707	29.21
	20-25	0.5	4700	3201	0.681	31.89
DIRECT CARBONATION OF $X < 0.200 \mu\text{m}$ TRIAL 2	0-5	0.5	11945	9996	0.836	17
	5-10	0.5	10206	4150	0.396	60.31
	10-15	0.5	7350	4995	0.679	32.04
	15-20	0.5	6011	4129	0.686	31.3
	20-25	0.5	4900	3195	0.652	34.79
INDIRECT CARBONATION TRIAL 1	0-5	0.5	11801	6966	0.59	40.97
	5-10	0.5	9783	5095	0.52	48
	10-15	0.5	8632	3100	0.35	64.08
	15-20	0.5	6844	2041	0.302	69.73
	20-25	0.5	5805	3110	0.535	46.42
	0-5	0.5	11856	6993	0.589	41.04

INDIRECT CARBONATION TRIAL 2	5-10	0.5	9658	5125	0.53	46.93
	10-15	0.5	8734	3028	0.346	65.33
	15-20	0.5	7112	2295	0.322	67.73
	20-25	0.5	5669	3199	0.564	43.57

Both carbonation processes were compared in terms of their relative performance, shown by comparing a representative sample of the two products, direct and indirect carbonation of BOF slag as shown in Fig. 10. Throughout all of the different configurations used, some time/duration range produced consistently higher efficiencies than others. The ranges that produced the best results were considered from 10-15 minutes of connection time between CO₂ and slag based on Fig. 9., which shows the optimum conditions between direct and indirect carbonation of BOF slag occurring in this range. Generally evaluating the data obtained, contact time has proven to be the most important factor affecting CO₂ sequestration capabilities with the optimum time established to be 10-15 minutes, to achieve maximum CO₂ removal from the atmosphere.

