

Carbon Dioxide (CO₂) Mineralization in Solid Waste-Based Grouting Slurry: A Review

Safiwu Alhaji^{1,2}, Baobin Gao^{1,2,3*}, Wenjie Zhu^{1,2}, Kaihang Liu^{1,2}

¹Key Laboratory of Coalbed Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo, China

²Collaborative Innovative Centre for Safe Production and Clean and Efficient Utilization of Coal, Henan Polytechnic University, Jiaozuo, China

³Zhengzhou Institute for Advanced Study, Henan University of Science and Technology, Zhengzhou, China

Email: *gaobaobin@hpu.edu.cn

How to cite this paper: Alhaji, S., Gao, B. B., Zhu, W. J., & Liu, K. H. (2025). Carbon Dioxide (CO₂) Mineralization in Solid Waste-Based Grouting Slurry: A Review. *Journal of Geoscience and Environment Protection*, 13, 121-155.

<https://doi.org/10.4236/gep.2025.131008>

Received: December 5, 2024

Accepted: January 17, 2025

Published: January 20, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Carbon dioxide (CO₂) is a substantial contributor to global warming owing to its long atmospheric lifetime and high potential for global warming. It is related to the processes of raw material mining and industry, which is fundamental to economic development but also has negative impacts on the environment, namely the increase of global temperature and solid waste. To address this, various carbon capture, storage, utilization, and mineralization methods have emerged, but they remain at an early stage of development. This review discusses the applicability of solid waste materials, and slurry form in particular, for CO₂ mineralization. It analyzes frequently researched materials, carbonation capabilities, reaction mechanisms, and industrial uses. Industrial waste materials, cement, and demolition waste are widely used in carbonation reactions because of their abundance and high Ca/Mg oxide content. The review also discusses carbonation types, including two major types—direct and indirect—which fall under the ex-situ category. The key factors influencing the carbonation efficiency include the CO₂ concentration, temperature, pressure, particle size, and reaction chamber type. The construction sector is the principal beneficiary of carbonated materials due to the cementitious characteristics of recarbonated byproducts and precipitated calcium carbonate (PCC). Other industries, such as paper, plastics, and pharmaceuticals, also find applications for PCC. Future research is recommended to explore new materials for slurry carbonation, with potential applications in underground mine support for carbon sequestration and subsidence control.

Keywords

Solid Waste-Based Slurry, Mineral Carbonation, CO₂ Sequestration, Global Warming, CCUS

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) reported in their climate change 2023 synthesis that atmospheric carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) concentrations increased to 410 ppm, 1866 ppb and 332 ppb, respectively, as of 2019, revealing high concentration levels of these greenhouse gases (GHGs) all-time (Calvin et al., 2023). Additionally, the energy sector contributed to the release of 20 GtCO₂-eq, representing 34% of the net global emissions, whereas 14 GtCO₂-eq, representing 24%, came from industry in 2019 alone (Calvin et al., 2023). Large amounts of carbon dioxide released from the combustion of fossil fuels through industrial processes (e.g., iron and steel manufacturing, cement production, etc.) and energy generation (e.g., coal-fired power plants, thermal gas plants, etc.) in addition to other anthropogenic activities play a significant role in the increasing global concentration. Globally, the International Energy Agency (IEA) reports that approximately 85% of carbon dioxide emissions emanate from China, the United States and India during energy generation from coal-fired power plants (Alturki, 2022; International Energy Agency, 2020). The trajectory of CO₂ emissions is projected to elevate concentration levels to unprecedented figures between 600 ppm to 1550 ppm, leading to detrimental impacts on climate change and global warming (Alturki, 2022). As a result, there is an urgent need to find solutions to lower carbon emissions with the aim of not exceeding the maximum 1.5°C to 2°C global temperature range proposed by the Paris Agreement (Paris Agreement, n.d.). In addition to the global warming potential of carbon emissions, which is lower than that of methane gas but has a high residence time in the atmosphere, there is also the challenge of acid rain formation, which causes corrosion of exposed metals and accelerates chemical weathering.

Against the backdrop of the above background, researchers have proposed several carbon capture and storage or utilization or mineralization technologies (CCS, CCU, CCUS and CCUM) to absorb atmospheric as well as point source emissions of CO₂ gas and sequester the gas through direct storage in underground voids with favorable geological attributes to avoid leakage or through direct or indirect mineralization with suitable solid waste materials and liquids for industrial application, building and construction and underground backfill. The process begins with carbon capture, which has received much attention in research and industrial applications in some parts of the globe.

To date, the most widely reported broad classes of capture technologies are pre-combustion, oxy-fuel combustion and postcombustion (Buckingham et al., 2022; Krishnan et al., 2023; Mukherjee et al., 2019). In precombustion capture, fuel reacts with steam, air or oxygen to form synthesis gas (syngas), which yields CO₂, H₂ and CO; therefore, CO₂ is subsequently removed to obtain hydrogen-rich gas for energy generation (Buckingham et al., 2022). In oxygen-fuel combustion, pure oxygen reacts with fuel in the presence of recycled CO₂ to generate flue gas with a high concentration of CO₂. The highly concentrated CO₂ flue gas is then subjected to carbon capture agents (Buckingham et al., 2022; Mukherjee et al., 2019). The

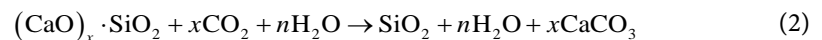
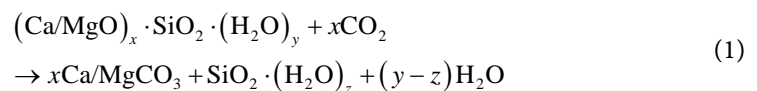
postcombustion capture technique involves the use of materials with good affinity for the CO₂ reaction to capture CO₂ gas in the flue gas emanating from industrial point sources (Buckingham et al., 2022; Mukherjee et al., 2019). During precombustion, adsorption, absorption, membrane separation and cryogenic distillation methods are deployed for capture. Bose et al. (2024) extensively discussed these techniques, highlighting some of the solid-liquid agents (zeolites, carbon nanotubes, activated carbons, amine-immobilized adsorbents, monoethanolamine (MEA), mixtures of amine-based solutions, etc.) utilized in direct or indirect capture as well as manufacturing of other capture agents. These materials generally exhibit good carbon dioxide capture properties, sometimes reaching as high as 90% v/v CO₂ capture in the case of MEA absorption pilot studies in the EU CASTOR project in Denmark between 2004 and 2008 (Albarracin Zaidiza et al., 2017); however, there are associated challenges with the recovery of solvents due to mixing with water and their high evaporability, high energy demand for temperature swings and pressure swing requirements in sorption-desorption for adsorbents and the general economic feasibility of the technologies (Buckingham et al., 2022; Mukherjee et al., 2019). In addition to capturing CO₂ from point source emissions, direct air capture (DAC) technology, introduced in 1999 (Lackner, 2009), is deployed to capture distributed CO₂ emissions, typically relying on chemisorbents to capture low concentrations of CO₂ gas in the air (Buckingham et al., 2022; Jeong-Potter & Farrauto, 2021; Sanz-Pérez et al., 2016).

Despite the advantages associated with some of these capture reagents, agents and technologies, the materials, including liquid amines such as monoethanolamine (MEA), diethanolamine (DEA), triethanolamine (TEA), glucosamine (GA), N-methyldiethanolamine (MDEA), etc., or alkali hydroxides such as KOH or metal organic frameworks (MOFs), mesoporous silica, zeolites and many others used in the carbon capture process, have limitations in terms of their gaseous phase selectivity, surface area in relation to porosity, energy consumption costs, ready availability of raw materials, stability after carbonation, etc. (Bose et al., 2024; Mukherjee et al., 2019). For example, Bose et al. (2024) highlighted the emergence of membrane, chemical looping combustion and pressure swing adsorption techniques to minimize the energy consumption and cost associated with pure oxygen production for oxy-fuel combustion capture technology.

Moreover, researchers have focused on the high accumulation of solid waste, whose current annual discharge is reported to be approximately 1.3 billion tons worldwide, and it is projected to reach approximately 40 billion tons by 2050 (Khandelwal et al., 2019). Pan et al. (2020) reported that alkaline solid wastes have the potential to reduce global CO₂ levels when utilized as carbon capture and mineralization materials. Considering these developments coupled with the previously underscored drawbacks in carbon capture technologies, myriads of solid waste materials, including fly ash (Ji & Yu, 2018; Kaithwas et al., 2012; Ngo et al., 2024; Wicaksono & Triwigati, 2023) construction demolition waste (Ho et al., 2024; Li et al., 2023; Meijssen et al., 2023; Zhang et al., 2023), carbide slag (Hargis

et al., 2021; Ma et al., 2024), municipal solid waste (Pour et al., 2018), cement kiln dust (Chai et al., 2024), mine tailings (Kusin et al., 2020; Rashid et al., 2023; Stokreef et al., 2022), slags (Han et al., 2020; Pan, Shah et al., 2017; Reddy et al., 2019; Wang et al., 2024) and many others, have been applied in mineral carbonation experiments for carbon capture, storage and utilization. These solid wastes commonly have relatively suitable mineralogical compositions and can undergo carbonation reactions upon exposure to pure and diluted CO₂ gas (flue gas) under ambient temperature and pressure conditions. However, the amount of alkali and alkaline-earth oxides, which inevitably determines the concentration of their respective ions when dissociated in solvents to react with CO₂ gas, is among the critical factors for the success of mineralization using solid wastes.

Comprehensive investigations have been undertaken on various carbonation types: direct (Zou et al., 2024), indirect (Liu et al., n.d.), ex situ (Córdoba & Rojas, 2024), and additional carbonation methodologies, alongside reaction kinetics optimized for maximal CO₂ absorption utilizing several solid waste-derived industrial materials. Furthermore, the utilization of carbonated products for other industrial applications has also been highlighted in the literature. Ambarita et al. (2024) performed an indirect mineral carbonation reaction involving the dissolution of Ca ions from asphalt waste using acidic and alkaline solutions before carbonation. According to reports, the paper and plastics industries could benefit from the precipitated calcium carbonate (PCC), which was identified as vaterite (75.6 - 3.7 wt%) and calcite (24.4 - 56.3 wt%). By using accelerated carbonation, also known as CO₂ mineralization curing (CMC), in a chamber reactor, Wang et al. (2022) produced carbonated concrete blocks with fly ash, furnace blast slag, steel slag, and carbide slag and attained a carbon conversion ratio of more than 98%. Researchers estimate that the CMC technology's 182 kg CO₂-eq/m³ product CO₂ mineralization capacity could help mitigate global warming. Two generalized theoretical reaction pathways that take into account the major calcium and magnesium (Ca/Mg) compositions of solid waste materials and OPC support this industrial-scale carbon capture and utilization project (Wang et al., 2022).



Equation (1) represents the valorization of solid waste-based materials as feedstock for CMC technology, whereas equation (2) represents the case in which OPC is utilized.

From the above perspectives, research on CO₂ mineralization in solid waste-based materials is a hot topic, and the vast majority of applications of these technologies may contribute to curbing global warming through capture, storage and utilization processes. By adopting an approach similar to systematic review, this review seeks to identify solid waste-based materials that are equally suitable for

grouting and have been applied in various mineral carbonation experiments, categories of carbonation processes at the laboratory and industrial scales and engineering applications. This review further discusses some future research directions on the basis of the current trends.

2. Materials and Methods

2.1. Materials Search

Science Direct was the principal database from which the papers were downloaded as a result of its structured approach for searching articles via keywords and filters. Google scholar and Semantic scholar augmented the search with the same keywords. The combinations of keywords used to find literature included “solid waste and grout”, “carbon dioxide and grout”, “carbon mineralization and solid waste” and “carbon sequestration and grout”. The articles were initially filtered on the databases on the basis of the year of publication, i.e., from 2014-2024, the accessibility of the article (open access), and the type of article (restricting it to research and review articles), and 250 articles were ultimately selected on the basis of their titles in relation to the review theme. The articles were then imported into Mendeley and Zotero and further sorted after the titles and abstracts were read, which led to 158 articles being more relevant to the subject. Furthermore, a detailed reading of the 158 articles for relevant information related to the research questions led to 79 most relevant papers that also satisfied the inclusion criteria:

- a. CO₂ mineralization and sequestration are related to industrial wastes, natural minerals and synthetic adsorbents made from these wastes and minerals.
- b. Research and review articles
- c. Publications in the last 10 years (2014-2024)
- d. English Language articles

2.2. Insights into the Bibliography

On the basis of the topic under consideration, papers that typically consider grout and its related materials such as concrete and mortar preparation and their subsequent carbonation during or after mixing and, to a lesser extent, use carbonated solid waste-based materials and carbon dioxide adsorbents in grout, concrete and mortar preparation were considered. Among these papers, those published in English and that doubled as research and review articles were included. **Figure 1** shows the trend of publication volume reporting on solid waste-based materials applied in carbonation and grout formation. In the year 2024 alone, as many as 25 articles were published as at the time of this review was conducted, demonstrating the relevance of this research area. The sharp drop in research output recorded in 2021 could be attributed to the global shutdown during the pandemic, which affected not only trade but also educational and research institutions observing lockdown protocols, thereby limiting research output, especially for laboratory-based experiments.

