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Review on the Potential Co-Application of Aqueous CO_2 Solution in Cementitious Material

Zulhaziq Khan Zuljar[a], Warid Wazien Ahmad Zailani[a*], Nazirah Mohd Apandi[a], Khanom Simarani[b] & Norlia Mohamad Ibrahim[c]

[a]*School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

[b]*Institute of Biological Sciences, Faculty of Science, College of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Wilayah Persekutuan Kuala Lumpur*

[c]*Faculty of Civil Engineering and Technology, Universiti Malaysia Perlis, 02609 Arau, Perlis, Malaysia*

[*]*Corresponding author: waridwazien@uitm.edu.my*

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ABSTRACT

The escalating concerns over climate change and the urgent demand for sustainable development have propelled significant efforts to mitigate carbon footprints by sequestering carbon dioxide (CO_2) into cementitious materials. One promising approach involves the incorporation of calcium-rich materials along with super-saturated aqueous solutions in cement, a method demonstrated to be effective in various studies. However, further research is necessary to address technical challenges and optimize the process. This paper presents a comprehensive review of the existing knowledge on the impact of different calcium-rich materials and curing conditions on the workability and compressive strength of concrete, with a particular focus on aqueous CO_2. Utilizing the Systematic Literature Review (SLR) method, this study identifies the problem, selects the subject of investigation, and gathers pertinent information from suitable databases. The selected documents were analyzed, evaluated, and synthesized to combine the findings. Additionally, the parameters of carbonated concrete utilized in recent studies were analyzed and discussed, providing a thorough understanding of the current advancements and areas requiring further investigation.

Keywords: Carbonic acid; compressive strength; hydration; calcium rich materials; dolomite

INTRODUCTION

In the current age where modern technology role is indispensable in shaping our society and its various aspects, a variety of remarkable human inventions, including but not limited to automation, mechanisation, electricity, and a multitude of other innovations, rely on fossil fuels as their primary source of energy (Arutyunov & Lisichkin 2017). The rapid population expansion has further increased the use of these ever-depleting fossil fuels. This reliance on fossil fuels, however, has resulted in an alarming dilemma. The exponential increase in their consumption has led to the accelerated depletion of these finite resources, raising significant concerns regarding their long-term sustainability (Adebayo 2022; Hanif et al. 2019). The production of ordinary Portland cement (OPC), a vital building material, is heavily dependent on fossil fuels. The manufacturing process involves the high-temperature calcination of calcium carbonate ($CaCO_3$) into calcium oxide (CaO), emitting significant amounts of carbon dioxide (CO_2), as shown in Equation (1) (Milanova & Kearsley, 2021).

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (1)$$

Approximately 1.5 billion tonnes of carbon dioxide were emitted annually as a result of OPC manufacturing (Owuamanam & Cree 2020; Ramakrishna et al. 2017; Summaries 2021). According to the International Energy Agency (IEA), this figure accounts for around 5% of all

CO_2 emissions caused by humans, and the amount will eventually reach 7% by 2020 if this current negative practice continues as illustrated in Figure 1. Malaysia on the other hand was reported to manufactured an excess value of 10 million tons of cements in 2022 only which prove to be at an alarming state for the future of our younger generations (IEA 2021; Summaries 2021). Extraction, transportation and consumption of fossil fuels and raw materials used in cement manufacture such as coke and coal (Nidheesh & Kumar 2019), emerges as one of the most important drivers of the global emission of greenhouse gas that significantly contributes to the phenomenon of global warming, thereby posing a grave threat to the delicate balance of our planet's climate system (Mushtaq et al. 2013; Shukla et al. 2022).

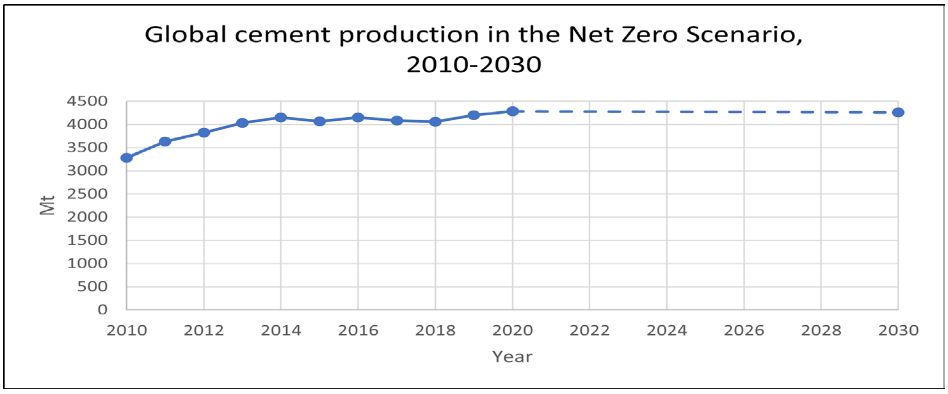

FIGURE 1. Global cement production in Net Zero Scenario from 2010 to 2030 (IEA 2021).

Ongoing and persistent issue of global warming has sparked a growing interest in exploring ways to reuse carbon dioxide (CO_2) in cementitious construction materials, particularly OPC, through a process known as carbon sequestration. This exploration is driven by the imperative to minimize environmental degradation in alignment with the Sustainable Development Goals (SDGs) while also enhancing economic viability (Kusin et al. 2020b; Monkman & Shao 2010). It is crucial to reduce the usage of OPC in concrete production, as doing so will effectively decrease the substantial amount of CO_2 emissions associated with concrete manufacturing. The need for reduction arises from the fact that certain components involved in cement production, such as calcined clay and limestone, carry significant environmental risks due to their contribution to CO_2 decarbonation (Bendouma et al. 2020; Shen et al. 2014).

One promising approach is the incorporation of CO_2 into the hydrated matrix of cementitious materials through a process called carbonation. This method has been found, through numerous research studies, to improve the physical, mechanical, and durability characteristics, as well as the overall performance, of cementitious materials. It has been discovered that the addition of CO_2 can lead to a substantial increase in the strength of cementitious materials, ranging from 10% to 100%, depending on the specific design mix parameters. This strength enhancement plays a crucial role in reducing greenhouse gas emissions related to cement production, thereby contributing to efforts aimed at mitigating the impact of cement manufacturing on the environment (Lippiatt et al. 2019). This study reviews the possibilities of utilizing aqueous CO_2 or carbonic acid (H_2CO_3) along with Calcium (Ca) rich materials as a catalyst in enhancing calcium silicate hydrate (C-S-H) during cement hydration process. H_2CO_3 will be generated through injection of CO_2 into water (H_2O), which is then utilised as an alternative to H_2O with fresh concrete in addition to $CaCO_3$ as an admixture, which is then cast in cube, brick and block mould form. H_2CO_3 will be analysed through its data in providing the adequate standard working condition in order to increase the strength of cement and the mechanisms underlying the development of such strength. The increased risk of corrosion of the reinforcing steel due to low alkalinity following carbonation, restricts the applicability of this study to the manufacturing of concrete alone, rather than the application on reinforced concrete. Initiatives in implementing CO_2 in OPC could contribute in minimization of environmental problem generated from carbon emission related activities mainly from oil and gas production and cement manufacturing. Sequestered CO_2 is an eco-friendly resource, and has a wide potential to be implemented and add value to product especially in concrete while benefiting the relevant construction industries in terms of creating a new green business opportunity.

METHODOLOGY

Systematic literature review (SLR), is one of the most commonly used techniques were utilised to summarize research findings in the area of building engineering and construction materials (Tranfield et al. 2003). A five-step process was utilized in accordance with the SLR method with the process involved the following actions: (1) identifying the problem and choosing the subject of investigation, (2) selecting a suitable database to gather the necessary and pertinent information, (3) choosing the documents that were relevant to the subject being studied, (4) carefully analyzing, evaluating, and assessing the chosen documents, and (5) combining the discoveries made in the previous steps.