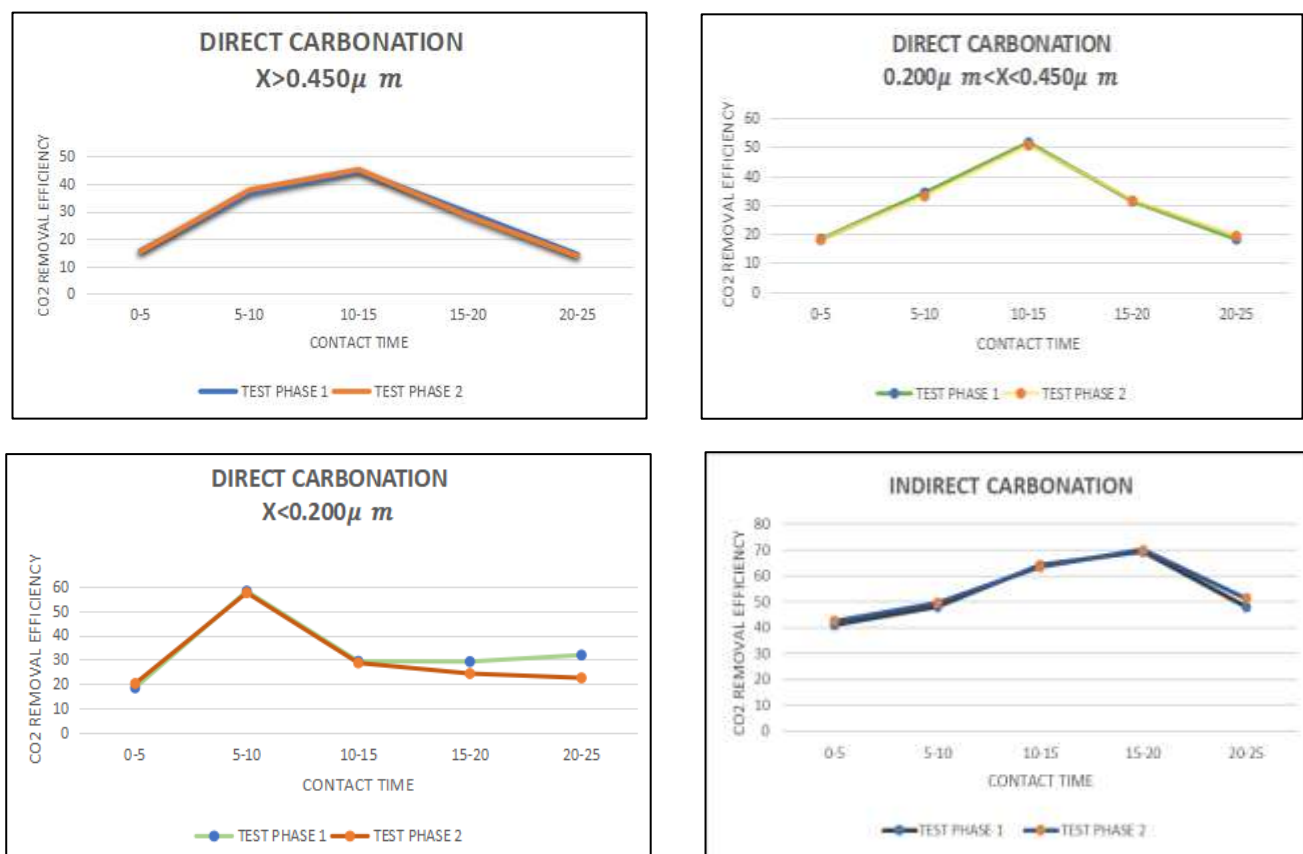
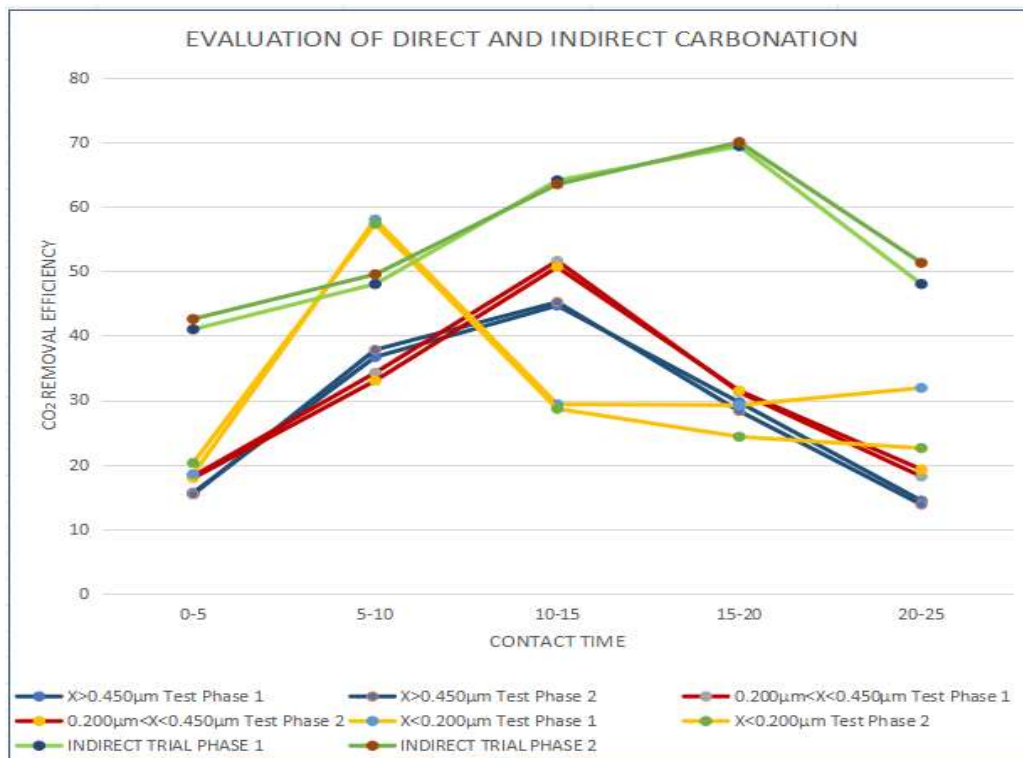


Fig. 9. Various optimum conditions of Direct and Indirect Carbonation of BOF slag



3.8 Reutilization of steel slag from Direct and Indirect Carbonation:

Steel slag is currently being explored for carbon dioxide (CO₂) removal using both direct and indirect methods of carbonation (given that you will be reusing this material as a low-cost sorbent). The direct method involved contacting CO₂ directly with the solid steel slag under controlled conditions to determine how effective the removal of CO₂ could be. The particle size of the steel slag, as well as contact time with CO₂, were found to have a considerable effect on CO₂ removal efficiency. The efficiency of removal for the larger slag particles (>0.450 μm) was 44-45%, whereas the efficiency of smaller pieces (0.200-0.450 μm) increased up to 50-51%. The smaller pieces had the maximum efficiency of approximately 58%, indicating that smaller particles provide more surface area for calcium to react with the CO₂ and therefore improve the availability of reactive Ca for CO₂ removal.