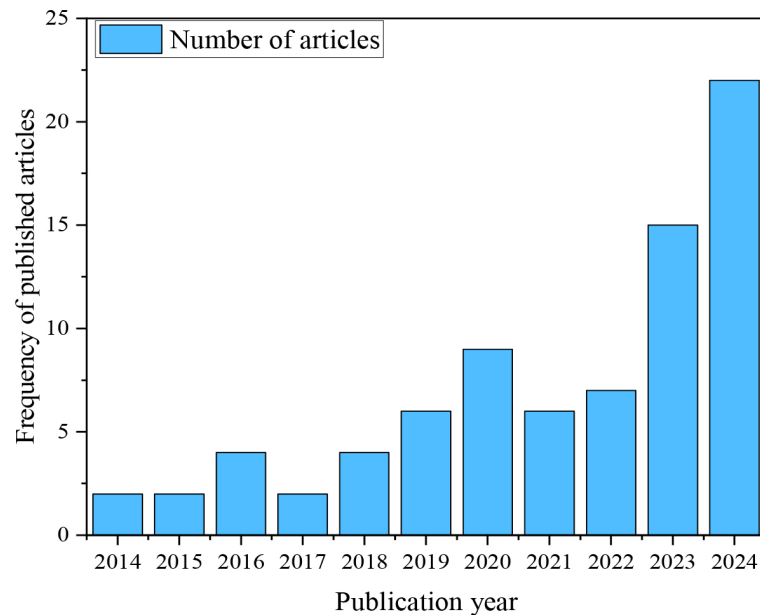


Figure 1. Distribution of the most relevant articles, including original research and review articles discussing the carbonation of solid waste-based materials from 2014-2024.

A critical look into the article types revealed that many publications were devoted to reviewing previous research. Consequently, the data were broadly classified into review and research articles to provide clarity for analysis. The original and review articles totaled 47 and 32 publications, respectively, each addressing specific materials and/or CO₂ mineralization technologies.

3. Results and Discussion

3.1. Carbonation Materials

3.1.1. Solid Waste-Based Materials (Industrial Waste Materials)

The collected data revealed that a number of original research articles deployed solid waste-based materials in single and mixtures to either become carbonated in dry or slurry form. Currently, there seems not to be a standardized classification for these feedstocks. Researchers often report the names of the materials, describe the source and provide information on their physical properties and chemical or mineralogical composition in the literature, except for review papers, which do not strictly follow that reporting style. In **Figure 2**, the solid waste-based materials and other raw materials applied in the forty-seven (47) original research articles are categorized as the main carbonation materials or sources of Ca/Mg ions that react with CO₂.

Twenty-four (24) research studies exclusively employed a singular source or a combination of industrial wastes in carbonation tests. [Lin et al. \(2024\)](#) and [Chen et al. \(2023\)](#) carbonated ladle refining slag, fly ash, and red mud from bauxite residue, respectively, achieving commendable outcomes. In the carbonation experiment conducted by [Lin et al. \(2024\)](#), the ladle refining slag exhibited a CaO con-

tent of 71.13%, resulting in a carbonation of 217.2 kg CO₂ equivalent per tonne of slag. Additionally, around nineteen (19) of the remaining twenty-four (24) articles combined various industrial wastes, such as BFS, BOFS, EAFS, MSW, GGBFS or GGBS, LFG, SS, CG, ASR, NHL, SF, CFA, CFD fly ash, FGD gypsum, DG, raw and recycled glass, and soda lime, to constitute the primary feedstock for the carbonation experiments. [Qin et al. \(2023\)](#) examined the potential for causticity reduction in fresh red mud, which was partially combined with gypsum, through both active and passive carbonation methods. In the active scenario, CO₂ gas was introduced at a flow rate of 0.5 ml/min, while the passive scenario involved slurry carbonation under ambient conditions. In a separate experiment, a composite of cork fly ash (CFA), municipal solid waste fly ash and bottom ash (MSW-FA and MSW-BA) underwent accelerated carbonation in a chamber with 99.99% pure 1 g of CO₂ at 15 bar pressure and ambient temperature for a duration of 72 hours, yielding 0.82 g of CO₂ sequestration. Samples of the identical feedstock exposed to natural carbonation for one month sequestered 2.6 g of CO₂ ([Sorrentino et al., 2024](#)).

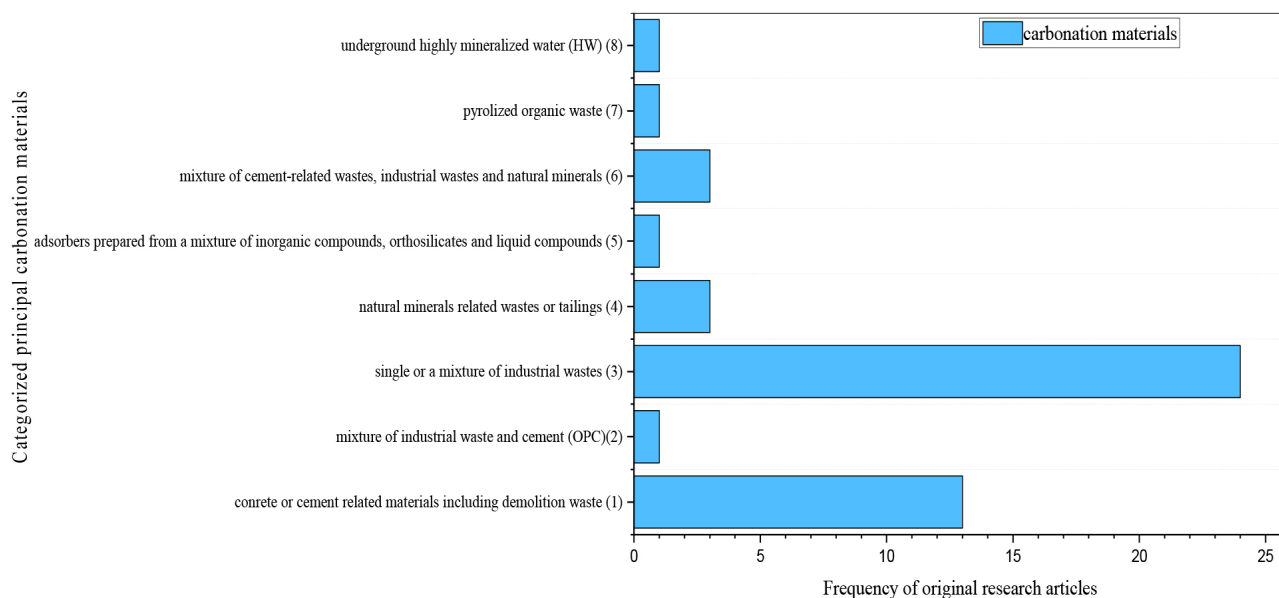


Figure 2. Classified raw materials utilized in carbonation experiments from the original research articles.

Concrete or cement-related materials, including demolition waste, followed purely industrial waste materials, and their mixtures were the second most commonly used raw material in the original research, which focused on carbon mineralization. [Suescum-Morales et al. \(2021\)](#) performed accelerated carbonation in a climatic chamber with 5% CO₂ on a mixture of natural aggregates (NA), recycled masonry aggregate (RMA) and OPC and achieved sequestration of 27 kg CO₂/t of mix. The researchers further highlighted the decrease in the porosity, increase in bulk density, enhanced mechanical properties and shortened curing time of the mixture through the accelerated carbonation method using these raw materials. Similarly, [Kaliyavaradhan et al. \(2020\)](#) achieved 20.4% CO₂ uptake under opti-

mal conditions for a 7-day period when concrete slurry waste with a water/solid ratio in the range of 0 - 0.70 was carbonated via the accelerated carbonation approach.

The remaining material combinations have not received much attention, as the original research samples for this work all fall below five (5) publication articles. Nevertheless, Yuen et al. (Yuen et al., 2016) and Martins et al. (Martins et al., 2018) demonstrated that natural mineral-based wastes or tailings and mixtures of cement-based wastes, industrial wastes and natural minerals have good carbon mineralization potential. **Table 1** summarizes the raw materials, their major carbonation compositions and methods of carbonation for industrial wastes, concrete-based wastes and their mixtures.

Table 1. Relevant studies that investigated the carbonation of grout, concrete or mortar of solid waste-based materials and cement, including the degree of carbonation and the carbonation type.

solid waste or materials for grout/concrete /mineralization	carbonation chemical or mineralogical phase	Carbonation amount /efficiency/degree	carbonation experiment /technology and conditions /limitations	Reference
construction cement waste, cement kiln dust (CaO), solid component of cement and mortar (with OPC)	CaO in CKD and construction cement waste	4.5 GtC stored from 1930 to 2013 in cement products; From 0.10 GtC yr ⁻¹ in 1998 to 0.25 GtC yr ⁻¹ in 2013	carbonation under ambient conditions (exposure to atmospheric CO ₂ /pressure /temperature)	Xi et al. (2016)
Fly ash and OPC	CaO, MgO, Al ₂ O ₃ , SiO ₂ - OPC; SiO ₂ , Fe ₂ O ₃ and Al ₂ O ₃ - Fly ash	CFB-2: 5.6%; CFB-4: 7.5% CFB-6: 9.9%	indirect carbonation of fly ash and OPC by first subjecting foam to CO ₂ before mixing with solid wastes	Ngo et al. (2024)
Carbide slag	CaO = 70.84%; MgO = 0.194%	22 g CO ₂ per liter of solution	direct carbonation; however, process fits the indirect carbonation definition.	Hargis et al. (Ma et al., 2024)
blast furnace slag, basic oxygen furnace slag and electric arc furnace slag	35 slag minerals (listed in the article)	CO ₂ mineralization potential from 2020 to 2100 is estimated to be between 26 to 42 gigatonnes (Gt) of CO ₂	direct carbonation of 39 slag minerals	Myers et al. (2019)
fly ash from municipal solid waste incineration	Ca/Mg ions in solid waste	Up to 0.25 t- CO ₂ stored per t-MSWI fly ash	direct and indirect carbonation	Wicaksono & Triwigati (2023)
municipal solid waste (MSW) and landfill gas (LFG) combustion to generate energy	MSW comprises C, H, O, N and S	MSW-CCS = -0.7 kg of CO ₂ /kg MSW; LFG-CCS = 0.56 kg CO ₂ -eq	postcombustion capture method with MEA system fixed in incinerator; chemical absorption using monoethanolamine (MEA) solution	Pour et al. (2018)
ground granulated blast furnace slag (GGBS), steel slag (SS), ammonia-soda residue (ASR) and desulfurization gypsum (DG).	not provided	0.63 - 0.67 t of CO ₂	-	Xu et al. (2024)

Continued

Cork fly ash (CFA) (3 different types) and Municipal solid waste incineration (MSWI) fly ash (MSWI-FA) and bottom ash (MSWI-BA)	CaO, Ca(OH) ₂ , and CaClOH	Combined with MSWI Fly Ash (MSWI FA), 0.82 g of CO ₂ is sequestered in AC experiments from a 33.6 g starting mass combination. In NC the amount of CO ₂ sequestered increases to 2.6 g.	natural carbonation (NC) and accelerated carbonation (AC).	Sorrentino et al. (2024)
waste cement and blast furnace slag	CaO [waste cement = 23.14%, BFS = 471.5%]; MgO [waste cement = 1.77%, BFS = 3.34%]	0.06 kg CO ₂ /kg cement; 0.09 kg CO ₂ /kg blast furnace slag	indirect carbonation	Mun & Cho (2013)
blast furnace slag (BFS) and water-quenched Ti-bearing BFS	CaO [BFS = 27.33%, Ti-bearing slag = 18.24%]; MgO [BFS = 6.09%, Ti-bearing slag = 4.07%]	236.1 kg of CO ₂ mineralized by one ton of BF slag	microwave roasting technology	Han et al. (2020)
magnesium tailings of serpentine origin	serpentine Mg ₃ Si ₂ O ₅ (OH) ₄ with Mg content ranging from 42 to 43%	CO ₂ fixation efficiency achieved 66.64% Mg ²⁺ leaching in 120 min.	indirect carbonation	Liu et al. (n.d.)
Circulation Fluidized Bed (CFD) Fly ash (FA)	CaO = 62.8%	Carbonation conversion of FA was 77.2% at optimal conditions	high gravity carbonation method;	Pan et al. (2016)
Raw glass with 20 wt% recycled glass, soda lime, dolomite, limestone, alumina, SiO ₂	cullet, SiO ₂ , Na ₂ O, CaO, MgO, Al ₂ O ₃	CO ₂ emissions reduction of -152 to -528 kg/ton	different carbonation cases mostly involving flue gas-absorption liquid reaction in glass manufacturing.	Caudle et al. (2023)
mortar waste	CaO = 29.5%; MgO = 1.4%	CO ₂ sequestration capacity of mortar waste was approximately 164 g CO ₂ /kg; Mortar samples' CO ₂ sequestration was determined at 112 g CO ₂ /kg.	indirect mineralization	Li et al. (2024)
recycled concrete aggregate (RCA) [0 - 4 mm]	high Ca content	0.9 kg/hr of CO ₂ .	indirect carbonation method in mobile pilot plant.	Pan et al. (Meijssen et al., 2023)
recycled concrete aggregate (RCA) [0 - 4 mm]	CaO = 27.8 wt%	39.0 kg per ton of RCA	indirect mineral carbonation of RCA in packed bed reactor (PBR) in comparison with stirred batch reactor (SBR). For AN concentration of 0.25 - 2.0 mol/kg, the packed bed reactor extracted 27% - 55% more calcium than the stirred batch reactor at equal solid throughput and solvent consumption.	Gasós et al. (2024)
Buton-asphalt waste	Ca (Raw waste) = 80.51%; Ca (calcined waste) = 84.52%	CO ₂ capture of 92.787 wt%	indirect mineral carbonation reaction	Ambarita et al. (2024)
ladle-refining slag (LRS)	CaO = 71.13%; SiO ₂ = 21.13%; MgO = 1.96%	217.2 kg CO ₂ eq./t steel slag	not specified	Lin et al. (2024)