Google Scholar and Scopus, two extensively acknowledged bibliographic sources, were selected specifically to compile the relevant information. These resources were considered appropriate for the task of acquiring the required data and specific information. Topics of investigation concerning the CO_2 in cementitious material with the search string utilized to acquire the topic-related documents was: (TITLE-ABS-KEY ((hydration OR sequestration OR carbonation) AND CO_2 AND cement) AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (EXACTKEYWORD, “Carbon Dioxide”) OR LIMIT-TO (EXACTKEYWORD, “Carbonation”) OR LIMIT-TO (EXACTKEYWORD, “Cements”) OR LIMIT-TO (EXACTKEYWORD, “Hydration”) OR LIMIT-TO (EXACTKEYWORD, “Portland Cement”) OR LIMIT-TO (EXACTKEYWORD, “Compressive Strength”) OR LIMIT-TO (EXACTKEYWORD, “Calcium Carbonate”) OR LIMIT-TO (EXACTKEYWORD, “Carbon Sequestration”) OR LIMIT-TO (EXACTKEYWORD, “Concretes”) OR LIMIT-TO (EXACTKEYWORD, “Cement”) OR LIMIT-TO (EXACTKEYWORD, “Curing”) OR LIMIT-TO (EXACTKEYWORD, “X Ray Diffraction”) OR LIMIT-TO (EXACTKEYWORD, “CO_2 Sequestration”) OR LIMIT-TO (EXACTKEYWORD, “PH”)) which involves the title, and abstract of documents. In total, 2050 number of English-language research publications spanning from the year 1981 to 2023 were obtained. Annual and cumulative numbers of research articles on CO_2 sequestered concrete indexed in Scopus from 1981 until 2023 can be observed in Figure 2a which were derived from the acquired publications in Scopus. Research in sequestration of CO_2 in cement has seen a surge in trend with the increased numbers of publications throughout the years. Figure 2b illustrates a pie chart of the top 10 highest number of publications amongst countries where China has the largest number of publications, followed by the United States with a total of 590 and 318 respectively. The data indexed from Scopus was then analyzed as depicted in Figure 2c, according to its network of co-authorship.

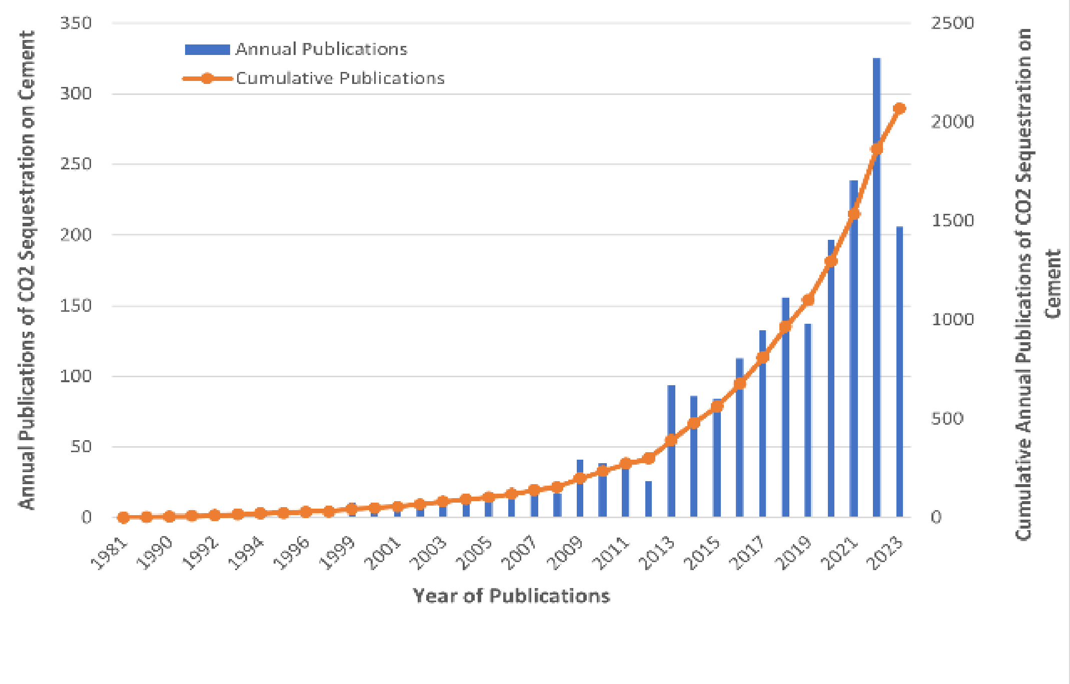

FIGURE 2a. Annual trend of published documents on the topic of interest.

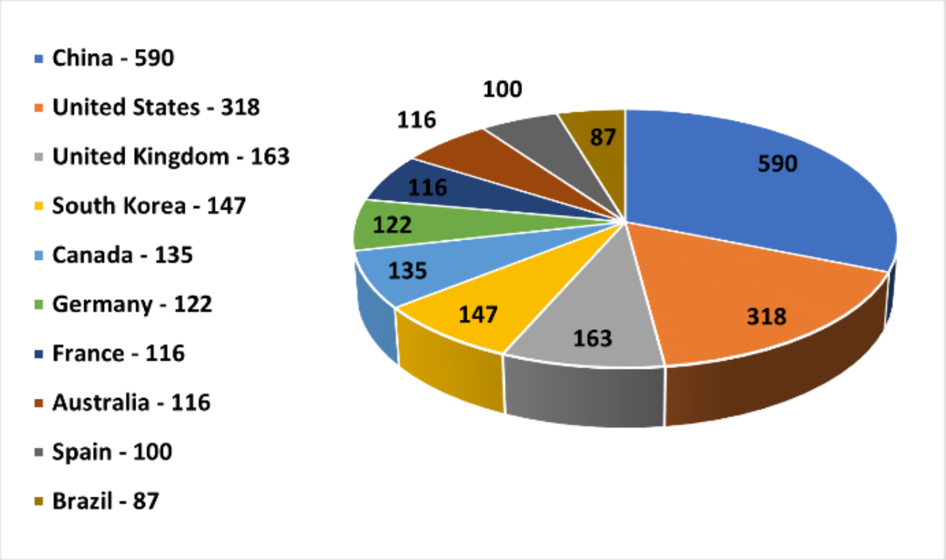

FIGURE 2b. Countries with the largest number of publications on the topic of interest.

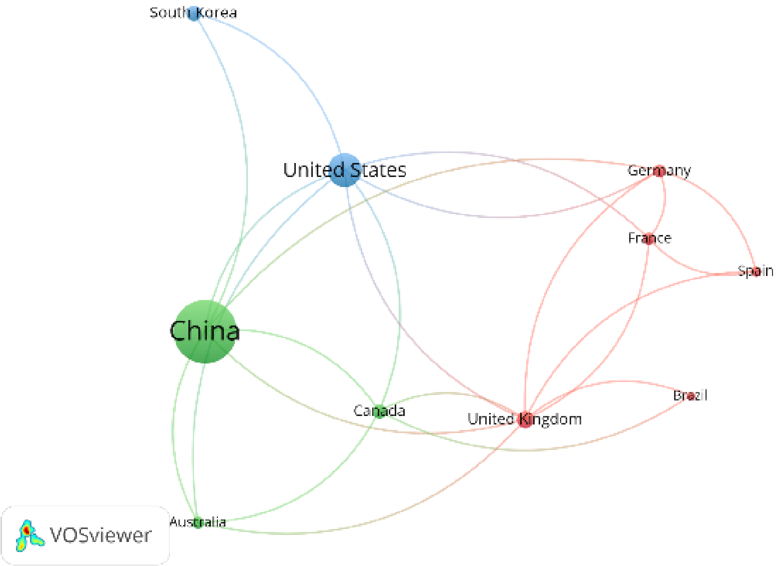

FIGURE 2c. Network map showing the co-authorship between countries of publications on the topic of interest between countries related, and identifications of ten countries with the largest number in publications using a bibliometric visualizer and construction software tool, VOS Viewer.