Efficiency also changed with contact time, as optimal removal of CO₂ occurred in the 10 to 15 min range with removal declining after 15 mins. This is because the ability of additional CO₂ to diffuse into the inner Ca-rich portion of the slag was limited after forming a dense layer of CaCO₃ (calcium carbonate) on its surface. Therefore, even though direct carbonation is a simple process with minimal operational requirements, it is still limited by both kinetic constraints and incomplete use of reactive calcium sites. To address this limitation, extraction of reactive calcium from steel slag and its subsequent indirect carbonation was undertaken using ammonium acetate as the leachate. This resulted in calcium becoming more available in solution, thereby increasing the efficiency of interaction with carbon dioxide (CO₂). Based on results obtained using the indirect carbonation methodology, the approximate 69-70% removal efficiency when reaction conditions are optimized is significantly better than observed for the direct carbonation method; improvements in overall performance are due to greater control of reaction conditions, improved mass transfer, and increased availability of calcium ions than when using solid-phase reactions with the direct carbonation method.

Indirect carbonation allows for the conversion of carbon dioxide (CO₂) into stable, value-added products such as calcium carbonate (CaCO₃), which has many applications in construction, cementing systems, as a filler, and in other industrial processes. Therefore, use of industrial waste as a resource adds to reuse of resources in a circular economy by converting waste materials to high-value, beneficial products.

In summary, while direct carbonation provides a simple, low-cost technique for CO₂ capture, indirect carbonation yields higher efficiency and better process control. Taken together, these two methods present a viable pathway towards scalable CO₂ capture and reuse through the use of industrial by-products.

4. APPLICATION IN REAL WORLD

The present study was conducted at laboratory scale using a 500ml round bottom flask containing 25g of carbonated slag samples under controlled operating conditions. Based on the experimental findings, the process demonstrates potential for large-scale industrial implementation in flue gas treatment systems. For industrial applications, a tray-type reactor or setup or packed-bed chamber can be installed within or adjacent to existing chimney and flue gas ducts. The dimensions and number of trays can be designed according to the flue gas flow rate, chimney diameter, and required CO₂ removal efficiency. Carbonated BOF slag can be uniformly distributed over the trays, allowing effective contact between the flue gas stream and the sorbent material. Where economic considerations are important, direct carbonation of BOF slag may be preferred due to its lower processing cost, although with comparatively lower CO₂ sequestration efficiency. When maximum carbonation and sorbent performance are desired, indirect carbonation can be adopted despite its higher operational requirements. The carbonated slag produced through either route can be utilized as the active sorbent in the flue gas treatment unit.

To improve resource utilization and sustainability, a separate collection and regeneration chamber may be incorporated into the system. The spent slag can be periodically collected, preprocessed for potential reuse or secondary applications, and recirculated where feasible. Such an integrated system would promote waste valorization, reduce disposal requirements, and enhance the overall environmental benefits of BOF slag utilization for industrial emission control.

5. CONCLUSION:

High-calcium steelmaking slag has great potential to be a low-cost, green CO₂ sorbent because of its high CaO content and favorable characteristics. Based on the available experimental data as well as from characterization studies performed on the steelmaking slag, the following conclusions can be drawn:

1. There is a large amount of CaO (43.66 wt%) in steelmaking slag and it is alkaline in nature, which makes it a good candidate for capturing CO₂ and remediating the environment.
2. Two types of carbonation methods were evaluated: direct carbonation (gas–solid reaction) and indirect carbonation (soluble calcium removed from the solid). Each method has its own advantages.
3. The length of time the CO₂ is in contact with the steelmaking slag has a dramatic impact on the efficiency of carbon capture. Most effective carbon capture occurs when CO₂ contacts the steelmaking slag between 10 and 15 minutes.
4. When the length of exposure to the steelmaking slag exceeds 15 minutes, the carbon capture efficiency decreases, due to the saturation of active sites on the steelmaking slag and the formation of a CaCO₃ layer that inhibits further CO₂ diffusion into the steelmaking slag.
5. Reducing the size of the steelmaking slag particles maximises the carbon capture efficiency because it provides a larger surface area and therefore a better gas–solid interaction.
6. Characterisation studies indicate that highly reactive phases (CaO and CaFe₂O₄) and a porous microstructure exist in the steelmaking slag and contribute to the reactivity and effective capture of carbon dioxide by the steelmaking slag.
7. Though direct carbonation is simple and inexpensive, the rate of reaction is limited by the time required for diffusion of the gases through to the steelmaking slag.
8. The indirect method of carbonation, while more complex than the direct method, makes more calcium available to react with the CO₂ and significantly improves mass transfer, achieving approximately 69–70% efficiency for CO₂ capture.
9. CaCO₃ is a stable end product, providing the potential for a value-added use, whilst also substantially lowering atmospheric carbon dioxide emissions.