Continued

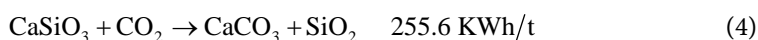
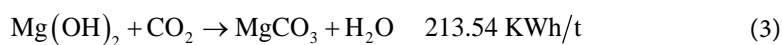
Stale refined slag, carbonated slag (brick), magnetic grains	CaO [bulk slag = 35.4% & 35.2%, brick = 33.6%, magnetic grains = 28.53%]; MgO [bulk slag = 8.05% & 7.80%, brick = 8.68%, magnetic grains = 10.39%]	carbonization can reach 20% of initial slag mass	not specified	Sariyev et al. (2024)
coal fly ash (CFA) to form amine modified silica	CaO = 2.612%, Al ₂ O ₃ = 40.010%, SiO ₂ = 48.616%	SBA-15-W-PEI70 exhibits the highest CO ₂ adsorption capacity of 1.92 mmol/g. SBA-15-R-PEI30 shows promising CO ₂ uptake of 0.83 mmol/g	-	Jia et al. (2024)
steel slag, concrete waste, municipal solid waste incineration (MSWI) ash, and olivine		CO ₂ reduction ranging from -1.30 to -0.58 kg CO ₂ eq.kg ⁻¹ feed maximum CO ₂ uptake of CSW was 20.4% at optimal condition; The maximum CO ₂ uptake of CSW was 21.0 at optimal conditions	-	(Digulla & Bringezu, 2023)
fresh concrete slurry waste (CSW)	CaO (52.81%) and SiO ₂ (27.30%)	optimal condition; The maximum CO ₂ uptake of CSW was 21.0 at optimal conditions	accelerated carbonation	Kaliyavaradhan et al. (2020)
electric arc furnace slag	CaO = 56.4%, SiO ₂ = 26.6%, Al ₂ O ₃ = 6.3%, MgO = 5.3%	0.38 tons of CO ₂ mineralized per ton of EAFRS	accelerated carbonation (high-gravity carbonation process)	Pan, Chung et al. (2017)
FGD gypsum	calcium sulphate dihydrate CaSO ₄ .2H ₂ O	carbonation end-product displayed a CaCO ₃ content of 71.1%	ex situ carbonation	Córdoba & Rojas (2024)
Ordinary Portland cement (OPC)		CO ₂ absorption up to 40 vol%	direct carbonation of OPC slurry in a tight chamber	Kim et al. (2024)
limestone aggregates and Siliceous aggregates	CaO of limestone aggregates = (27.34%, 35.51%, 50.13%); siliceous aggregates = (12.29%, 9.88%; SiO ₂ of limestone aggregates = (34.49%, 23.74%, 6.62%); siliceous aggregates = (69.35%, 70.61%)	Maximum carbonation reached after 72 hours, fixing 6.5 wt CO ₂	not specified	Aparicio et al. (2022)
fly ash, furnace blaster slag, steel slag, and carbide slag		98.97% CO ₂ conversion rate	CO ₂ mineralization curing (CMC)/accelerated carbonation	Wang et al. (2022)
natural aggregates (NA) and recycled masonry aggregate (RMA)and OPC	CaO% (NA = 5.60, RMA = 12.18, OPC = 45.61); MgO% (NA = 1.06, RMA = 1.65, OPC = 1.00)	27 kg CO ₂ /t of mix	accelerated carbonation in a climatic chamber (with 5% CO ₂) and conventional climate chamber (0.04% CO ₂) as reference base	Suescum-Morales et al. (2021)

Continued

white slag (WS) and refractory wastes (RWs)	CO ₂ sequestration capacity: 359.79 g CO ₂ /kg slag (pure CO ₂): Carbonation degree: 79% for Tundish RW	direct mineralization using rolling mill furnace off-gases	Capelo-Avilés et al. (2024)
---	---	--	-----------------------------

3.1.2. Natural Mineral and Industrial Waste Carbonation

In the literature, many experiments have sourced natural minerals as feedstocks for carbon mineralization. **Table 2** presents a list of carbon mineralization experiments in which mixtures of natural minerals and industrial wastes containing alkali and alkaline silicate minerals were utilized as feedstock raw materials. Magnesium-rich mafic and ultramafic minerals present favorable mineralogy for carbonation reactions because of the presence of Mg, Ca and Fe ions, whose physically, chemically or thermally activated oxides and hydroxides have the potential to undergo spontaneous reactions in the presence of CO₂ under ambient conditions. Brucite is a mineral with excellent reactivity for mineral carbonation (Stokreef et al., 2022). From their literature review, Stokreef et al. (2022) highlighted the influence of the degree of serpentinization on the amount of brucite generated in ultramafic mine tailings, which could serve as raw materials for mineral carbonation. Xie et al. (2016) studied the carbon mineralization of wollastonite [Ca₃(Si₃O₉)], brucite [Mg(OH)₂], manganite [MnO(OH)], olivine [(Mg,Ca,Fe)₂SiO₄], etc., together with coal combustion fly ash, red mud, lime mud, municipal solid waste and some other industrial wastes. The advantages associated with carbonating naturally occurring ultramafic silicate minerals transcend beyond atmospheric CO₂ reduction. Theoretically, the Gibbs free energy released from the spontaneous reaction between carbon dioxide and ultramafic silicate minerals is considered a potential source for electricity generation (Xie et al., 2016). The chemical equations (3) and (4) demonstrate the case of brucite and wollastonite reacting with CO₂ to form MgCO₃ and CaCO₃ with free energy released.



In practice, natural minerals are not essentially mined and crushed for carbonation experiments; however, the discussions in the literature demonstrate that the tailings emanating from mining operations where the target mineral exists in mafic and ultramafic rock deposits are used in experiments for ex situ or in situ carbonation in tailings storage facilities (TSFs) (Li et al., 2018). One important consideration when using some of these raw materials for carbonation experiments is pretreatment (Li et al., 2018; Stokreef et al., 2022). Broadly, Li et al. (2018) classified pretreatment methods into three categories (3): thermal, chemical and mechanical methods. Subjecting ultramafic rock tailings and industrial wastes to these pretreatment processes enhances reactivity and accelerates carbonation un-

der specified test conditions by liberating Ca/Mg/Fe ions through heating, leaching and increasing the surface area and promoting their bonding with carbonate ions.

Table 2. Some relevant reviews on the carbon mineralization of natural minerals and industrial wastes sorted from relevant research.

Solid waste or materials	Chemical or mineralogical phase relevant to carbonation	Carbonation experiment /technology	CCS/CC U/CCUS	Reference
waste includes fly ash, ore minerals of basaltic origin, etc.	CaO, MgO	direct and indirect carbon mineralization	-	(Alturki, 2022)
magnesium-containing materials specifically magnesium ore in saltlake brine and seawater	Mg ions	direct (dry and wet) carbonation and indirect (leaching of cations and passing CO ₂ gas)	CCUS	(Li et al., 2023)
potassium feldspar, clay, fly ash, OPC and calcium aluminate cement	K ₂ CO ₃ , K ₂ Mg(CO ₃) ₂ , K ₂ Ca(CO ₃) ₂ , K ₂ SiO ₃ , KAl(CO ₃)(OH) ₂	-	CCUS	(Guo et al., 2021)
natural minerals and industrial byproducts	not specified	-	CCUS	(Romanov et al., 2015)
ultramafic rocks and their tailings from mines	Mg,Ca, Fe-rich rocks and tailings	direct carbonation (aqueous and gas-solid methods) and indirect carbonation (acid extraction)	-	(Stokreef et al., 2022)
alkali and alkaline minerals, industrial alkaline solid wastes (steel slag, carbide slag, coal combustion fly ash, municipal solid wastes, burning fly ash, lime mud, red mud, salt sludge) and waste water (NaOH based alkaline wastewater, Ca(OH) ₂ , Mg(OH) ₂ based alkaline wastewater).	Wollastonite [Ca ₃ (Si ₃ O ₉)], Brucite [Mg(OH) ₂], Manganite [MnO(OH)], Olivine [(Mg,Ca,Fe) ₂ SiO ₄], etc.	-	-	(Xie et al., 2016)
natural minerals (e.g. dunite) and waste materials (list of 16 waste materials).	-	carbonation processes (single-stage carbonation, two-stage carbonation, acid dissolution, pH swing process) and preprocess and concurrent grinding.	-	(Rashid et al., 2023)
bifunctional materials derived from industrial synthesis and using natural minerals and industrial solid wastes	limestone, dolomite, magnesite, marble dust and carbide slag	chemical looping CO ₂ capture and in situ conversion (CLICCC).	CCU	(Jin et al., 2024)
Industrial waste: coal ash, bottom ash, fly ash, deinking ash, stainless steel slag, and waste cement; Silicate minerals: olivine, serpentine, enstatite and wollastonite	-	direct and indirect methods; sub-types comprise gas-solid carbonation and aqueous carbonation; CO ₂ sequestration methods are Geological, Ocean, Biological and Mineral Carbonation.	CCS	(Neeraj & Yadav, 2020)
steel-making wastes (principal), natural minerals and other industrial wastes.	Composition of CaO, MgO, SiO ₂ , Fe ₂ O ₃ , and Al ₂ O ₃ of all the slags (BOFS, BSF, Steel Slag, LFS, APC, EAF, BFS)	direct mineral carbonation (main); direct and indirect mineral carbonation process	CCS	(Ibrahim et al., 2019)

3.2 CO₂ Mineralization Methods

Different terms have been used to describe carbon dioxide sequestration or utili-

zation mineralization processes in the literature. Analysis of the literature compiled for this review reveals that there is probably no unified or standardized nomenclature system for the classification of CO₂ mineralization reactions, leading to different names and descriptions for the process. Some of the reaction pathways and sequestration mechanisms are depicted in **Figure 3**.

From the literature compiled, two-way classification terms include direct and indirect carbonation; single-stage and two-stage carbonation; ex situ and in situ carbonation; natural carbonation and accelerated carbonation; and active and passive carbonation. There are sub-types for direct, indirect, single-stage,

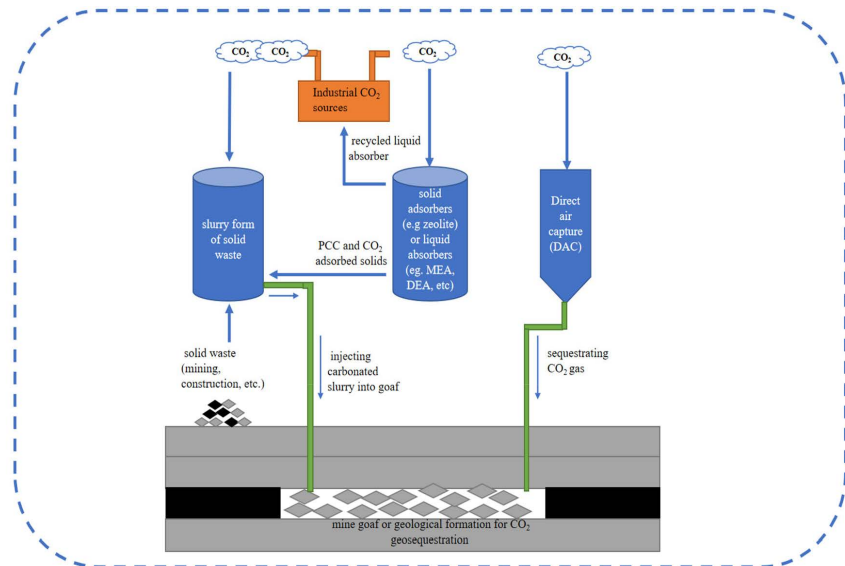


Figure 3. Schematic diagram of some mineral carbonation types and geosequestration concepts.

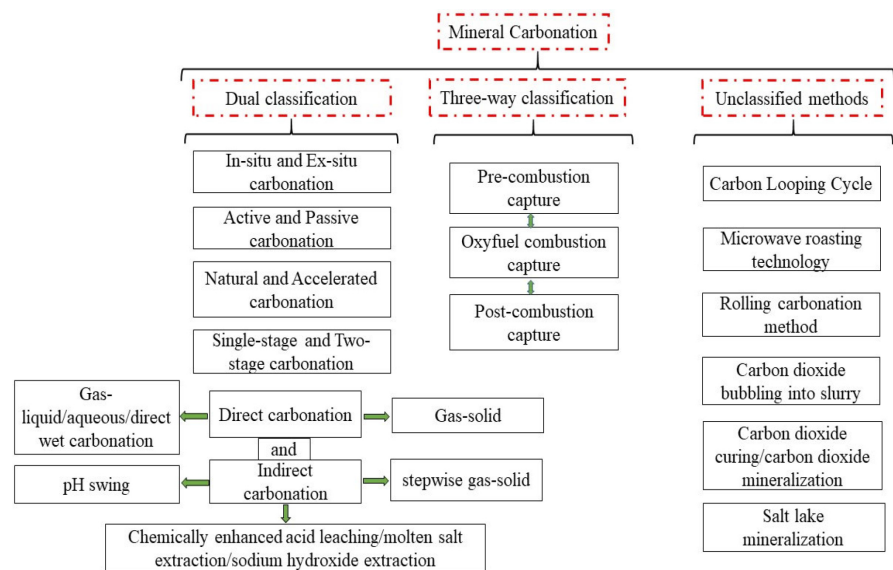


Figure 4. Summarized and classified mineral carbonation types from the analyzed literature.

two-stage, ex situ and in situ carbonation types, and myriads of carbonation types are classified in **Figure 4**. Mineral direct air carbon capture (MACC), mineral carbon capture (MCC), the rolling carbonation method, CO₂ bubbling in slurry, CO₂ curing, microwave roasting technology, high gravity carbonation, flue gas absorption liquid reactions and calcium looping cycle technology are the remaining carbonation methods reported in the literature.