Repetitively appeared keywords in relevant publications were then analyzed and illustrated as pie chart in their respective frequency of terms as observed in Figure 3. Five (5) terms incorporating of “carbonation”, “carbon dioxide sequestration”, “microstructure”, “cementitious material”, and “compressive strength” are the most frequently encountered terms derived from the analyzed publications. Relevant keywords were outlined using VOS Viewer according to its co-occurrence, revealing twelve (12) distinct clusters represented by different colours which are depicted in the figure.

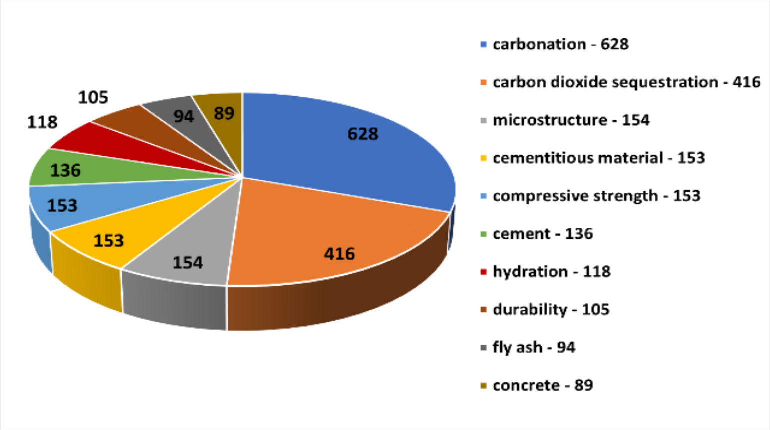

FIGURE 3. Pie chart depicting frequently appeared keywords of the publications related to topic of interest.

These clusters were generally categorized corresponding to its nodes, as an observation, cement related composition and carbon dioxide associated testing were primarily pertained in red-coloured and green-coloured lines respectively.

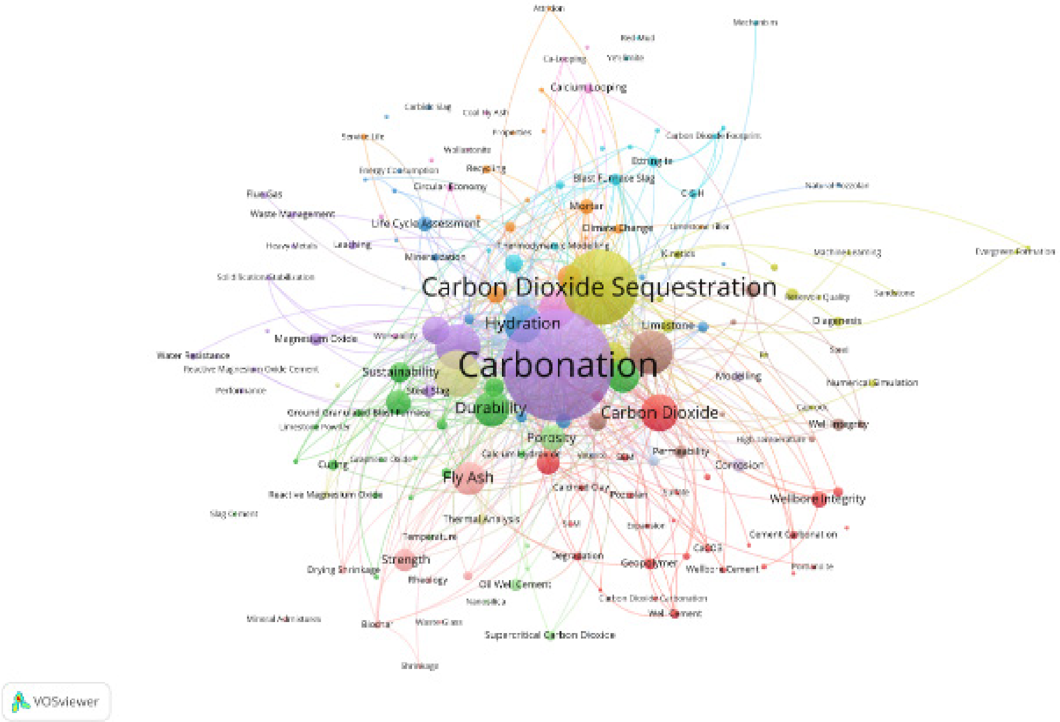

FIGURE 4. Network map showing the keywords co-occurrence of the publications related to topic of interest.

TABLE 1. Variation of cementitious materials integrated into CO_2 fused concrete, and findings

Materials											CO_2 Form Conversions			Findings	Remarks	Ref
Aggregates		Lime-stone Cement	OPC	Sand	Water	Fly Ash	Super-plasticizer	Slag	CO_2	Others	Gas to Solid	Gas to Liquid	Liquid to Solid			
Course	Fine															
✓	✓		✓				✓		✓		✓			Decrease drying shrinkage by 25% to 45% Reduce pore volume	Significantly improve early age compressive strength	(Xiao et al. 2022)
									✓		✓	✓		Reduce H_2O absorption by 16.4% Lower permeability rate by 42.4%	Enhance strength gained (up to 6 times)	(Meng et al. 2022)
✓	✓	✓		✓	✓		✓		✓		✓			H_2O absorption ability remain	Higher compressive strength	(Russo & Lollini, 2022)
✓			✓						✓	Carbonated & non-carbonated reinforced concrete aggregate	✓		✓	Higher compressive strength than recycled aggregate by 24.1% and 32.9% Decrease H_2O absorption by 15.2% to 20.6% Reduce drying shrinkage by 16.6% to 25.1% Reduce porosity	Comparable with neutral aggregate	(Lu et al. 2021)
✓	✓		✓		✓	✓		✓	✓				✓	No change in workability	Reduce binder (7% to 8%) reducing compressive strength	(Monkman & MacDonald, 2017)
✓	✓		✓	✓	✓		✓		✓		✓			Greater surface resistivity Lower porosity		(Xian & Shao, 2021)
✓	✓		✓						✓	Carbonated masonry aggregates		✓		Increase dry bulk density	Improve mechanical properties	(Suescum-Morales et al. 2022)
✓	✓		✓	✓	✓		✓		✓	Recycled concrete aggregates	✓			Enhance flexural strength Reduce the usage of natural aggregate by up to 60%		(Xuan et al. 2016)

continue ...

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✓	✓	✓	✓		✓	✓	Crushed pavement concrete aggregates	✓	Higher compressive strength than recycled aggregate by 2.3% to 14.5%	(Luo et al. 2018)
✓	✓		✓			✓	Carbonated sand & gravel, & CEM II/A Cement	✓	Improve the compressive strength	(Torrenti et al. 2022)
		✓	✓			✓	Carbonated & non-carbonated reinforced concrete aggregates	✓	Higher compressive strength by 17% on 28th day Higher compressive strength by 12% on 90th day	(Li et al. 2017)
		✓	✓			✓	Limestone and Quartz Powder	✓	Higher electrical resistivity	(Lin & Wang, 2021)
✓	✓	✓	✓			✓	Carbonated & non-carbonated recycled aggregate	✓	Reduce brittleness	(Lu et al. 2022)
						✓	Cement paste	✓	Flowability	(Wu et al. 2022)
✓	✓		✓	✓	✓	✓		✓	Enhance compressive strength	(Xian, Zhang, et al. 2022)