The method also provides a sustainable means of utilising waste materials and aligns with the principles of a circular economy by converting industrial byproducts into beneficial resources. In terms of providing an effective means of CO₂

capture from steelmaking slag, the combination of direct and indirect carbonation provides greater efficiency and also improves the flexibility of the overall process.

DECLARATIONS

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Consent for publication: Not applicable

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REFERENCES

1. Dziejarski, B., Krzyżyńska, R., & Andersson, K. (2023). Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. *Fuel*. <https://doi.org/10.1016/j.fuel.2023.127776>.
2. Gür, T. (2022). Carbon Dioxide Emissions, Capture, Storage and Utilization: Review of Materials, Processes and Technologies. *Progress in Energy and Combustion Science*. <https://doi.org/10.1016/j.pecs.2021.100965>.
3. Rajabloo, T., Valee, J., Marenne, Y., Coppens, L., & De Ceuninck, W. (2022). Carbon capture and utilization for industrial applications. *Energy Reports*. <https://doi.org/10.1016/j.egy.2022.12.009>.
4. Yoro, K., & Daramola, M. (2020). CO2 emission sources, greenhouse gases, and the global warming effect. , 3-28. <https://doi.org/10.1016/b978-0-12-819657-1.00001-3>.
5. Bala, R., Kaur, M., Thakur, H., Kashyap, P., Karnwal, A., & Malik, T. (2025). A Sociotechnical Review of Carbon Capture, Utilization, and Storage (CCUS) Technologies for Industrial Decarbonization: Current Challenges, Emerging Solution, and Future Directions. *International Journal of Chemical Engineering*. <https://doi.org/10.1155/ijce/7195300>.
6. Gan, M., Gao, Z., Liu, L., Fan, X., Zhang, L., Li, Y., Wei, J., Sun, Z., & Ji, Z. (2025). Leaching variability of calcium-bearing phases in steel slag treated with ammonium acetate and ultrasonic enhancement mechanism. *Separation and Purification Technology*.
7. Wang, T., Yi, Z., Song, J., Zhao, C., Guo, R., & Gao, X. (2022). An industrial demonstration study on CO2 mineralization curing for concrete. *iScience*, 25. <https://doi.org/10.1016/j.isci.2022.104261>.
8. Rashid, M., Yaqoob, Z., Mujtaba, M., Kalam, M., Fayaz, H., & Qazi, A. (2024). Carbon capture, utilization and storage opportunities to mitigate greenhouse gases. *Heliyon*, 10. <https://doi.org/10.1016/j.heliyon.2024.e25419>.
9. Y. Sun, M. Chen, D. Chen, S. Liu, X. Zhang, and S. Wu, "Laboratory Preparation and Performance Characterization of Steel Slag Ultrafine Powder Used in Cement-Based Materials," *Sustainability*, vol. 14, no.22, p. 14951, Nov. 2022, doi:[10.3390/su142214951](https://doi.org/10.3390/su142214951)
10. Alturki, A. (2022). The Global Carbon Footprint and How New Carbon Mineralization Technologies Can Be Used to Reduce CO2 Emissions. *ChemEngineering*. <https://doi.org/10.3390/chemengineering6030044>.
11. Hanifa, M., Agarwal, R., Sharma, U., Thapliyal, P., & Singh, L. (2023). A review on CO2 capture and sequestration in the construction industry: Emerging approaches and commercialised technologies. *Journal of CO2 Utilization*. <https://doi.org/10.1016/j.jcou.2022.102292>.
12. R. S. R. R. C. A.S. Balaganesh, "Synthesis and Characterization of Porous Calcium Oxide Nanoparticles (CaO NPS)," *IJITEE*, Dec. 2018, Accessed: Oct. 06, 2025. [Online]. Available: <https://www.ijitee.org/wpcontent/uploads/papers/v8i2s/BS2653128218.pdf>
13. B. K. A. M. S. C. A. S. K. C. Ragunath N, "BOF Slag :Turning Waste Into Value ," in *Iron and Steel Technology Conference* , Kolkata: M. N. Dastur & Co. (P) Ltd, May 2019.