3.2.1. *In situ* and *Ex situ* Carbonation

Many studies have used these terms to describe mineral carbonation. According to **Pan et al. (2015)**, in situ carbonation involves the direct injection of CO₂ into underground geologic formations, such as basalt or other igneous rocks. When CO₂ is injected into these formations, it reacts with minerals present in the rock (such as calcium or magnesium silicates), forming stable carbonate minerals and effectively locking away the CO₂ (**Stokreef et al., 2022**). This process occurs in a deep underground environment, ensuring long-term storage. In situ carbonation benefits from leveraging existing geological formations to permanently fix CO₂ as solid carbonates within the host rock, making it a promising solution for large-scale CO₂ sequestration. However, factors such as the capacity of geological formations, the availability of reactive minerals, and the cost of injecting and monitoring CO₂ storage can pose challenges (**Pan et al., 2015; Stokreef et al., 2022**).

Ex situ carbonation occurs above ground in regulated industrial environments. It employs calcium or magnesium silicate feedstocks, comprising natural ores or industrial byproducts, to react with CO₂ (**Pan et al., 2015**). *Ex situ* carbonation may be categorised by two methodologies (**Stokreef et al., 2022**): direct carbonation and indirect carbonation. The specifics of the sub-types are addressed in the next section. *Ex situ* carbonation provides versatility in feedstock selection, and the reaction parameters may be refined to enhance efficiency. Nonetheless, it is presently less economically feasible because to the substantial energy requirements for processing and managing materials. Nonetheless, *ex situ* carbonation presents opportunities in industry, particularly in contexts where alkaline wastes are abundant and may be converted into valuable products like green cementitious materials (**Pan et al., 2015**).

3.2.2. Direct Carbonation and Indirect Carbonation

Direct and indirect carbonation are two primary methods for mineral carbonation, each with distinct mechanisms and efficiencies. It is the most widely used term to describe carbonation according to the analysis of the literature used in this review, as visualized in **Figure 3**. Direct carbonation is a simpler, one-step process in which CO₂ reacts directly with solid materials, often in either a gas-solid or aqueous phase, which are the two main sub-types of direct carbonation (**Wicaksono & Triwigati, 2023**). In gas-solid carbonation, minerals such as calcium oxide (CaO) react with CO₂ to form stable carbonates such as calcium carbonate (CaCO₃). In aqueous carbonation, CO₂ dissolves in water to form carbonic acid, which dissociates into bicarbonate and carbonate ions that combine with metal

ions such as calcium. The main advantages of direct carbonation include its simplicity and ability to encapsulate heavy metals. However, it suffers from slow reaction kinetics, low carbonation efficiency, and the need for high energy to optimize reactions (Zhang et al., 2023).

Indirect carbonation, by contrast, is a multistep process that first extracts metal ions (e.g., calcium and magnesium) from solid feedstocks via a leaching agent and then reacts these extracted ions with CO₂ to form carbonates. This method allows for more control over the reaction conditions and typically results in higher carbonation efficiency and purer products. However, the use of chemicals such as acids or ammonium salts increases the complexity and cost of operation, and scaling up the process for industrial use poses challenges. Despite the higher operational complexity, indirect carbonation shows greater promise for high-efficiency carbon sequestration (Wang et al., 2024). Table 3 summarizes the main concepts of direct and indirect carbonation with some authoritative literature on the concepts.

Table 3. Some useful references on the most popular classification of carbonation: direct and indirect carbonation.

Major carbonation experiment/technology	Description	Reference
indirect carbonation	<ol style="list-style-type: none"> 1. It involves the dissolution or pretreatment of solids with solvents (water, alkaline and acidic) to release metal ions before carbonation. 2. Capturing CO₂ with alkaline solutions before mixing with solid waste slurry for carbonation reaction to take place. 	(Ambarita et al., 2024; Li et al., 2024; Liu et al., n.d.; Ma et al., 2024; Ngo et al., 2024)
direct carbonation	Direct carbonation involves the reaction between CO ₂ gas and the solid or liquid material to be carbonated. It is often categorized into gas-solid and gas-liquid (aqueous) carbonation.	(Bullock et al., 2023; Capelo-Avilés et al., 2024; Kim et al., 2024; Li et al., 2019; Myers et al., 2019)

3.2.3. Natural Carbonation (NC) and Accelerated Carbonation (AC)

In other studies, natural and accelerated carbonation have been used to describe mineral carbonation. Natural carbonation is simply the carbonation of materials under atmospheric conditions of temperature, pressure, humidity and CO₂ concentration. For example, Sorrentino et al. (2024) prepared solid waste-based slurry of cork fly ash and municipal solid waste fly ash with ultrapure deionized water with a solid-liquid ratio of 0.91 and exposed samples of the slurry to atmospheric conditions (natural carbonation) for one month. In the same experiment, samples prepared in the same way as those used for natural carbonation were carbonated in a reactor containing pure pumped gas of 99.99% CO₂ at 15 bar pressure corresponding to 1 g of CO₂; this was the case for accelerated carbonation. The duration of the experiment was 72 hours, and samples were taken at designated times for analysis. In the AC experiments, 0.82 g of CO₂ was captured from an initial mixture weighing 33.6 g. In the NC tests, the amount of CO₂ sequestered increased to 2.6 g, which was attributed to a greater availability of CO₂ and an extended test duration. Owing to the fact that accelerated carbonation is designed to enhance

quick carbonation, factors such as temperature, pressure, the concentration of CO₂ gas, the flow rate of slurry and gas, and the rotating speed of the reactor (given that the reaction occurs in a rotating pack bed reactor) must be critically considered in such experiments.

To investigate the quick carbonation of electric arc furnace slag (EAFRS) (Pan, Chung et al., 2017) applied accelerated carbonation, also referred to as high-gravity carbonation (Pan et al., 2016), to an EAFRS slurry in a rotating pack bed reactor, taking into consideration the variations in the pH of the reaction with time. At a solid-liquid ratio of 25 mL/g, a gas flow rate of 2.5 L/min, a slurry flow rate of 0.6 - 1.5 L/min and other preset conditions, the process achieved a total carbonation of 0.38 kg CO₂ per kg of EAFRS in a duration of 40 minutes.

3.2.4. Active Carbonation and Passive Carbonation

Qin et al. (2023) applied these terms to describe their carbonation experiments with red mud and gypsum slurry. The slurry was prepared by mixing 50 g of red mud together with 0, 4, 6, 8, or 10% gypsum replacement with 100 mL of deionized water. In the passive carbonation experiment, samples were exposed to atmospheric conditions for a total of 168 days, which, in essence, is no different from the natural carbonation (NC) explained by Sorrentino et al. (2024). The underlying reaction mechanism involves atmospheric CO₂ in air dissolving in the aqueous component to form bicarbonate and carbonate ions, which subsequently react with the divalent metallic ions leached into the aqueous component from the solid waste materials to form carbonates. Active carbonation, which is also not different from accelerated carbonation, uses the same samples, but the samples are carbonated in a closed system where captured air or CO₂ is injected at a predetermined flow rate into the reaction chamber for carbonation to occur. In the work of Qin et al. (2023), the prepared slurry was fed into a bottle supplied with gas at 0.5 mL/min flow rate for 8 hours. The samples were collected at specified time intervals for drying and further analyses to determine the degree of carbonation.

3.2.5. Single-Stage and Two-Stage Carbonation

In the introduction, the activation mechanisms commonly deployed to induce faster reaction kinetics during mineral carbonation are thermal, physical or mechanical and chemical activation techniques. A commonly deployed mechanical activation method involves grinding samples to reduce the particle size for large surface areas, which in effect increases the rate of carbonation.

Whereas grinding can take place separately before the ground samples are exposed to carbonation reactions (Rashid et al., 2023), researchers have also explored the technique of concurrently grinding and carbonating samples (Benhelal et al., 2018; Julcour-Lebigue et al., 2015). Julcour-Lebigue et al. (2015) explained that the inefficiency of direct aqueous carbonation is partly due to the formation of a passivation layer during carbonation, which shields the inner unreacted raw materials from becoming carbonated. The process of grinding while carbonating

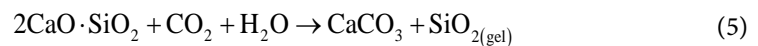
(concurrent carbonation) tends to break the passivation layer and exposes new surfaces for mineralization to occur. Grinding solid waste materials and conducting carbonation in tandem constitute single-stage carbonation. In a study conducted by Rashid et al. (2023), olivine, dunite and lizardite feedstocks concurrently ground and carbonized achieved six times the degree of carbonation in a reference experiment without grinding media. Zirconia, alumina and stainless steel were some of the grinding media that were initially used to study optimum grinding conditions while considering the media particle size, temperature, time and blade length of the turbine. Furthermore, they explain the two-stage carbonation as the initial dissolution step followed by the carbonate precipitation step, in which the grinding aspect is still integral. However, the two-stage approach can occur either in an open (bubbling) system or a closed system with controlled pressure and temperature conditions for a specified reaction time. A major challenge associated with concurrent grinding and carbonation is the wear and tear of the reaction chamber caused by the grinding media and reacting components (Rashid et al., 2023). Therefore, a proposal is made for either periodically changing the lining of the chamber or preprocessing the grinding before carbonation or reducing the quantity of grinding media (Rashid et al., 2023).

3.2.6. CO₂ Curing, CO₂ Mineralization Curing or Carbon Curing

Under this method of carbonation, different approaches have been discussed in the literature. Carbonated products can be generated via freshly demolished concrete waste and activated natural minerals, as is the case in (Rim et al., 2021), in which they deployed the mechanism of bubbling CO₂ gas into deionized water (DI) to form carbonic acid, which subsequently dissolves and leaches Ca/Mg/Si ions in freshly demolished concrete waste with some degree of hydration, including C-S-H gels, Ca(OH)₂ and ettringite, and heat-activated serpentine. To induce precipitation, the pH swinging through the initially bubbled CO₂ was undertaken by injecting air into the setup until the pH increased to an alkaline regime favorable for leached divalent metals to react with the carbonate ions initially formed during CO₂ bubbling. In separate experiments, strong 3 M HCl acid was used as the lixiviant to leach the metal ions in the concrete waste and serpentine, while CO₂ bubbling at a flow rate of 30 mL/min was performed in the same system. The pH of the system was maintained at 9 by adding measured NaOH (50 wt%) to ensure the precipitation of carbonates. Whereas the calcium carbonate precipitated from the two-phase pH swing proved to be excellent in replacing cement in concrete, they also concluded that Mg-silicate minerals proved more satisfactory in the pH swing process than did the calcium ions released from hydrated cement waste because of the low solubility of CaCO₃ in the pH regime created by CO₂ bubbling (Rim et al., 2021). The pH swing, in essence, has been mostly categorized as indirect carbonation. However, Rim et al. (2021) reported that a different approach, i.e., CO₂ bubbling and air degassing, was used to achieve the swing instead of the well-established procedure described in the second case of using strong acid and sodium hydroxide to control the pH. Notably, the slurry density (solid-liquid ratio) and temperature are critical fac-

tors that Rim and colleagues considered in their study.

In addition to the CO₂ bubbling approach, other studies have investigated the carbonation of solid waste in its concrete forms after slurry formation. Red mud artificial aggregates (RMAAs) prepared from sintering red mud (SRA) at different solid-liquid ratios before pelletization were subjected to CO₂ curing in a simulated environment with 20% CO₂ and a 60°C temperature, mimicking the coal power plant gas environment (Chen et al., 2023). Standard curing of the samples was continued for seven (7) days after CO₂ curing for a 3-day period. Among other results, XRD analysis revealed that the initial high peaks of dicalcium silicate (C₂S) substantially decreased after one (1) day of CO₂ curing, whereas high peaks of calcium carbonate were observed, possibly because of its reaction with CO₂ to form calcium carbonate (CaCO₃). Equation (5) is the reaction pathway (Chen et al., 2023).



Moreover, thermogravimetric analysis (TGA) was performed on the original and carbonated samples to reveal the effects of the 0%, 10%, 20% and 30% water-solid (w/s) ratios on the carbon dioxide uptake and degree of calcium conversion, and the results revealed that the samples with 20% and 30% w/s ratios presented the highest CO₂ uptake rates of approximately 18.5% and 59.3%, respectively, with a calcium conversion degree (CCD), particularly up to the third (3rd) day of carbon curing (Chen et al., 2023). The CO₂ uptake estimates were performed via the expressions in equations (6) and (7). Water is essential for the hydration reaction to occur to make the hydration products, which are carbonable to be present for the dissolved CO₂ in the same available moisture for the carbon mineralization reaction and sequestration to complete, available. As a result, the samples prepared at 0 and 10% w/s did not have adequate hydration products or sufficient water to dissolve the CO₂ for the carbonation reaction to occur at a faster rate. However, researchers have reported that in the presence of high w/s, the rate of carbonation is initially impeded or slowed because excess water shields red mud particles from CO₂ gas as well as slows holistic diffusion of the gas.

$$\text{CO}_2 (\text{wt}\%) = \frac{\Delta m_{\text{CO}_2}}{m_{150^\circ\text{C}}} \times 100 \quad (6)$$

$$\text{CO}_2 \text{ update} (\text{wt}\%) = \frac{\text{CO}_{2\text{carbonated}(\text{wt}\%)} - \text{CO}_{2\text{initial}(\text{wt}\%)}}{100 - \text{CO}_{2\text{carbonated}(\text{wt}\%)}} \quad (7)$$

In equation one, Δm_{CO_2} is the mass loss between 500°C to 850°C due to the decomposition of CaCO₃ resulting from carbonation, and $m_{150^\circ\text{C}}$ is the mass of the dry sample at 105°C. In equation (2), $\text{CO}_{2\text{carbonated}(\text{wt}\%)}$ is the mass loss rate of the carbonated sample owing to CaCO₃ decomposition, and $\text{CO}_{2\text{initial}(\text{wt}\%)}$ represents the mass loss rate of the original sample due to CaCO₃ decomposition. In carbonation experiments, another established formula for estimating the degree of carbonation is the use of the degree of calcium conversion computed via equation (8) (Chen et al., 2023).

$$\delta_{Ca} (\%) = \frac{\frac{\frac{\Delta m_{CO_2}}{m_{150^\circ C}} \times \frac{1}{M_{CO_2}}}{100 - \frac{\Delta m_{CO_2}}{m_{150^\circ C}}} \times 100}{\frac{CaO_{total} \text{ wt\%}}{M_{CaO}}} \quad (8)$$

where $\delta_{Ca} (\%)$ represents the degree of calcium conversion (CCD), M_{CO_2} represents the molar mass of carbon dioxide, M_{CaO} represents the molar mass of CaO, and $CaO_{total} \text{ wt\%}$ represents the total percentage of calcium oxide in the raw material. The remaining parameters are the same as those explained in the previous equations. Theoretically, the quantity of absorbable CO_2 during the carbonation reaction can be estimated via Huntzinger's formula or Steinour's formula, as shown in equations (9) and (10) (Ahmed et al., 2024; Huntzinger et al., 2009; Steinour, 1959).