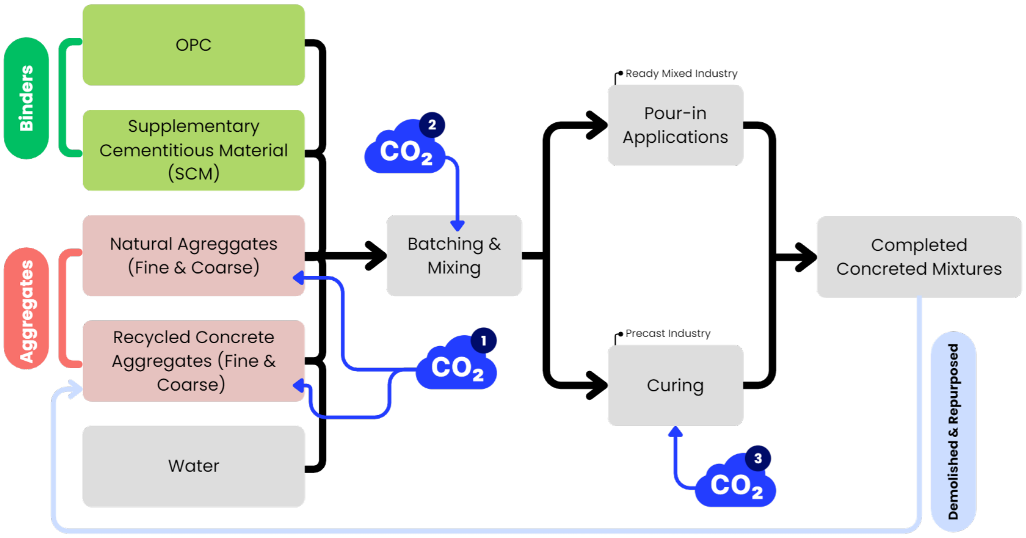

FIGURE 5. Proposed Methods of Carbonation Curing in cementitious materials. Acronyms: Ordinary Portland Cement (OPC). (Amended from (Lim et al. 2019)).

CO_2 SEQUESTERED CONCRETE METHOD AND MECHANISM

Numerous studies have focused on exploring the potential of utilizing CO_2 to enhance the properties of concrete as a more ecological method in concrete manufacturing in the construction industries. The following section will discuss the methods and technologies highlighting their significance in advancing sustainable concrete production as evident in Table 1. Numerous studies have focused on using CO_2 to improve concrete's properties. This method is more ecological for concrete manufacturing in the construction industry. The following section discusses methods and technologies, highlighting their significance in advancing sustainable concrete production, as shown in Table 1. CO_2 sequestration in concrete involves capturing CO_2 and incorporating it into the mix. This reduces emissions and enhances concrete properties. The primary mechanisms are carbonation curing and mineral carbonation. Carbonation curing cures concrete in a CO_2-rich environment, accelerating the carbonation process. This process reacts CO_2 with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$). The benefits include increased compressive strength, reduced permeability, and CO_2 storage. Mineral carbonation reacts CO_2 with minerals like magnesium and calcium silicates to form stable carbonates. This process can enhance concrete durability and utilize industrial by-products. Another method involves injecting CO_2 directly into the concrete mix. This allows CO_2 to react with hydrating cement, forming stable compounds. Key advantages include improved workability and reduced cement content. Supercritical CO_2 treatment uses CO_2 in its supercritical state, enhancing penetration and carbonation. Benefits include rapid carbonation and enhanced mechanical properties. Integrating CO_2 sequestration methods in concrete production promotes sustainable development. Significant benefits include a reduced carbon footprint, resource efficiency, and enhanced material performance. Table 1 summarizes these methods and their advantages in sustainable concrete production.

CARBONATION IN CONCRETE

CO_2 carbonation in concrete has emerged as a subject of extensive research in recent years, reflecting to the growing interest in the Carbon Capture, Usage and Storage (CCUS) framework. A comprehensive analysis, as depicted in Figure 4, reveals a remarkable total of keywords in 628 publications dedicated to this topic of interest. The research has explored various techniques associated with concrete carbonation, including carbonation curing, mineral carbonation, and early-age carbonation as described in Table 1 and depicted according to its phase of concrete production in Figure 5. These techniques are continually being investigated and refined to optimize the benefits of CO_2 carbonation in concrete construction while addressing challenges and ensuring long-term performance (Liu & Meng, 2021). The sequestration rate of CO_2 within the concrete is limited, although the generated strength improvement presents an opportunity to reduce the cement content in concrete production. This reduction in cement content not only contributes to a lower carbon footprint of the concrete but also demonstrates the possibility of achieving comparable performance while requiring less cement (Winnefeld et al. 2022).

MINERAL CARBONATION

Extensive research comprising both experimental and theoretical studies had been conducted in exploring mineral carbonation and examining its potential as a method for sequestering CO_2 in concrete (Huang et al. 2019; Kusin et al. 2020a; Molahid et al. 2021). The process of mineral carbonation involves acceleration of weathering process with silicate aggregates containing Ca, Iron (Fe) and Magnesium (Mg) substantial minerals consisting of olivine, serpentine, brucite, wollastonite, or basalt, through exposing it to CO_2, leading to the formation of stable $CaCO_3$ or Magnesium Carbonate (MgCO3) (Kusin et al. 2023; Owais et al. 2019; Wang et al. 2021). These silicate minerals will produce a reaction with CO_2 according to Equation (2), Equation (3), Equation (4), and Equation (5) below.

$$Mg_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2MgCO_3 + H_4SiO_4 \quad (2)$$

$$Mg_3Si2O_5(OH)_4 + 3CO_2 + 2H_2O \rightarrow 3MgCO_3 + 2H_4SiO_4 \quad (3)$$

$$Fe_2SiO_4 + 2CO_2 + 2H_2O \rightarrow 2FeCO_3 + H_4SiO_4 \quad (4)$$

$$CaSiO_3 + CO_2 + 2H_2O \rightarrow CaCO_3 + H_4SiO_4 \quad (5)$$

The implemented mechanism of carbonation reactor was similar as in Figure 5. Resulting carbonated aggregates, either from recycled (RA) or naturally extracted (NA), are then mixed with other concrete ingredients (Winnefeld et al. 2022). Mineral carbonation offers several advantages, particularly in improving bonding between aggregates and cementitious matrix (Nedunuri et al. 2021), enhancing mechanical properties (Ren et al. 2021), and reducing susceptibility to alkali-silica reactions (ASR) (Shoji et al. 2015). According to a recent finding, the mineralization of recycled concrete aggregates, composed of 65 to 68 weight percentage (wt) % of quartz, causes the pore diameters to decrease from 15 to 5nm which undertake only 5 days of reaction time. Higher carbonation performance was observed when using smaller grain sizes and longer reaction times. Favorable conditions such as low pressure, low temperature, and low energy requirements resulted in approximately 6.5 wt% retention of CO_2. These conditions not only contribute to the efficient carbonation process but also offer environmental benefits by minimizing energy consumption and promoting environmental protection (Aparicio et al. 2022).

EARLY-AGE CARBONATION CURING

Early age carbonation in concrete concerns the rapid carbonation process that coincide the exposure of CO_2 towards fresh concrete, typically during hydration of cement initial stage, resulting in a denser and stronger concrete (Kamal et al. 2020). Figure 6 shows the cycle of cementitious material reaction through early-age carbonation were particularly exothermic and impulsive in terms of its characteristics which was discussed discretely in the steps below:

1. This sequential reaction was initiated from the diffusion of gaseous CO_2 through the macro pores of fresh concrete mixture.
2. CO_2 were dissolved and infused with cementitious materials to obstruct its porosity.
3. Gaseous CO_2 sustaining solvation process which converts the gaseous CO_2 into an aqueous CO_2 solution during the fresh concrete liquid phase.
4. H_2CO_3 was formed through deliberate hydration process of aqueous CO_2.
5. The formation of H_2CO_3 subsequently ionizes into hydrogen ions (H^+), bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{2-}).
6. The rapid and cyclic dissolution of cement phases C_3S and C_2S commenced while accompanied by heat release in the early stage of cement hydration. Cement grains are coated with a loosely bound layer of calcium silicate hydrate gel that dissolves, resulting in the release of calcium (Ca^{2+}) and silicate (SiO_4^{4-}) ions.
7. Nucleation produces the formation of thermodynamically stable $CaCO_3$ and the conventional formation of calcium-silicate-hydrate (C-S-H) gel.
8. The precipitation of $CaCO_3$ as a solid phase occurs, with calcite being the preferred crystal structure.
9. CO_2 and the cement paste sustained reaction through secondary carbonation causing the decalcification of the initially formed C-S-H gel, leading to the production of a calcium-depleted silicate hydration (SH) and $CaCO_3$.