14. S. R. S. T. Sowmiya, "Spectroscopic analysis of slags-Preliminary observations," in *International conference on Molt and Slags Fluxes and Salts*, South Africa : The South African Institute of Mining and Metallurgy, 2004
15. B. Konar and K. Chattopadhyay, "BOF Slag: Turning Waste Into Value," 2019.
<https://www.researchgate.net/publication/333089511>
16. Ibrahim, M., El-Naas, M., Benamor, A., Al-Sobhi, S., & Zhang, Z. (2019). Carbon Mineralization by Reaction with Steel-Making Waste: A Review. *Processes*. <https://doi.org/10.3390/pr7020115>.
17. Meng, J., Liao, W., & Zhang, G. (2021). Emerging CO₂-Mineralization Technologies for Co-Utilization of Industrial Solid Waste and Carbon Resources in China. *Minerals*, 11, 274. <https://doi.org/10.3390/min11030274>.
18. Z. Sun *et al.*, "Synergistic enhancement of chemical looping-based CO₂ splitting with biomass cascade utilization using cyclic stabilized Ca₂Fe₂O₅ aerogel," *J Mater Chem A Mater*, vol. 7, no. 3, pp. 1216–1226, 2019, doi: [10.1039/C8TA10277E](https://doi.org/10.1039/C8TA10277E).
19. I. Z. Yildirim and M. Prezzi, "Chemical, Mineralogical, and Morphological Properties of Steel Slag," *Advances in Civil Engineering*, vol. 2011, pp. 1–13, 2011, doi: [10.1155/2011/463638](https://doi.org/10.1155/2011/463638)
20. C. Ma *et al.*, "Sustainable Utilization Strategies for Basic Oxygen Furnace Slag: Properties, Processing, and Future Directions," *Metals (Basel)*, vol. 15, no. 5, p. 537, May 2025, doi: [10.3390/met15050537](https://doi.org/10.3390/met15050537).
21. B. M. Mercado-Borrayo, R. Contreras, A. Sánchez, X. Font, R. Schouwenaars, and R. M. Ramírez-Zamora, "Optimisation of the removal conditions for heavy metals from water: A comparison between steel furnace slag and CeO₂ nanoparticles," *Arabian Journal of Chemistry*, vol. 13, no. 1, pp. 1712–1719, Jan. 2020, doi: [10.1016/j.arabjc.2018.01.008](https://doi.org/10.1016/j.arabjc.2018.01.008)
22. X. Liu, Y. Zou, R. Geng, T. Zhu, and B. Li, "Simultaneous Removal of SO₂ and NO_x Using Steel Slag Slurry Combined with Ozone Oxidation," *ACS Omega*, vol. 6, no. 43, pp. 28804–28812, Nov. 2021, doi: [10.1021/acsomega.1c03572](https://doi.org/10.1021/acsomega.1c03572).
23. B. Das, S. Prakash, P. S. R. Reddy, and V. N. Misra, "An overview of utilization of slag and sludge from steel industries," *Resour Conserv Recycl*, vol. 50, no. 1, pp. 40–57, Mar. 2007, doi: [10.1016/j.resconrec.2006.05.008](https://doi.org/10.1016/j.resconrec.2006.05.008).
24. P. Chaurand *et al.*, "Environmental impacts of steel slag reused in road construction: A crystallographic and molecular (XANES) approach," *J Hazard Mater*, vol. 139, no. 3, pp. 537–542, Jan. 2007, doi: [10.1016/j.jhazmat.2006.02.060](https://doi.org/10.1016/j.jhazmat.2006.02.060).
25. M. Tossavainen, F. Engstrom, Q. Yang, N. Menad, M. Lidstrom Larsson, and B. Bjorkman, "Characteristics of steel slag under different cooling conditions," *Waste Management*, vol. 27, no. 10, pp. 1335–1344, Jan. 2007, doi: [10.1016/j.wasman.2006.08.002](https://doi.org/10.1016/j.wasman.2006.08.002).
26. H. Y. Poh, G. S. Ghataora, and N. Ghazireh, "Soil Stabilization Using Basic Oxygen Steel Slag Fines," *Journal of Materials in Civil Engineering*, vol. 18, no. 2, pp. 229–240, Apr. 2006, doi: [10.1061/\(ASCE\)08991561\(2006\)18:2\(229\)](https://doi.org/10.1061/(ASCE)08991561(2006)18:2(229)).
27. L. M. Juckes, "The volume stability of modern steelmaking slags," *Mineral Processing and Extractive Metallurgy*, vol. 112, no. 3, pp. 177–197, Dec. 2003, doi: [10.1179/037195503225003708](https://doi.org/10.1179/037195503225003708).
28. Li, G., Kong, S., Guo, J., Xia, H., Li, K., Feng, G., & Xu, X. (2025). Study on the Mechanism of the Wet Carbonation Reaction and Performance Characterization of Ammonium Chloride-Modified Steel Slag. *ACS Omega*, 10, 49896 - 49923. <https://doi.org/10.1021/acsomega.5c06000>.