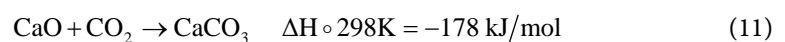
$$M_{th} (\%) = 0.785(CaO - 0.56CaCO_3 - 0.7SO_3) + 1.091MgO + 0.71Na_2O + 0.468(K_2O - 0.632KCl) \quad (9)$$

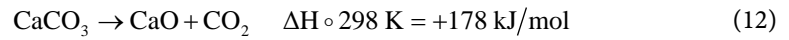
$$M_{th} (\%) = 0.785(CaO - 0.7SO_3) + 1.091MgO + 1.42Na_2O + 0.935K_2O \quad (10)$$

where $M_{th} (\%)$ represents the hypothetical CO_2 sequestration potential. The higher the sequestration potential is, the higher the carbonation efficiency (Ahmed et al., 2024). However, Ahmed et al. (2024) underscored the point that these theoretical estimates assume idealized conditions and should not be applied in actual estimates where many variables are at play. A carbon curing study was conducted on concrete prepared with OPC and varying amounts of wood-based biochar (WBC) by Roychand et al. (2023). In addition to investigating the optimum mixture for suitable mechanical properties, the optimum mixture samples were cured in a chamber containing 10% CO_2 , 23°C temperature and 70% relative humidity for 7 and 28 days. The carbonation depth after the test duration was ascertained via phenolphthalein solution (0.5% in 50% ethanol) such that regions on the cured concrete block with hydration products such as $Ca(OH)_2$ turned pink, whereas the carbonated regions showed no coloration due to the presence of carbonated compounds. The compressive strength test revealed greater strength in the samples cured with carbon for 28 days than in the samples cured for 7 days and the uncarbonated control samples (Roychand et al., 2023).

3.2.7. Other Carbonation Types

The calcium looping cycle comprises two main steps: carbonation and calcining (Afandi et al., 2024). These two steps work through interconnected circulating reactors in which CaO sorbents capture flue gas CO_2 to form $CaCO_3$ in the carbonator between 600°C and 700°C, and the pure CO_2 generated from calcining the $CaCO_3$ in the calciner yields back the CaO, which is recirculated for continuation of the reactions shown below in equations 11 and 12 (Afandi et al., 2024).





Sorbents are generally synthesized from industrial wastes, natural minerals and synthetic materials. Regardless of the benefits, high energy consumption is associated with this reversible reaction as well as the sintering and attrition effects resulting from the mechanical movement, pressure and temperature/heat under which the sorbents are subjected (Erans et al., 2016), thereby affecting the sorbent's stability and number of carbonation cycles (Afandi et al., 2024).

The microwave roasting method applied by (Han et al., 2020) was not specific to the carbonation step but rather focused on the roasting of blast furnace slag and its subsequent leaching. Instead of traditional roasting or heating of the samples to activate particles, they employed the microwave roasting technique, in which ground BF slag uniformly mixed with ammonium sulfate $(\text{NH}_4)_2\text{SO}_4$ at a 1:2 mass ratio was roasted in a microwave supplied with 1200 W of power, a 2.45 GHz frequency and a temperature of 340°C for several minutes. The roasted samples were then subjected to leaching and carbonation tests, and the results were satisfactory, with low energy consumption, a reaction time of 2 minutes, a high sulfation rate and the potential to absorb 261.1 kg CO_2 /ton BF slag (Han et al., 2020). Carbonation types classified and unclassified on the basis of the literature used in this review are depicted in Figure 5.

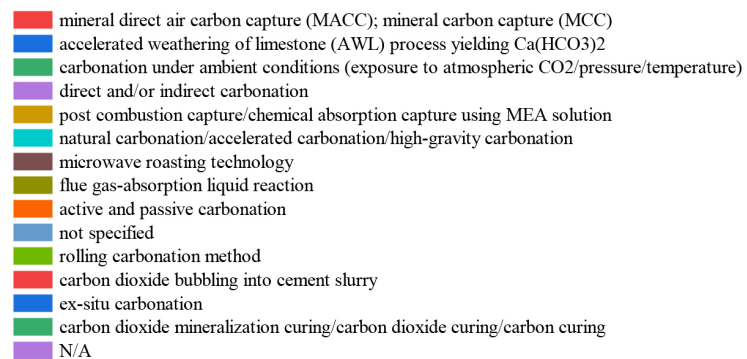


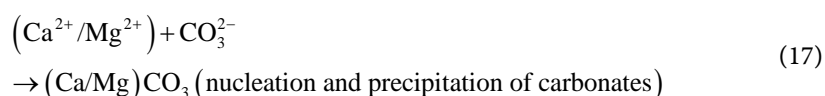
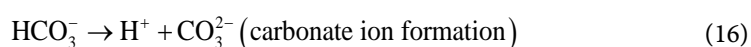
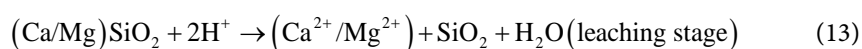
Figure 5. Distribution of terms used in categorizing carbonation types, including ambiguous descriptions and completely unclassified types (N/A represents “not available”).

3.3. Chemical Reaction Mechanism between CO₂ and Solid Wastes in Grout Slurry

3.3.1. Reaction Pathways in Dry and Solution-Based Approaches

A careful analysis of the reaction pathways leading to carbon mineralization and sequestration in direct and indirect carbonation approaches demonstrates reaction pathways either by direct reactions between divalent metallic ions in the solid component and CO₂ gas or the leaching of metallic ions and their subsequent carbonation from the dissolved CO₂ gas in the aqueous medium.

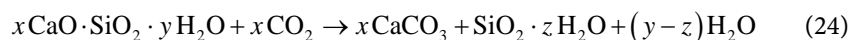
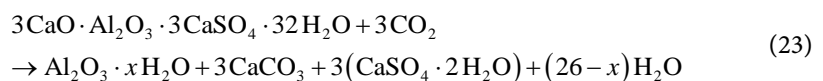
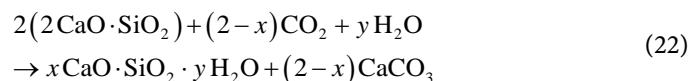
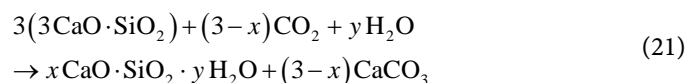
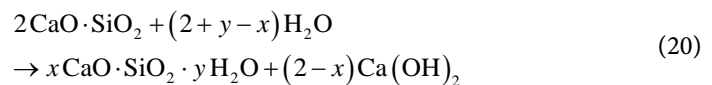
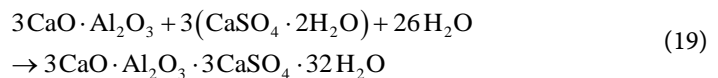
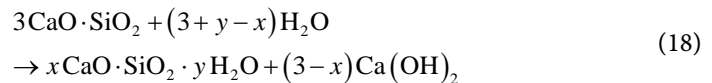
In the direct gas–solid reaction pathway, challenges have been raised with respect to slow reaction kinetics, which is partly due to the stable form in which solid waste or natural minerals may exist. Henceforth, activation mechanisms can excite ions in both the solid and gaseous phases, increase the surface area or leach ions to increase the reaction rates and achieve adequate carbonation in ex situ carbonation. Comparatively, it is easier to mechanically, thermally or chemically activate samples in ex situ carbonation studies or projects than in situ carbonation in geosequestration projects. Researchers have considered the energy demands associated with some activation mechanisms and how they affect the overall aim of sequestering carbon dioxide when it is released in such processes. Life cycle assessment (LCA) and technoeconomic assessment (TEA) have been conducted to determine the energy and cost balances of some mineralization techniques (Digulla & Bringezu, 2023). Direct aqueous carbonation offers an enhanced reaction pathway by first dissolving and leaching metals from solid waste and simultaneously hydrolyzing CO₂ gas to form carbonate and bicarbonate ions to aid in faster reactions and high degrees of carbonation. Typical reaction pathways for this carbonation mechanism are presented below (AzdarPour et al., 2018; Benhelal et al., 2019; Farhang et al., 2019; Sanna et al., 2014).



Indirect carbonation also uses similar reaction pathways in separate steps. Additionally, the acids, bases and ammonium salts used in the leaching process present faster reaction rates in the dissolution stage than water in direct aqueous carbonation technology does. The carbonation step occurs immediately after or simultaneously with the dissolution phase, thereby precipitating carbonates. These experiments are often undertaken at various temperatures, pressures, humidities, CO₂ concentrations, particle sizes, grain sizes and water–solid (w/s) or solid–liquid (s/l) ratios and in reactors that synergistically contribute to optimum carbonation reactions and products.

3.3.2. Reaction Pathways in the Concrete-Based Curing Approach

Compared with solution-based methods, carbon curing has a slightly different reaction pathway. During carbonation during CO₂ curing, the gas reacts with the hydration products developed after mixing and curing the samples (standard curing) for 24 hours. Although the samples may contain hydrated water depending on the amount of water used and the nature of the solid components, they are not inundated, as in the case of direct aqueous and indirect techniques. As such, researchers have reported the reaction pathway between the hydration products of dicalcium or tricalcium silicates and aluminates (C₂S/C₃S/C₃A) hydrolyzing to form C-S-H or C-A-S-H gels, Ca(OH)₂ and ettringite, which subsequently enter the carbonation phase to form various carbonate polymorphs, such as calcite, aragonite and vaterite. [Ahmed et al. \(2024\)](#) presented a series of generalized reaction pathways leading to the carbonation of cement-based slurry hydration products in equations 18 to 24 ([Digulla & Bringezu, 2023](#); [Myers et al., 2019](#); [Pan, Shi et al., 2017](#); [Zhan et al., 2019](#)). Reactions 18 to 20 correspond to the hydration stage, and reactions 21 to 24 involve the carbonation reaction.



In the course of mineral carbonation, researchers have established several relevant factors that impede reaction rates and general reaction kinetics. Mathematical models have therefore been devised to model and study the interplay of these factors slowing reactions. The shrinking core model and surface coverage model are the two most common mathematical models discussed in the literature for investigating the reaction kinetics of CO₂ mineralization.

The shrinking core model assumes that reaction particles are spherical in shape and nonporous and react isothermally with the surrounding fluid to yield a non-reactive outer layer surrounding a reactive inner core ([Digulla & Bringezu, 2023](#); [Myers et al., 2019](#)). Equation (25) is the general mathematical law governing reaction rates according to the shrinking core model parameters ([Myers et al., 2019](#)).

$$t = \frac{\rho r^2}{6DC_g} \left\{ 1 - 3 \left(\frac{r-\delta}{r} \right)^2 + 2 \left(\frac{r-\delta}{r} \right)^3 \right\} \quad (25)$$

where the time required to achieve a given reaction depth (δ) as a function of diffusivity (D) is (t), the unreacted material density is (ρ), the particle radius is (r), and the gas phase CO_2 concentration is (C_g). Myers et al. (2019) noted that the general equation does not consider the surface roughness factor (RF) of the grains and particles, which could impact the initial reaction rates and reaction depth (δ). Considering this factor, the new equation for estimating the accelerated reaction time (t') is as follows:

$$t' = \frac{\frac{\rho r^2}{6DC_g} \left\{ 1 - 3 \left(\frac{r-\delta}{r} \right)^2 + 2 \left(\frac{r-\delta}{r} \right)^3 \right\}}{(H/\delta)RF} \quad (26)$$

H is the largest scale at which the fractal dimension of a sample is constant, as determined by the box-counting method (Myers et al., 2019). They further suggested replacing the diffusivity (D) with bulk diffusivity (D_{bulk}) when studying heterogeneous samples.

Four underlying assumptions are considered for the surface coverage model in the mineral carbonation reaction according to (Chen et al., 2020).

- As carbonates form, they cover the surface of the solid particles.
- The carbonation reaction only occurs at the unreacted solid matrix sites.
- The active reaction surface (φ) is not covered by the reacted products and is not affected by the reaction rate.
- The highest reaction conversion (δ_{max}) on the solid particle surface represents the steady-state reaction.

The general equation is shown below:

$$r_s = k_s \varphi = \frac{1}{S_g M} \left(\frac{d\delta_{CaO}}{dt} \right) \quad (27)$$

where k_s is the rate constant ($\text{mole} \cdot \text{min}^{-1} \cdot \text{m}^{-2}$), φ represents the fraction of active sites uncovered by the reacted products, M (g/mol) is the molecular weight of the reactant solid particle, S_g ($\text{m}^2 \cdot \text{g}^{-1}$) is the initial specific surface area of the solid particle, and $\frac{d\delta_{CaO}}{dt}$ is the rate of carbonation conversion. However, these models have rarely been applied in studies of the reaction kinetics of solid waste-based slurry or grouts carbonated for geotechnical support.