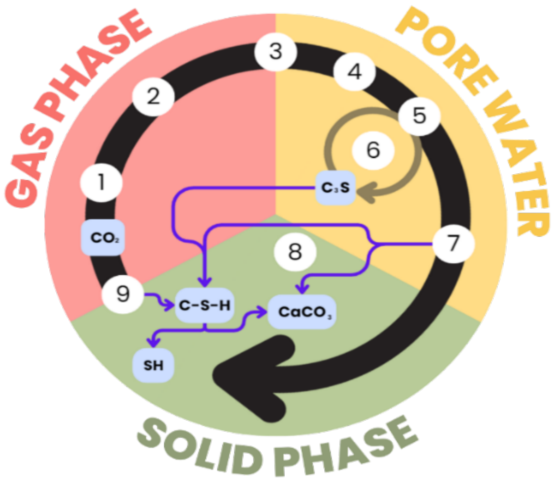

FIGURE 6. Illustration of accelerated carbonation mechanism through Early-age Carbonation. (Adopted from (Bertos et al. 2004) with minor modification)

Carbonation reactions occur during the early stages of concrete formation can potentially affect the availability of calcium, forming $CaOH_2$ and increasing the pH reading through hydration process (Francioso et al. 2019; Xian, Logan, et al. 2022; Xian et al. 2023). It is discovered that early age carbonation does not impede the long-term development of the concrete microstructure as it matures. Formation of $CaOH_2$ resumes during the later stages of hydration while the pH evolution of the pore solution proceeds normally once the carbonation process concluded (Hu et al. 2022). This suggests that despite the initial impact on Ca availability and pH, the overall hydration process and subsequent microstructural development of the concrete remain unaffected by early age carbonation. Research by Zhang reveals that at the initial stage (0 hours) of CO_2 uptake estimation in relation to pre-carbonation hydration, the thermogravimetric analysis (TGA) discovers the reading at a percentage of 9.6% for OPC and 10.2% for PLC as depicted in Figure 7. Early-age carbonation process however releases heat causing the present water to evaporate which subsequently decreasing the mass of sample compared to the CO_2 uptake. It is observed that the CO_2 uptake and the pre-carbonation hydration duration correlates inversely while the sample mass kept on escalating. At the 71-hour mark, carbonation of the samples yielded a CO_2 uptake of approximately 6.1% for OPC and 5.4% for PLC, which closely aligned with the observed increase in mass, measuring 5.1% for OPC and 4.6% for PLC. This indicates that as the hydration age progressed, the carbonation process exhibited diminishing intensity, as evidenced by a decrease in CO_2 uptake and reduced water loss attributable to the heat released during the reaction.

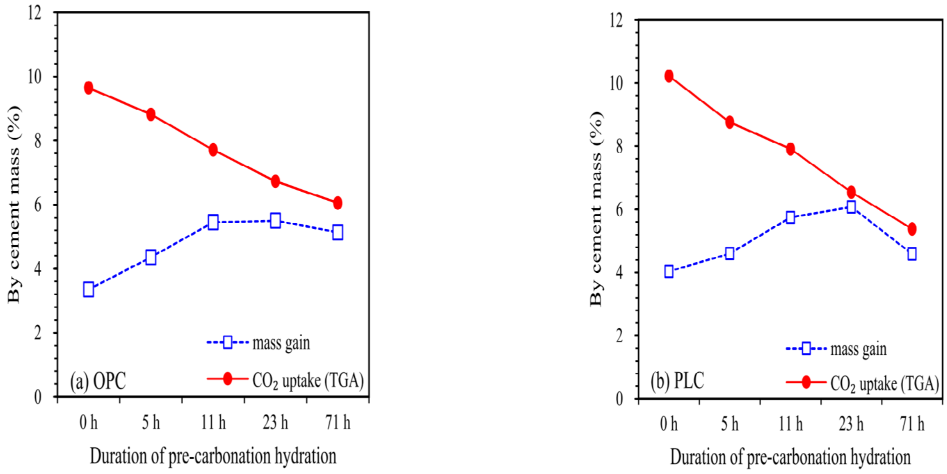

FIGURE 7. Early-age Carbonation Mass Gain and CO_2 Uptake on cement mortar sample: (a) OPC and (b) PLC. Acronyms: Portland-Limestone Cement (PLC). (Adopted from (Zhang et al. 2020)).

TABLE 2. Method and duration of compressive strength testing

Methods									References
Hardened-state Compressive strength	Compressive Strength Test (Days)								
	1	3	7	14	28	56	90	180	
√			√		√	√	√	√	(Xiao et al. 2022)
√									(Meng et al. 2022)
√			√		√		√		(Russo & Lollini, 2022)
	√	√		√		√	√		(Lu et al. 2021)
√			√	√	√				(Monkman & MacDonald 2017)
√	√				√				(Xian & Shao 2021)
√	√	√	√						(Suescum-Morales et al. 2022)
√									(Xuan et al. 2016)
√									(Luo et al. 2018)
√	√		√		√		√		(Torrenti et al. 2022)
√			√		√		√		(Li et al. 2017)
√		√	√		√				(Lin & Wang 2021)
√		√			√				(Lu et al. 2022)
√	√	√	√	√	√				(Wu et al. 2022)
√	√			√					(Xian, Zhang, et al. 2022)
√				√					(Liang et al. 2020)
√	√			√					(Zhang & Shao, 2016)
√									(Ahmad et al. 2017)
√		√		√					(Feng et al. 2023)

The systems of flow-through and enclosed reactor were utilized with high flow rate at atmospheric pressure and pressurized gas respectively, as depicted in Figure 8a and 8b. Enclosed reactor system were particularly implemented for a research at a laboratory scale due to its efficiency in obtaining higher carbonation rates and degrees from the diffusion of CO_2 through highly pressured gas (Pan et al. 2019; Pan et al. 2017). Formation of $CaCO_3$ precipitated within the concrete matrix also enhance the densification, reducing the porosity and amplifying the carbonated cementitious material matrix's interfacial properties (Chen & Gao 2019; Gupta et al. 2022).

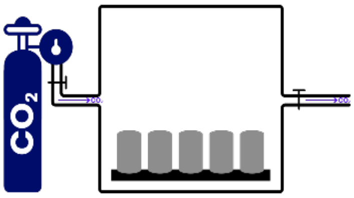

FIGURE 8a. Flow-through reactor carbonation reaction system. (Adopted from (Liu & Meng 2021)).

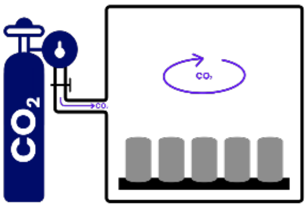

FIGURE 8b. Enclosed reactor carbonation reaction system. (Adopted from (Liu & Meng 2021)).