3.4. Engineering Applications of Carbonated Grout Slurry

Mineral carbonation reactions not only target reducing the global emissions of carbon dioxide gas but also generate useful products for industrial applications. Largely, the building and construction industry has emerged as having the potential to be an enormous beneficiary of mineral carbonation according to the literature. The demand for cement and the continuous expansion of cities and munic-

ipalities in terms of building construction, bridges, dams and roads influence the copious release of CO₂ gas into the atmosphere and, at the same time, cement waste and construction demolition waste generation. The mining and metallurgical industries, on the other hand, also contribute to waste generation in the form of waste rocks, tailings and slags. In a similar vein, power generation sectors, which rely on burning coal, leave behind fly ash and other wastes, including the flue gas released into the atmosphere. Through continuous research, researchers have found that the reactivity of these waste streams, which was previously discussed, is favorable for mineral carbonation to produce cement-based materials, thus recarbonating (Ho et al., 2024) and precipitating calcium carbonate (PCC) (Meijssen et al., 2023) for concrete, mortar and grout, which is useful in the construction industry. Therefore, **Table 4** shows a number of engineering construction applications in which carbonated solid waste materials in solid or slurry forms were applied.

In investigations of carbonated solid waste applied in concrete or mortar slurry, researchers commonly study engineering strength by testing the uniaxial compressive strength and tensile strength (Kim et al., 2024; Zhang et al., 2016; Assagaf et al., 2019) to compare the strength of control samples, which are practically verifiable, as they conform to national and international standardized tests such as the Chinese GB/T and ASTM standards. The strength test is the only requirement to meet for safe practical use of a material, and if the material meets the set specification, its usage is approved. However, this is not always the case. Further tests for environmental safety have been conducted, as was the case in some of the literature (Chen et al., 2023). The heavy metal leaching test is a ubiquitous test for solid waste-based concrete and slurry products with the potential to leach lead, arsenic, zinc, chromium and a number of other heavy metals or potentially toxic elements that could be associated with the raw materials before the carbonation reaction is carried out. Hydration products such as C-A-S-H gels have been demonstrated to stabilize heavy metal ions (Liu et al., 2018). Considering that carbon is sequestered through CO₂ bubbling into the slurry and injecting into underground voids for ground stability and CO₂ fixation and storage, leaching tests are relevant to ensure groundwater safety prior to injecting the slurry. In such cases, both mechanical and leachability tests should be undertaken for ground stability and safety assurance. The paper and plastics industries are also reported to utilize PCC as a raw material for production (Ambarita et al., 2024).

Table 4. Engineering and industrial applications of carbonated solid waste slurry.

Engineering/industrial application of carbonated product or slurry	Solid waste or materials for grout/concrete mineralization	CCS/CU/CC US	Reference
carbonated fly ash used as supplementary cementitious material, geopolymer, road basement materials, cement clinker and waste stabilization/solidification	fly ash	CCU	(Ji & Yu, 2018)
recarbonate generated through MACC/MCC were applied in concrete mix by partially replacing fine aggregates.	concrete sludge and demolition waste	CCU/C CUS	(Ho et al., 2024)

Continued

a binder for partial or full replacement of cement	cement kiln dust (CKD) and bicarbonate lime mortar (BLM)	CCU	(Chai et al., 2024)
carbonated wastes applied in concretes	many industrial solid wastes, recycled concrete aggregates; recycled concrete fines; concrete slurry waste; waste concrete; agricultural waste		(Zhang et al., 2023)
carbonation products applicable in construction, pharmaceuticals, etc.	different wastes including fly ash, ore minerals of basaltic origin, etc.		(Alturki, 2022)
backfill material for filling underground voids in coal mines	fly ash and OPC	CCUS	(Ngo et al., 2024)
carbon cured concrete applied in building construction	coal gangue (CG), coal gasification slag (CGS), fly ash (FA)	CCUS	(Zou et al., 2024)
tailings used in concrete production as supplementary cementitious materials (SCM)	mine waste comprising limestone waste and gold tailings		(Kusin et al., 2020)
concrete mortar	circulation fluidized bed (CFD), fly ash (FA)	CCUS	(Pan et al., 2016)
carbonated red mud slurry (not used in engineering project)	fresh red mud and analytical grade gypsum	CCS/CUS	(Qin et al., 2023)
concrete was prepared with the leached RCA and PCC.	recycled concrete aggregate (RCA)[0-4 mm]	CCUS/CSS	(Meijssen et al., 2023)
potential usage of leached RCA for concrete preparation	recycled concrete aggregate (RCA)[0-4 mm]		(Gasós et al., 2024)
PCC usage in the paper and plastic industries.	buton-asphalt waste	CCUS	(Ambarita et al., 2024)
carbonated materials applicable in building construction	stale refined slag, carbonated slag (brick), magnetic grains		(Sariyev et al., 2024)
carbonated concrete blocks for engineering building	coal fly ash, steel slag, phosphogypsum, blast furnace slag and carbide slag	CCUS	(Meng et al., 2021)
carbonated CSW can be used as a partial replacement for cement	fresh concrete slurry waste (CSW)		(Kaliyavaradhan et al., 2020)
carbonated red mud artificial aggregates (RMAA) is applicable for use as construction material, storing CO ₂ and stabilizing heavy metals.	red mud (also known as bauxite residue)		(Chen et al., 2023)
blended cement mortars for construction	electric arc furnace slag		(Pan et al., 2020)
carbonated waste materials exhibit substantial potential in sustainable construction practices	steel slag, cement waste, and fly ash	CCU	(Ahmed et al., 2024)
carbonate cement is applicable in the building industry	carbide lime sludge	CCU	(Hargis et al., 2021)
carbonation products useful as cement in concrete, aggregates in concrete and production of precipitated calcium carbonate (PCC).	steel-making slags like BOFS, fly ash (FA) or bottom ash (BA), etc., are generally discussed	CCUM	(Pan et al., 2015)
concrete blocks for construction which were carbonated through carbon curing process.	fly ash, furnace blaster slag, steel slag, and carbide slag		(Wang et al., 2022)

4. Conclusion and Future Research Prospects

Mineral carbonation has great potential to absorb CO₂ in quantities good enough to minimize global warming while also generating products useful for industrial

and engineering applications. In this systematic review, the mineral carbonation reaction involving solid waste-based materials and their slurries was the main focus. Among the numerous literature articles that investigate carbonation reactions in one way or the other, the most relevant ones related to the theme of this review were selected, analyzed and discussed.

Industrial solid waste materials applied in combination or mostly as mixtures represent the most widely used materials for carbonation-related research, especially slurry materials. Cement- and concrete-related materials such as demolition waste represent the second largest group of materials utilized in slurry carbonation research. Mine tailings of natural mineral origin are also frequently utilized. The calcium and magnesium ions present in these solid wastes make them favorable for carbonation experiments. The abundance of these oxides or their ions directly influences the degree of carbonation, given that all other factors are considered.

Different nomenclatures exist for mineral carbonation types. Two-way classifications include *in situ* and *ex situ*, direct and indirect, active and passive, natural and accelerated, and single-stage and two-stage carbonation. Direct and indirect carbonation are identified as sub-types of *ex situ* carbonation that occur either at industrial point source emissions of CO₂ or in the laboratory. Direct and indirect carbonation are further sub-classified into direct-gas solid, direct aqueous, indirect gas-solid, chemical leaching (using acids, bases and ammonium salts) and pH swing methods. Precombustion, oxy-fuel combustion and postcombustion are key carbon capture techniques that can involve the use of liquid-based capture absorbers or solid adsorbers prepared from solid wastes, natural minerals and synthetic materials. Other classification terms, such as the calcium looping cycle, microwave roasting, carbon curing, salt mineralization and rolling carbonation, exist in the literature but are not broadly discussed as direct and indirect techniques under which many of these carbonation types may be classified. In addition, research on the temperature, pressure, particle size, grain size, reaction time, reactor type, solid-liquid ratio, CO₂ concentration, diffusivity and other factors in relation to these carbonation types has been conducted.

In terms of the reaction pathways and kinetics, several researchers have presented chemical equations underlying the carbonation reaction. Similarly, only a few researchers have discussed the shrinking core model and surface coverage model and how they affect reaction rates during the carbonation of solid waste in slurries. Nevertheless, the engineering or industrial applications of carbonated materials are often highlighted in relation to the purpose of carbonation. To date, common fields of application include the building and construction industry, where re-carbonated and precipitated calcium carbonate (PCC) can be used for partial replacement of OPC in concrete slurries. Directly carbonated solid waste-based concrete blocks are used in building or pavement construction. The paper, plastic and pharmaceutical industries are mentioned as beneficial users of pure PCC.

Despite these advancements, there are essential gaps that need to be filled in the

future carbonation of slurries. These gaps also serve as the limitations of this literature research for which future works may consider addressing.

1. Although new waste streams are added yearly in response to the demand for technology, energy and infrastructure by the increasing global population, solid waste from the industry, construction and mining sectors has not been fully utilized. This calls for further research into the best mixtures of solid wastes that can be carbon-mineralized and utilized to reduce waste accumulation in stockpiles and reduce global warming.

2. Backfill mining uses mining waste to fill underground voids while stabilizing the land for reuse. Geosequestration projects also target injecting captured CO₂ into underground voids with suitable geological structures and formations for storage without leakage. Researchers can explore the *in situ* direct or indirect carbonation of solid wastes or mining wastes and backfilling into mining goafs for sequestration and land surface stability. Both the geotechnical support and the environmental sustainability of such carbonated backfill materials could be studied in detail.

3. The carbonation reaction aims to reduce CO₂ emissions, but the process may ultimately release a substantial amount of CO₂ into the atmosphere. Intensifying the study into the energy demand for activation in the process design, the environmental impacts of the lixivants used and the economic feasibility of the process are still needed.

4. Numerical studies on the carbonation of slurries for application in backfill mining seem limited in the literature. Researchers can investigate the carbonation kinetics of grouting slurry for filling mining goafs via any suitable software and perform geotechnical analysis aiming to establish the degree of support the carbonated grouting slurry can provide.

Acknowledgements

Safiwu Alhaji: conceptualization, formal analysis, methodology, data visualization, original draft writing, review and editing; Gao Baobin: conceptualization, funding acquisition, methodology, supervision and review and editing; Zhu Wenjie: conceptualization, formal analysis, methodology, data visualization, original draft writing, review and editing; Liu Kaihang: conceptualization, formal analysis, methodology, data visualization, original draft writing, review and editing.

Funding

This project was funded by the Key Support Project of the Joint Fund for Regional Innovation and Development of the National Natural Science Foundation of China (Grant No. U23A20600).

Credit Authorship Contribution Statement

Safiwu Alhaji: conceptualization, formal analysis, methodology, data visualization,

original draft writing, review and editing; Gao Baobin: conceptualization, funding acquisition, methodology, supervision and review and editing.

Data Availability

The data are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Afandi, N., Satgunam, M., Mahalingam, S., Manap, A., Nagi, F., Liu, W. et al. (2024). Review on the Modifications of Natural and Industrial Waste CaO Based Sorbent of Calcium Looping with Enhanced CO₂ Capture Capacity. *Heliyon*, *10*, e27119. <https://doi.org/10.1016/j.heliyon.2024.e27119>
- Ahmed, O., Ahmad, S., & Adekunle, S. K. (2024). Carbon Dioxide Sequestration in Cementitious Materials: A Review of Techniques, Material Performance, and Environmental Impact. *Journal of CO₂ Utilization*, *83*, Article ID: 102812. <https://doi.org/10.1016/j.jcou.2024.102812>
- Albarracin Zaidiza, D., Belaissaoui, B., Rode, S., & Favre, E. (2017). Intensification Potential of Hollow Fiber Membrane Contactors for CO₂ Chemical Absorption and Stripping Using Monoethanolamine Solutions. *Separation and Purification Technology*, *188*, 38-51. <https://doi.org/10.1016/j.seppur.2017.06.074>
- Alturki, A. (2022). The Global Carbon Footprint and How New Carbon Mineralization Technologies Can Be Used to Reduce CO₂ Emissions. *ChemEngineering*, *6*, Article No. 44. <https://doi.org/10.3390/chemengineering6030044>
- Ambarita, M., Ardiansyah, D., Schmahl, W. W., Pusparizkita, Y. M., Ismail, R., Jamari, J. et al. (2024). Indirect Mineral Carbonation of Natural Asphalt Extraction Solid Waste Residue via pH and Temperature Control. *Case Studies in Chemical and Environmental Engineering*, *9*, Article ID: 100715. <https://doi.org/10.1016/j.csee.2024.100715>
- Aparicio, P., Martín, D., Baya-Arenas, R., & Flores-Alés, V. (2022). Behaviour of Concrete and Cement in Carbon Dioxide Sequestration by Mineral Carbonation Processes. *Boletín de la Sociedad Española de Cerámica y Vidrio*, *61*, 220-228. <https://doi.org/10.1016/j.bsecv.2020.11.003>
- Assaggaf, R., Adekunle, S., Ahmad, S., Maslehuddin, M., Al-Amoudi, O., & Ali, S. (2019). Mechanical Properties, Durability Characteristics and Shrinkage of Plain Cement and Fly Ash Concretes Subjected to Accelerated Carbonation Curing. *Journal of the South African Institution of Civil Engineering*, *61*, 73-81. <https://doi.org/10.17159/2309-8775/2019/v61n4a7>
- Azdarpour, A., Afkhami Karaei, M., Hamidi, H., Mohammadian, E., & Honarvar, B. (2018). CO₂ Sequestration through Direct Aqueous Mineral Carbonation of Red Gypsum. *Petroleum*, *4*, 398-407. <https://doi.org/10.1016/j.petlm.2017.10.002>
- Benhelal, E., Rashid, M. I., Holt, C., Rayson, M. S., Brent, G., Hook, J. M. et al. (2018). The Utilisation of Feed and Byproducts of Mineral Carbonation Processes as Pozzolanic Cement Replacements. *Journal of Cleaner Production*, *186*, 499-513. <https://doi.org/10.1016/j.jclepro.2018.03.076>
- Benhelal, E., Rashid, M. I., Rayson, M. S., Brent, G. F., Oliver, T., Stockenhuber, M. et al. (2019). Direct Aqueous Carbonation of Heat Activated Serpentine: Discovery of Unde-

- irable Side Reactions Reducing Process Efficiency. *Applied Energy*, 242, 1369-1382. <https://doi.org/10.1016/j.apenergy.2019.03.170>
- Bose, D., Bhattacharya, R., Kaur, T., Pandya, R., Sarkar, A., Ray, A. et al. (2024). Innovative Approaches for Carbon Capture and Storage as Crucial Measures for Emission Reduction within Industrial Sectors. *Carbon Capture Science & Technology*, 12, Article ID: 100238. <https://doi.org/10.1016/j.ccst.2024.100238>
- Buckingham, J., Reina, T. R., & Duyar, M. S. (2022). Recent Advances in Carbon Dioxide Capture for Process Intensification. *Carbon Capture Science & Technology*, 2, Article ID: 100031. <https://doi.org/10.1016/j.ccst.2022.100031>
- Bullock, L. A., Fernandez-Turiel, J., & Benavente, D. (2023). Experimental Investigation of Multiple Industrial Wastes for Carbon Dioxide Removal Strategies. *International Journal of Greenhouse Gas Control*, 129, Article ID: 103990. <https://doi.org/10.1016/j.ijggc.2023.103990>
- Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Péan, C. et al. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]*. IPCC, Intergovernmental Panel on Climate Change. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Capelo-Avilés, S., Tomazini de Oliveira, R., Gallo Stampino, I. I., Gispert-Guirado, F., Casals-Terré, A., Giancola, S. et al. (2024). A Thorough Assessment of Mineral Carbonation of Steel Slag and Refractory Waste. *Journal of CO₂ Utilization*, 82, Article ID: 102770. <https://doi.org/10.1016/j.jcou.2024.102770>
- Caudle, B., Taniguchi, S., Nguyen, T. T. H., & Kataoka, S. (2023). Integrating Carbon Capture and Utilization into the Glass Industry: Economic Analysis of Emissions Reduction through CO₂ Mineralization. *Journal of Cleaner Production*, 416, Article ID: 137846. <https://doi.org/10.1016/j.jclepro.2023.137846>
- Chai, S. Y. W., How, B. S., Chin, M. Y., & Ngu, L. H. (2024). Utilization of Accelerated Weathering of Limestone Captured Carbon Dioxide (CO₂) with Cement Kiln Dust to Produce Building Material. *Journal of Cleaner Production*, 468, Article ID: 143047. <https://doi.org/10.1016/j.jclepro.2024.143047>
- Chen, T., Jiang, W., Shen, A., Chen, Y., Pan, S., & Chiang, P. (2020). CO₂ Mineralization and Utilization Using Various Calcium-Containing Wastewater and Refining Slag via a High-Gravity Carbonation Process. *Industrial & Engineering Chemistry Research*, 59, 7140-7150. <https://doi.org/10.1021/acs.iecr.9b05410>
- Chen, Z. X., Zhang, N. T., Yan, S. R., Fish, J., & Chu, S. H. (2023). CO₂ Mineralization into Waste-Valorized Lightweight Artificial Aggregate. *Construction and Building Materials*, 409, Article ID: 133861. <https://doi.org/10.1016/j.conbuildmat.2023.133861>
- Córdoba, P., & Rojas, S. (2024). Carbon Sequestration through Mineral Carbonation: Using Commercial FGD-Gypsum from a Copper Smelter for Sustainable Waste Management and Environmental Impact Mitigation. *Journal of Environmental Chemical Engineering*, 12, Article ID: 112510. <https://doi.org/10.1016/j.jece.2024.112510>
- Digulla, F., & Bringezu, S. (2023). Comparative Life Cycle Assessment of Carbon Dioxide Mineralization Using Industrial Waste as Feedstock to Produce Cement Substitutes. *Energies*, 16, Article No. 4118. <https://doi.org/10.3390/en16104118>
- Erans, M., Manovic, V., & Anthony, E. J. (2016). Calcium Looping Sorbents for CO₂ Capture. *Applied Energy*, 180, 722-742. <https://doi.org/10.1016/j.apenergy.2016.07.074>

- Farhang, F., Oliver, T. K., Rayson, M. S., Brent, G. F., Molloy, T. S., Stockenhuber, M. et al. (2019). Dissolution of Heat Activated Serpentine for CO₂ Sequestration: The Effect of Silica Precipitation at Different Temperature and pH Values. *Journal of CO₂ Utilization*, *30*, 123-129. <https://doi.org/10.1016/j.jcou.2019.01.009>
- Gasós, A., Meijssen, M., & Mazzotti, M. (2024). Indirect Mineral Carbonation of Recycled Concrete Aggregate: Enhancing Calcium Extraction Using a Packed Bed Reactor. *Journal of Cleaner Production*, *449*, Article ID: 141745. <https://doi.org/10.1016/j.jclepro.2024.141745>
- Guo, Y., Sun, J., Wang, R., Li, W., Zhao, C., Li, C. et al. (2021). Recent Advances in Potassium-Based Adsorbents for CO₂ Capture and Separation: A Review. *Carbon Capture Science & Technology*, *1*, Article ID: 100011. <https://doi.org/10.1016/j.ccst.2021.100011>
- Han, Z., Gao, J., Yuan, X., Zhong, Y., Ma, X., Chen, Z. et al. (2020). Microwave Roasting of Blast Furnace Slag for Carbon Dioxide Mineralization and Energy Analysis. *RSC Advances*, *10*, 17836-17844. <https://doi.org/10.1039/d0ra02846k>
- Hargis, C. W., Chen, I. A., Devenney, M., Fernandez, M. J., Gilliam, R. J., & Thatcher, R. P. (2021). Calcium Carbonate Cement: A Carbon Capture, Utilization, and Storage (CCUS) Technique. *Materials*, *14*, Article No. 2709. <https://doi.org/10.3390/ma14112709>
- Ho, H., Izumi, Y., & Izuka, A. (2024). A CO₂ Removal Technology Based on Mineral Carbonation and the Stability of Product Carbon Storage in a Cement Matrix. *Environmental Technology & Innovation*, *34*, Article ID: 103623. <https://doi.org/10.1016/j.eti.2024.103623>
- Huntzinger, D. N., Gierke, J. S., Kawatra, S. K., Eisele, T. C., & Sutter, L. L. (2009). Carbon Dioxide Sequestration in Cement Kiln Dust through Mineral Carbonation. *Environmental Science & Technology*, *43*, 1986-1992. <https://doi.org/10.1021/es802910z>
- Ibrahim, M. H., El-Naas, M. H., Benamor, A., Al-Sobhi, S. S., & Zhang, Z. (2019). Carbon Mineralization by Reaction with Steel-Making Waste: A Review. *Processes*, *7*, Article No. 115. <https://doi.org/10.3390/pr7020115>
- International Energy Agency (2020). *Global Energy Review 2019*. <https://www.iea.org/reports/global-energy-review-2019>
- Jeong-Potter, C., & Farrauto, R. (2021). Feasibility Study of Combining Direct Air Capture of CO₂ and Methanation at Isothermal Conditions with Dual Function Materials. *Applied Catalysis B: Environmental*, *282*, Article ID: 119416. <https://doi.org/10.1016/j.apcatb.2020.119416>
- Ji, L., & Yu, H. (2018). Carbon Dioxide Sequestration by Direct Mineralization of Fly Ash. In *Carbon Dioxide Sequestration in Cementitious Construction Materials* (pp. 13-37). Elsevier. <https://doi.org/10.1016/b978-0-08-102444-7.00002-2>
- Jia, X., Wu, Z., Shi, H., Fan, Y., Zheng, R., & Wang, C. (2024). Direct Air CO₂ Capture Using Coal Fly Ash Derived SBA-15 Supported Polyethylenimine. *Carbon Capture Science & Technology*, *10*, Article ID: 100167. <https://doi.org/10.1016/j.ccst.2023.100167>
- Jin, B., Wang, R., Fu, D., Ouyang, T., Fan, Y., Zhang, H. et al. (2024). Chemical Looping CO₂ Capture and *In-Situ* Conversion as a Promising Platform for Green and Low-Carbon Industry Transition: Review and Perspective. *Carbon Capture Science & Technology*, *10*, Article ID: 100169. <https://doi.org/10.1016/j.ccst.2023.100169>
- Julcour, C., Bourgeois, F., Bonfils, B., Benhamed, I., Guyot, F., Bodéan, F. et al. (2015). Development of an Attrition-Leaching Hybrid Process for Direct Aqueous Mineral Carbonation. *Chemical Engineering Journal*, *262*, 716-726. <https://doi.org/10.1016/j.cej.2014.10.031>

- Kaithwas, A., Prasad, M., Kulshreshtha, A., & Verma, S. (2012). Industrial Wastes Derived Solid Adsorbents for CO₂ Capture: A Mini Review. *Chemical Engineering Research and Design*, 90, 1632-1641. <https://doi.org/10.1016/j.cherd.2012.02.011>
- Kaliyavaradhan, S. K., Ling, T., & Mo, K. H. (2020). CO₂ Sequestration of Fresh Concrete Slurry Waste: Optimization of CO₂ Uptake and Feasible Use as a Potential Cement Binder. *Journal of CO₂ Utilization*, 42, Article ID: 101330. <https://doi.org/10.1016/j.jcou.2020.101330>
- Khandelwal, H., Dhar, H., Thalla, A. K., & Kumar, S. (2019). Application of Life Cycle Assessment in Municipal Solid Waste Management: A Worldwide Critical Review. *Journal of Cleaner Production*, 209, 630-654. <https://doi.org/10.1016/j.jclepro.2018.10.233>
- Kim, W. K., Lee, J., Park, J., & Moon, J. (2024). Carbon Sequestration in Cementitious Systems through CO₂-Rich Hydration and Chemically Enforced CO₂ Mineralization. *Journal of CO₂ Utilization*, 84, Article ID: 102834. <https://doi.org/10.1016/j.jcou.2024.102834>
- Krishnan, A., Nighojkar, A., & Kandasubramanian, B. (2023). Emerging Towards Zero Carbon Footprint via Carbon Dioxide Capturing and Sequestration. *Carbon Capture Science & Technology*, 9, Article ID: 100137. <https://doi.org/10.1016/j.ccst.2023.100137>
- Kusin, F. M., Hasan, S. N. M. S., Hassim, M. A., & Molahid, V. L. M. (2020). Mineral Carbonation of Sedimentary Mine Waste for Carbon Sequestration and Potential Reutilization as Cementitious Material. *Environmental Science and Pollution Research*, 27, 12767-12780. <https://doi.org/10.1007/s11356-020-07877-3>
- Lackner, K. S. (2009). Capture of Carbon Dioxide from Ambient Air. *The European Physical Journal Special Topics*, 176, 93-106. <https://doi.org/10.1140/epjst/e2009-01150-3>
- Li, J., Hitch, M., Power, I., & Pan, Y. (2018). Integrated Mineral Carbonation of Ultramafic Mine Deposits—A Review. *Minerals*, 8, Article No. 147. <https://doi.org/10.3390/min8040147>
- Li, J., Luo, M., Wang, K., Li, G., & Zhang, G. (2023). Review of Carbon Dioxide Mineralization of Magnesium-Containing Materials. *Carbon Neutralization*, 2, 574-584. <https://doi.org/10.1002/cnl2.80>
- Li, L., Yu, H., Ji, L., Zhou, S., Dao, V., Feron, P. et al. (2024). Integrated CO₂ Capture and Mineralization Approach Based on KOH and Cement-Based Wastes. *Journal of Environmental Chemical Engineering*, 12, Article ID: 113382. <https://doi.org/10.1016/j.jece.2024.113382>
- Li, Y., Zhang, S., Wang, R., Zhao, Y., & Men, C. (2019). Effects of Carbonation Treatment on the Crushing Characteristics of Recycled Coarse Aggregates. *Construction and Building Materials*, 201, 408-420. <https://doi.org/10.1016/j.conbuildmat.2018.12.158>
- Li, Y., Zhao, S., Yao, Z., & Huang, X. (2023). Flexural Behavior of Reinforced Concrete Beams Strengthened Using Recycled Industrial Steel-Wire Mesh High-Performance Mortar. *Case Studies in Construction Materials*, 19, e02472. <https://doi.org/10.1016/j.cscm.2023.e02472>
- Lin, S., Chen, P., Xiang, W., Hu, C., Li, F., Liu, J. et al. (2024). Exploring the Effect of Moisture on CO₂ Diffusion and Particle Cementation in Carbonated Steel Slag. *Applied Sciences*, 14, Article No. 3631. <https://doi.org/10.3390/app14093631>
- Liu, J., Chen, H., & Zhang, M. (n.d.-a). *Mg²⁺ Leaching and CO₂ Sequestration of Magnesium Tailings Enhanced by External Field Coupled with Pretreatment*. <https://ssrn.com/abstract=4763920>
- Liu, X., Zhao, X., Yin, H., Chen, J., & Zhang, N. (2018). Intermediate-Calcium Based Cementitious Materials Prepared by MSWI Fly Ash and Other Solid Wastes: Hydration Characteristics and Heavy Metals Solidification Behavior. *Journal of Hazardous Materi-*