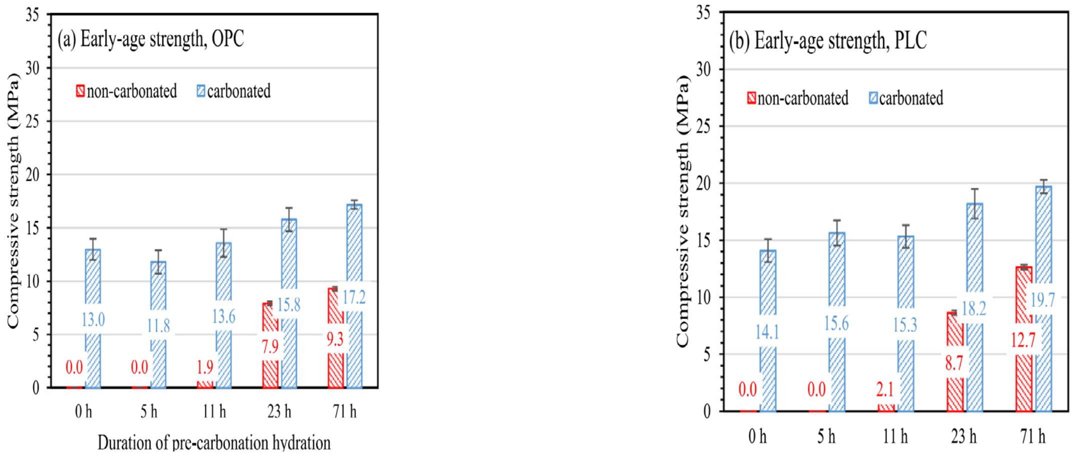

FIGURE 9. Early-age Carbonation Compressive strength in Mega Pascal (MPa) on OPC and PLC cement mortar sample. (Adopted from (Xian et al. 2022))

COMPRESSIVE STRENGTH OF CARBONATED CURED SPECIMEN

In terms of compressive strength, Mo et al. (Mo et al. 2020) discovers that concrete specimens infused with carbonated recycled aggregates (CRA) demonstrated a significant increase in compressive strength in accordance with the curing period. At an early age of 3 days, compressive strength of concrete specimens containing CRA exhibits an increase in value exceeding 30.0 MPa. Maintaining the curing period of the concrete specimens to 90 days resulting in the amplification of compressive strength value to a reading in the range of 56.0, 51.5 and 46.4 MPa. Additionally, Tang et al (Tang et al. 2023) stated that fully CRA infused concrete specimens displayed an increase of compressive strength upon aggregate carbonation up to 22.66% and 28.57%. This phenomenon was particularly due to the densification of cement paste from the generated CaCO3 through CO2 carbonation (Kaddah et al. 2022; Zajac et al. 2022).

The compressive strength of cement mortar through early-age carbonation in correlation with the duration of pre-carbonation hydration, were determined to obtain an equivalent strength of 13.0 MPa and 14.1 MPa for OPC and PLC specimen respectively as illustrated in Figure 9. Zhang disclosed that the escalation of hydration duration will significantly increase the gap of strength between carbonated and non-carbonated cement mortar samples at an early age. This was determined by the strength measurements conducted after a pre-carbonation hydration period of 71 hours, indicating a convergence in the development of strength between the two conditions. The compiled research on the CO$_2$ concrete testing parameters was summarized in Table 2 and Table 3.

DENSIFICATION OF CARBONATED CURED SPECIMEN

Figure 10a and 10b shows the Scanning Electron Microscopy (SEM) photomicrographs of uncarbonated and carbonated RA respectively. Uncarbonated RA as in Figure 10a, exhibits a highly porous structure with minimal presence of cement hydration products or hydraulic components.

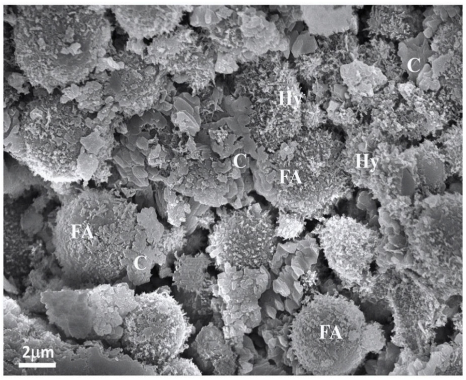

FIGURE 10a. SEM images of Carbonated CRA from steel slag. (Adopted from (Mo et al. 2020)).

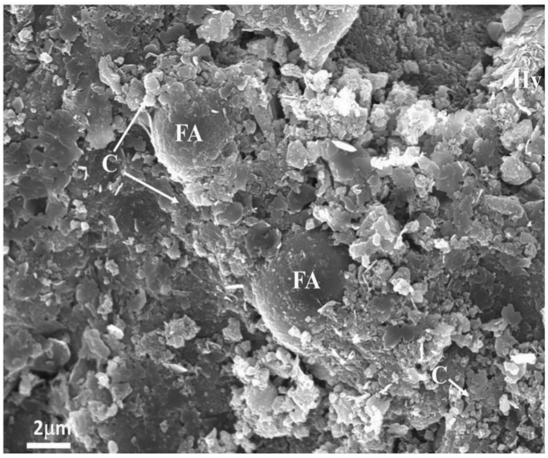

FIGURE 10b. SEM images of Uncarbonated CRA from steel slag. (Adopted from (Mo et al. 2020)).

TABLE 3. Compiled research on the CO_2 concrete testing parameters.

Parameter	Experimental Testing	CO_2 Detection Method	CO_2 Phase	Findings	References
Variety of Concrete Sample Mixture Volume Ratio of solid binder to aggregates	Compressive Strength Test pH value Testing SEM Test XRD Test MIP Test FT-IR Test TG-DTG Test CO_2 adsorption Test Carbonation Degree Test	Fixed CO_2 at a pressure of 0.7 Bar (NA)	Carbonation Curing (Gas)	High pH value (alkali) resulted to high compressive strength Combination of Silica Sand with CO_2 produce high compressive strength	(Soares & Castro-Gomes 2022)
Variation of $CaCO_3$ content Type of H_2O used (Distilled & Tap Water)	pH value Testing Compressive Strength Test XRD Test ITC Test TGA Test VICAT Test	Fixed CO_2 at a pressure of 8 Bar (NA)	Super-saturated aqueous (Gas to Liquid)	$CaCO_3$ powder in H_2O reduces setting time and increases strength. $CaCO_3$ in H_2CO_3 increase calcium in solution and hydration rate. Carbonation without $CaCO_3$ reduces compressive strength Carbonation solution increases rate of reaction.	(Lippiatt et al. 2019)
Variation of cement mix proportions	ITC Test Mortar Flow Test Compressive Strength Test XRD Test TGA Test MIP Test	Fixed CO_2 at a pressure of 8 Bar (NA)	Super-saturated aqueous (Gas to Liquid)	pH value of 4.2 causes rapid dissolution pH can be expected to increase overtime due to CO_2 degassing. Reduced further hydration due to equilibrium pH lower than if pure H_2O used Low pH value increases solubility phases and dissolution rate.	(Lippiatt & Ling, 2020)
Variation of Applied Temperature Duration of Curing Time	Compressive Strength Test Thickening Time Test Durability Test Shear Bond Test	Fixed CO_2 of H_2CO_3 (NA)	Aqueous H_2CO_3 Solution (Liquid)	Geopolymer can resists H_2CO_3 corrosion effect Portland cement is fragile due to H_2CO_3 infiltration	(Salehi et al. 2016)

The absence of CO_2 exposure resulted in inadequate interaction between the RA and the cementitious matrix, leading to a weak bond. Carbonated RA however, displayed a significantly increased density in its microstructure where the particles tightly bound by the carbonate and cement hydration products as aforementioned. Densification of the microstructure signifies the positive impact of mineral carbonation on enhancing the bonding and cohesion between the components within the aggregate (Ren et al. 2021).

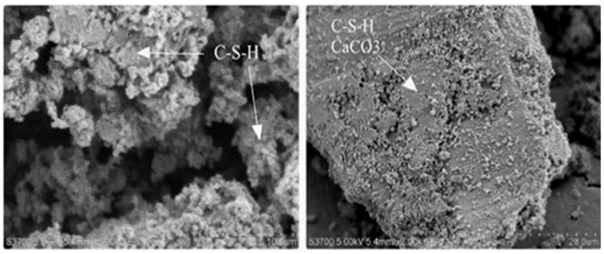

FIGURE 11a. Microstructure of Pre-carbonated Cement Paste through Carbonation Curing SEM. (Adopted from (Wang et al. 2017)).

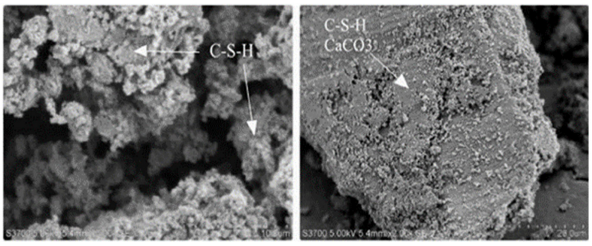

FIGURE 11b. Microstructure of Post-carbonated Cement Paste through Carbonation Curing from SEM. (Adopted from (Wang et al. 2017)).

CO_2 carbonation curing of cementitious materials generally produces a high in strength concrete, as the structure pores were filled with crystalline $CaCO_3$ and silica gel depicted from the SEM photomicrographs in Figure 10b. It is observed that carbonated cement apparently has a much denser microstructure following curing process in comparison with uncarbonated cement as shown in Figure 11a and Figure 11b respectively. This is because uncarbonated cement is at a predominant amorphous C-S-H phase where the presence of C2S and C3S remain unreacted. The densification of the microstructure in carbonated cement contributes to its enhanced strength properties.

INTEGRATING CALCIUM PRECURSOR WITH SUPER-SATURATED AQUEOUS CO_2 SOLUTION IN CEMENTITIOUS MATERIALS

Implementing calcium-rich materials with a super-saturated aqueous CO_2 solution or H_2CO_3, as a reactant in cementitious materials is an alternative approach in carbonation which provides several possibilities for the enhancement of concrete in terms of its performance and properties. Lippiat et al. (Lippiatt et al. 2019) reveals that the utilization of $CaCO_3$ as calcium rich materials, dissolute in H_2CO_3 leads to an increase in the concentration of dissolved Ca^{2+} in the solution which facilitates the formation of nano-carbonate nucleation sites, which expedite the rate of cement hydration. The reaction of H_2CO_3 and $CaCO_3$ were observed to strengthening the cement paste (Qian, 2017) through the reduction of the cement's setting time while escalating the strength by up to 10% and 20% than standard cement paste and water hydrated limestone cement respectively. Compressive strength of cement samples of 1-day curing period progressively amplified where the water carbonated mixed $CaCO_3$ sample has a higher relative strength than uncarbonated cement samples by 6% and 20% as observed in Figure 12.

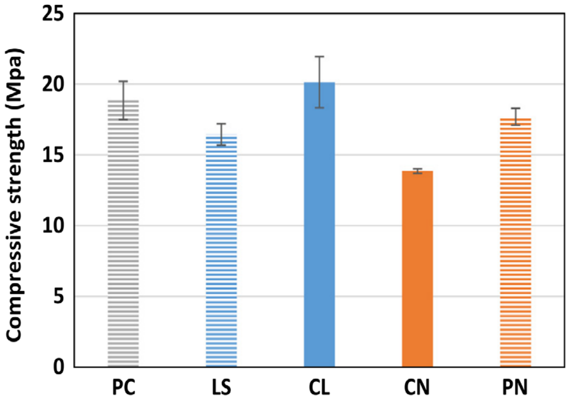

FIGURE 12. Compressive strength of cement pastes samples subject to 1-day of curing duration. Note: Dashed line and solid line bar are uncarbonated samples and carbonated samples respectively. (Adopted from (Lippiatt et al. 2019)).

On the contrary, the integration of this approach requires careful consideration of various factors, including the precise mixing conditions, pH concentrations, variety of calcium precursors and reaction kinetics, to achieve optimal results. These parameters is essential in order to prevent from affecting the porosity, reduced strength of cement, and uneven distribution of carbonation throughout the concrete matrix (Lippiatt & Ling, 2020). As such, dolomite is a calcium-rich materials alternative other than $CaCO_3$ that can be incorporated with H_2CO_3 with numerous researchers have taken an interest in studying its capabilities when applied in cementitious materials (Chen et al. 2021; Yang et al. 2015; Zhang et al. 2022). Table 4 shows the summarization of chemical composition of dolomite which was determined through XRF testing. It is observed that dolomite contains key components as a cement additive with 30.40%, 20.5%, and 56.6% of calcium oxide (CaO), magnesium oxide (MgO) and $CaCO_3$ respectively. The reactivity of H_2O with MgO content in dolomite shown in Equation (6), provides an accelerated carbonation (Gardeh et al. 2022).

$$MgO + H_2O \rightarrow Mg(OH)_2 \tag{6}$$

Gusain et al. (Gusain et al. 2023) discovers that utilizing 15% of dolomite in conventional concrete provides maximum flexural and compressive strength. Combining dolomite's properties with CO_2 carbonation would amplifies the strength of concrete rapidly due to its characteristics as a crystallization nuclei which in turn developed a skeleton of $CaCO_3$ nanometer (Yang et al. 2015).

TABLE 4. Chemical composition of dolomite and limestone (wt/%)

Components	Dolomite ($CaMg(CO_3)_2$) (Gusain et al. 2023)	Limestone ($CaCO_3$) (Nath & Dutta, 2010)
CaO	30.40	45.00
MgO	20.50	1.20
SiO_2	1.50	14.0
Al_2O_3	0.50	5.00
Fe_2O_3	0.30	3.50
$CaCO_3$	56.60	90.00

CARBONATED CONCRETE PARAMETER ANALYSIS

The overview of the research conducted on the testing parameters for carbonated concrete provides an insight on aqueous carbonated cementitious materials analysis. Based on the review, it is clearly observed that most researcher determined the carbonated concrete sample's composition and thermal stability, including the decomposition of hydrated cement phases and any changes induced by carbonation through thermogravimetric analysis (DTA-TG) (Hernández-Rodríguez et al. 2021; Lippiatt et al. 2019; Soares & Castro-Gomes, 2022). Incorporating SEM for microstructure testing provides valuable information on carbonation impacts towards concrete's internal structure, further enhancing the understanding of its chemical reactivity, performance and durability. Concrete samples were prepared, and cross-sectional slices are observed under the SEM, which provides high-resolution images, allowing researchers to analyze changes in the cement paste, aggregate distribution, and any microcracks or porosity induced by carbonation (Ashraf & Olek, 2016; Hernández-Rodríguez et al. 2021; Soares & Castro-Gomes, 2022; Zhang et al. 2018). Since the proposed carbonation is in aqueous solution, pH test is required to measure the pH scale of carbonated soluble (H_2CO_3) before and after mixing with cement additives (Lippiatt et al. 2019). Research by Lippiat et al. (Lippiatt & Ling, 2020; Lippiatt et al. 2019) mainly implements a consistent 8 Bar of CO_2 pressure of liquid CO_2 to incorporate with calcium rich materials, which provides a pH value of 3.58 to 3.74 (Ryu et al. 2017).

CONCLUSION

This paper provides a systematic review on the fundamental understandings of co-applicating dolomite as a calcium-rich materials other than $CaCO_3$ with an aqueous CO_2 solution in cementitious materials to improve the overall durability and mechanical properties. The following primary conclusions from this study:

1. Dolomite contains both Ca and magnesium carbonate $MgCO_3$, which react rapidly with liquid CO_2 in comparison to pure $CaCO_3$. This results in a faster carbonation rate, facilitating quicker transformation of CO_2 into stable carbonate minerals within the cementitious matrix.
2. Incorporation of magnesium carbonates from dolomite in the carbonation process contributes to the formation of more durable and stronger cementitious materials. The presence of magnesium ions in the carbonate minerals enhances the binding and crystalline structure, leading to higher compressive strength and reduced brittleness.
3. Dolomite-based carbonation provides the potential for greater carbon storage within the cement matrix due to the presence of two carbonation-reactive minerals in its chemical composition consisting of $CaCO_3$ and $MgCO_3$ which would increase the capacity for carbon storage while enhancing carbon sequestration potential.

Additionally, the long-term effects on the concrete's performance and structural integrity need to be thoroughly studied and validated to ensure its practical viability in real-world construction applications. However, further research and testing are necessary to fully understand the potential and limitations of this alternative approach in CO_2 carbonation for practical applications in the construction industry.

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Adebayo, T. S. 2022. Environmental consequences of fossil fuel in Spain amidst renewable energy consumption: a new insights from the wavelet-based Granger causality approach. *International Journal of Sustainable Development & World Ecology 29*(7): 579-592.