- als*, 349, 262-271. <https://doi.org/10.1016/j.jhazmat.2017.12.072>
- Ma, Y., Zhang, X., Du, Z., Hou, H., & Zheng, Y. (2024). Research on Utilizable Calcium from Calcium Carbide Slag with Different Extractors and Its Effect on CO₂ Mineralization. *Materials*, 17, Article No. 1068. <https://doi.org/10.3390/ma17051068>
- Martins, R. O. G., Alvarenga, R. d. C. S. S., Pedroti, L. G., Oliveira, A. F. d., Mendes, B. C., & Azevedo, A. R. G. d. (2018). Assessment of the Durability of Grout Submitted to Accelerated Carbonation Test. *Construction and Building Materials*, 159, 261-268. <https://doi.org/10.1016/j.conbuildmat.2017.10.111>
- Meijssen, M., Marinello, L., di Bella, C., Gasós, A., & Mazzotti, M. (2023). Industrial Demonstration of Indirect Mineral Carbonation in the Cement and Concrete Sector. *Journal of Environmental Chemical Engineering*, 11, Article ID: 110900. <https://doi.org/10.1016/j.jece.2023.110900>
- 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, Article No. 274. <https://doi.org/10.3390/min11030274>
- Mukherjee, A., Okolie, J. A., Abdelrasoul, A., Niu, C., & Dalai, A. K. (2019). Review of Post-Combustion Carbon Dioxide Capture Technologies Using Activated Carbon. *Journal of Environmental Sciences*, 83, 46-63. <https://doi.org/10.1016/j.jes.2019.03.014>
- Mun, M., & Cho, H. (2013). Mineral Carbonation for Carbon Sequestration with Industrial Waste. *Energy Procedia*, 37, 6999-7005. <https://doi.org/10.1016/j.egypro.2013.06.633>
- Myers, C. A., Nakagaki, T., & Akutsu, K. (2019). Quantification of the CO₂ Mineralization Potential of Ironmaking and Steelmaking Slags under Direct Gas-Solid Reactions in Flue Gas. *International Journal of Greenhouse Gas Control*, 87, 100-111. <https://doi.org/10.1016/j.ijggc.2019.05.021>
- Neeraj, & Yadav, S. (2020). Carbon Storage by Mineral Carbonation and Industrial Applications of CO₂. *Materials Science for Energy Technologies*, 3, 494-500. <https://doi.org/10.1016/j.mset.2020.03.005>
- Ngo, I., Ma, L., Zhao, Z., Zhai, J., Yu, K., & Wu, Y. (2024). Sol-Gel-Stabilized CO₂ Foam for Enhanced *In-Situ* Carbonation in Foamed Fly Ash Backfill Materials. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 10, Article No. 80. <https://doi.org/10.1007/s40948-024-00791-9>
- Pan, S., Chen, Y., Fan, L., Kim, H., Gao, X., Ling, T. et al. (2020). CO₂ Mineralization and Utilization by Alkaline Solid Wastes for Potential Carbon Reduction. *Nature Sustainability*, 3, 399-405. <https://doi.org/10.1038/s41893-020-0486-9>
- Pan, S., Chiang, A., Chang, E., Lin, Y., Kim, H., & Chiang, P. (2015). An Innovative Approach to Integrated Carbon Mineralization and Waste Utilization: A Review. *Aerosol and Air Quality Research*, 15, 1072-1091. <https://doi.org/10.4209/aaqr.2014.10.0240>
- Pan, S., Chung, T., Ho, C., Hou, C., Chen, Y., & Chiang, P. (2017). CO₂ Mineralization and Utilization Using Steel Slag for Establishing a Waste-to-Resource Supply Chain. *Scientific Reports*, 7, Article No. 17227. <https://doi.org/10.1038/s41598-017-17648-9>
- Pan, S., Hung, C., Chan, Y., Kim, H., Li, P., & Chiang, P. (2016). Integrated CO₂ Fixation, Waste Stabilization, and Product Utilization via High-Gravity Carbonation Process Exemplified by Circular Fluidized Bed Fly Ash. *ACS Sustainable Chemistry & Engineering*, 4, 3045-3052. <https://doi.org/10.1021/acssuschemeng.6b00014>
- Pan, S., Shah, K. J., Chen, Y., Wang, M., & Chiang, P. (2017). Deployment of Accelerated Carbonation Using Alkaline Solid Wastes for Carbon Mineralization and Utilization toward a Circular Economy. *ACS Sustainable Chemistry & Engineering*, 5, 6429-6437. <https://doi.org/10.1021/acssuschemeng.7b00291>

- Pan, X., Shi, C., Hu, X., & Ou, Z. (2017). Effects of CO₂ Surface Treatment on Strength and Permeability of One-Day-Aged Cement Mortar. *Construction and Building Materials*, 154, 1087-1095. <https://doi.org/10.1016/j.conbuildmat.2017.07.216>
- Paris Agreement (n.d.). United Nations. <https://www.un.org/en/climatechange/paris-agreement>
- Pour, N., Webley, P. A., & Cook, P. J. (2018). Potential for Using Municipal Solid Waste as a Resource for Bioenergy with Carbon Capture and Storage (BECCS). *International Journal of Greenhouse Gas Control*, 68, 1-15. <https://doi.org/10.1016/j.ijggc.2017.11.007>
- Qin, J., Ying, J., Wang, Y., Niu, A., Lin, C., Qiu, R. et al. (2023). Insights into Active and Passive Carbon Sequestration and Causticity Reduction in Hazardous Red Mud Slurry. *Carbon Research*, 2, Article No. 40. <https://doi.org/10.1007/s44246-023-00071-3>
- Rashid, M. I., Yaqoob, Z., Mujtaba, M. A., Fayaz, H., & Saleel, C. A. (2023). Developments in Mineral Carbonation for Carbon Sequestration. *Heliyon*, 9, e21796. <https://doi.org/10.1016/j.heliyon.2023.e21796>
- Reddy, K. R., Gopakumar, A., & Chetri, J. K. (2019). Critical Review of Applications of Iron and Steel Slags for Carbon Sequestration and Environmental Remediation. *Reviews in Environmental Science and Bio/Technology*, 18, 127-152. <https://doi.org/10.1007/s11157-018-09490-w>
- Rim, G., Roy, N., Zhao, D., Kawashima, S., Stallworth, P., Greenbaum, S. G. et al. (2021). CO₂ Utilization in Built Environment via the pCO₂ Swing Carbonation of Alkaline Solid Wastes with Different Mineralogy. *Faraday Discussions*, 230, 187-212. <https://doi.org/10.1039/d1fd00022e>
- Romanov, V., Soong, Y., Carney, C., Rush, G. E., Nielsen, B., & O'Connor, W. (2015). Mineralization of Carbon Dioxide: A Literature Review. *ChemBioEng Reviews*, 2, 231-256. <https://doi.org/10.1002/cben.201500002>
- Roychand, R., Li, J., Kilmartin-Lynch, S., Saberian, M., Zhu, J., Youssf, O. et al. (2023). Carbon Sequestration from Waste and Carbon Dioxide Mineralisation in Concrete—A Stronger, Sustainable and Eco-Friendly Solution to Support Circular Economy. *Construction and Building Materials*, 379, Article ID: 131221. <https://doi.org/10.1016/j.conbuildmat.2023.131221>
- Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., & Maroto-Valer, M. M. (2014). A Review of Mineral Carbonation Technologies to Sequester CO₂. *Chemical Society Reviews*, 43, 8049-8080. <https://doi.org/10.1039/c4cs00035h>
- Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct Capture of CO₂ from Ambient Air. *Chemical Reviews*, 116, 11840-11876. <https://doi.org/10.1021/acs.chemrev.6b00173>
- Sariyev, O., Kelamanov, B., Dossekenov, M., Davletova, A., Kuvatbay, Y., Zhuniskaliyev, T. et al. (2024). Environmental Characterization of Ferrochromium Production Waste (Refined Slag) and Its Carbonization Product. *Heliyon*, 10, e30789. <https://doi.org/10.1016/j.heliyon.2024.e30789>
- Sorrentino, G. P., Guimaraes, R., Cornelio, A., Zanoletti, A., Valentim, B., & Bontempi, E. (2024). Mitigating CO₂ Emissions through an Industrial Symbiosis Approach: Leveraging Cork Ash Carbonation. *Heliyon*, 10, e32893. <https://doi.org/10.1016/j.heliyon.2024.e32893>
- Steinour, H. H. (1959). Some Effects of Carbon Dioxide on Mortars and Concrete-Discussion. *Journal of American Concrete Institute*, 30, 905-907.
- Stokreef, S., Sadri, F., Stokreef, A., & Ghahreman, A. (2022). Mineral Carbonation of Ultramafic Tailings: A Review of Reaction Mechanisms and Kinetics, Industry Case Studies, and Modelling. *Cleaner Engineering and Technology*, 8, Article ID: 100491.

- <https://doi.org/10.1016/j.clet.2022.100491>
- Suescum-Morales, D., Kalinowska-Wichrowska, K., Fernández, J. M., & Jiménez, J. R. (2021). Accelerated Carbonation of Fresh Cement-Based Products Containing Recycled Masonry Aggregates for CO₂ Sequestration. *Journal of CO₂ Utilization*, *46*, Article ID: 101461. <https://doi.org/10.1016/j.jcou.2021.101461>
- Wang, S., Kim, J., & Qin, T. (2024). Mineral Carbonation of Iron and Steel By-Products: State-of-the-Art Techniques and Economic, Environmental, and Health Implications. *Journal of CO₂ Utilization*, *81*, Article ID: 102707. <https://doi.org/10.1016/j.jcou.2024.102707>
- 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*, Article ID: 104261. <https://doi.org/10.1016/j.isci.2022.104261>
- Wicaksono, P. B., & Triwigati, P. T. (2023). Potential Integration of Waste to Energy (WtE) and Carbon Mineralization Technology in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1199*, Article ID: 012008. <https://doi.org/10.1088/1755-1315/1199/1/012008>
- Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C. et al. (2016). Substantial Global Carbon Uptake by Cement Carbonation. *Nature Geoscience*, *9*, 880-883. <https://doi.org/10.1038/ngeo2840>
- Xie, H., Tang, L., Wang, Y., Liu, T., Hou, Z., Wang, J. et al. (2016). Feedstocks Study on CO₂ Mineralization Technology. *Environmental Earth Sciences*, *75*, Article No. 615. <https://doi.org/10.1007/s12665-016-5352-8>
- Xu, D., Liu, J., Du, H., Ma, B., Tang, C., Ni, W. et al. (2024). Performance Optimization and Carbon Reduction Effect of Solid Waste-Based Cementitious Materials from Iron and Steel Metallurgical Slags and Ammonia-Soda Residue. *Chemical Engineering Journal Advances*, *17*, Article ID: 100584. <https://doi.org/10.1016/j.ceja.2024.100584>
- Yuen, Y. T., Sharratt, P. N., & Jie, B. (2016). Carbon Dioxide Mineralization Process Design and Evaluation: Concepts, Case Studies, and Considerations. *Environmental Science and Pollution Research*, *23*, 22309-22330. <https://doi.org/10.1007/s11356-016-6512-9>
- Zhan, B. J., Xuan, D. X., Poon, C. S., & Shi, C. J. (2019). Mechanism for Rapid Hardening of Cement Pastes under Coupled CO₂-Water Curing Regime. *Cement and Concrete Composites*, *97*, 78-88. <https://doi.org/10.1016/j.cemconcomp.2018.12.021>
- Zhang, F., Mo, L. W., & Deng, M. (2016). Effect of Carbonation Curing on Mechanical Strength and Volume Stability of Steel Slag Concrete. *Journal of the Chinese Ceramic Society*, *44*, 640-646.
- Zhang, Q., Feng, P., Shen, X., Lu, J., Ye, S., Wang, H. et al. (2023). Utilization of Solid Wastes to Sequester Carbon Dioxide in Cement-Based Materials and Methods to Improve Carbonation Degree: A Review. *Journal of CO₂ Utilization*, *72*, Article ID: 102502. <https://doi.org/10.1016/j.jcou.2023.102502>
- Zhang, W., Li, S., Ma, J., Huang, D., Zhang, L., & Ma, C. (2023). Feasibility Study of the Synergistic Use of Sludge and Coal-Based Solid Waste to Produce Environmentally Friendly Grouting Materials. *ACS Omega*, *8*, 45854-45866. <https://doi.org/10.1021/acsomega.3c06596>
- Zou, Y., Song, Q., Zhang, P., Xu, S., Bao, J., Xue, S. et al. (2024). Research Status of Building Materials Utilization and CO₂ Curing Technology on Typical Coal-Based Solid Waste: A Critical Review. *Journal of CO₂ Utilization*, *84*, Article ID: 102860. <https://doi.org/10.1016/j.jcou.2024.102860>

List of Abbreviations

IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse Gases
PCC	Precipitated Calcium Carbonate
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CCUM	Carbon capture, utilization and mineralization
IEA	International Energy Agency
DAC	direct air capture
MEA	Monoethanolamine
DEA	Diethanolamine
TEA	Triethanolamine
MDEA	N-methyldiethanolamine
GA	glucosamine
MOFs	Metal-Organic Frameworks
CMC	Carbon mineralization curing
BFS	Blast Furnace Slag
BOFS	basic oxygen furnace slag
EAFS	Electric arc furnace slags
MSW	Municipal Solid Waste
GGBFS/GGBS	ground granulated blast furnace slags
LFG	Landfill gas
SS	Steel slag
CG	Coal gangue
ASR	ammonium-soda residue
CFA	Cork/coal fly ash
CFD	Circulating fluidized bed
DG	Desulfurization Gypsum