Ahmad, S., Assaggaf, R. A., Maslehuddin, M., Al-Amoudi, O. S. B., Adekunle, S. K., & Ali, S. I. 2017. Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing. *Construction and Building Materials 136*: 565-573.

Aparicio, P., Martín, D., Baya-Arenas, R., & Flores-Alés, V. 2022. Behaviour of concrete and cement in carbon dioxide sequestration by mineral carbonation processes. *Boletin de la Sociedad Espanola de Ceramica y Vidrio 61*(3): 220-228.

Arutyunov, V. S., & Lisichkin, G. V. 2017. Energy resources of the 21st century: Problems and forecasts. Can renewable energy sources replace fossil fuels. *Russian Chemical Reviews 86*(8): 777.

Ashraf, W., & Olek, J. 2016. Carbonation behavior of hydraulic and non-hydraulic calcium silicates: potential of utilizing low-lime calcium silicates in cement-based materials. *Journal of materials science 51*(13): 6173-6191.

Bendouma, S., Serradj, T., & Vapur, H. 2020. A case study of the life cycle impact of limestone quarrying on the environment. *International Journal of Global Warming 22*(4): 432-447.

Bertos, M. F., Simons, S., Hills, C., & Carey, P. 2004. A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO2. *Journal of hazardous materials 112*(3): 193-205.

Chen, T., Bai, M., & Gao, X. 2021. Carbonation curing of cement mortars incorporating carbonated fly ash for performance improvement and CO2 sequestration. *Journal of CO2 Utilization*, *51*, 101633.

Chen, T., & Gao, X. 2019. Effect of carbonation curing regime on strength and microstructure of Portland cement paste. *Journal of CO2 Utilization*, *34*, 74-86.

Feng, C., Cui, B., Guo, H., Zhang, W., & Zhu, J. 2023. Study on the effect of reinforced recycled aggregates on the performance of recycled concrete--synergistic effect of cement slurry-carbonation. *Journal of Building Engineering*, *64*, 105700.

Francioso, V., Moro, C., Martinez-Lage, I., & Velay-Lizancos, M. 2019. Curing temperature: A key factor that changes the effect of TiO2 nanoparticles on mechanical properties, calcium hydroxide formation and pore structure of cement mortars. *Cement and Concrete Composites 104*, 103374.

Gardeh, M. G., Kistanov, A. A., Nguyen, H., Manzano, H., Cao, W., & Kinnunen, P. 2022. Exploring mechanisms of hydration and carbonation of MgO and Mg (OH) 2 in reactive magnesium oxide-based cements. *The Journal of Physical Chemistry C 126*(14): 6196-6206.

Gupta, S., Kashani, A., & Mahmood, A. H. 2022. Carbon sequestration in engineered lightweight foamed mortar–Effect on rheology, mechanical and durability properties. *Construction and Building Materials 322*: 126383.

Gusain, P., Sharma, S., Debarma, S., Sharma, A. K., Mishra, N., & Dahale, P. P. 2023. Study of concrete mix by adding dolomite in conventional concrete as partial replacement with cement. *Mater. Today Proc*, *73*: 163-166.

Hanif, I., Raza, S. M. F., Gago-de-Santos, P., & Abbas, Q. 2019. Fossil fuels, foreign direct investment, and economic growth have triggered CO2 emissions in emerging Asian economies: some empirical evidence. *Energy 171*: 493-501.

Hernández-Rodríguez, A., Orlando, A., Montegrossi, G., Huet, B., Virgili, G., & Vaselli, O. 2021. Experimental analysis on the carbonation rate of Portland cement at room temperature and CO2 partial pressure from 1 to 51 bar. *Cement and Concrete Composites 124*: 104271.

Hu, L., Yang, H., He, Z., Chen, Z., Hu, J., & Zhang, S. 2022. Effect of rice husk ash on carbon sequestration, mechanical property and microstructure evolution of cement-based materials with early-age carbonation treatment. *Cement and Concrete Composites*, *133*, 104672.

Huang, H., Wang, T., Kolosz, B., Andresen, J., Garcia, S., Fang, M., & Maroto-Valer, M. M. 2019. Life-cycle assessment of emerging CO2 mineral carbonation-cured concrete blocks: Comparative analysis of CO2 reduction potential and optimization of environmental impacts. *Journal of Cleaner Production*, *241*, 118359.

IEA. 2021. *Global cement production in the Net Zero Scenario, 2010-2030*. IEA. Retrieved 29 August from https://www.iea.org/data-and-statistics/charts/global-cement-production-in-the-net-zero-scenario-2010-2030

Kaddah, F., Ranaivomanana, H., Amiri, O., & Rozière, E. (2022). Accelerated carbonation of recycled concrete aggregates: Investigation on the microstructure and transport properties at cement paste and mortar scales. *Journal of CO2 Utilization*, *57*, 101885.

Kamal, N. L. M., Itam, Z., Sivaganese, Y., & Razak, N. A. 2020. Carbon dioxide sequestered concrete. *International Journal of Integrated Engineering*, *12*(9): 45-51.

Kusin, F. M., Hasan, S. N. M. S., Hassim, M. A., & Molahid, V. L. M. 2020a. Mineral carbonation of sedimentary mine waste for carbon sequestration and potential reutilization as cementitious material. *Environmental Science and Pollution Research*, *27*, 12767-12780.

Kusin, F. M., Hasan, S. N. M. S., Hassim, M. A., & Molahid, V. L. M. 2020b. Mineral carbonation of sedimentary mine waste for carbon sequestration and potential reutilization as cementitious material. *Environmental Science and Pollution Research*, *27*(11): 12767-12780.

Kusin, F. M., Hasan, S. N. M. S., Molahid, V. L. M., Yusuff, F. M., & Jusop, S. 2023. Carbon dioxide sequestration of iron ore mining waste under low-reaction condition of a direct mineral carbonation process. *Environmental Science and Pollution Research 30*(9): 22188-22210.

Li, L., Poon, C. S., Xiao, J., & Xuan, D. 2017. Effect of carbonated recycled coarse aggregate on the dynamic compressive behavior of recycled aggregate concrete. *Construction and Building Materials*, *151*, 52-62.

Liang, C., Lu, N., Ma, H., Ma, Z., & Duan, Z. 2020. Carbonation behavior of recycled concrete with CO2-curing recycled aggregate under various environments. *Journal of CO2 Utilization*, *39*, 101185.

Lim, T., Ellis, B. R., & Skerlos, S. J. 2019. Mitigating CO2 emissions of concrete manufacturing through CO2-enabled binder reduction. *Environmental Research Letters*, *14*(11): 114014.

Lin, R.-S., & Wang, X.-Y. 2021. Effects of cement types and addition of quartz and limestone on the normal and carbonation curing of cement paste. *Construction and Building Materials*, *305*, 124799.

Lippiatt, N., & Ling, T.-C. 2020. Rapid hydration mechanism of carbonic acid and cement. *Journal of Building Engineering 31*, 101357.

Lippiatt, N., Ling, T.-C., & Eggermont, S. 2019. Combining hydration and carbonation of cement using super-saturated aqueous CO2 solution. *Construction and Building Materials 229*, 116825.

Liu, Z., & Meng, W. 2021. Fundamental understanding of carbonation curing and durability of carbonation-cured cement-based composites: A review. *Journal of CO2 Utilization 44*, 101428.

Lu, B., He, P., Liu, J., Peng, Z., Song, B., & Hu, X. 2021. Microstructure of Portland cement paste subjected to different CO2 concentrations and further water curing. *Journal of CO2 Utilization 53*, 101714.

Lu, Z., Tan, Q., Lin, J., & Wang, D. 2022. Properties investigation of recycled aggregates and concrete modified by accelerated carbonation through increased temperature. *Construction and Building Materials 341*, 127813.

Luo, S., Ye, S., Xiao, J., Zheng, J., & Zhu, Y. 2018. Carbonated recycled coarse aggregate and uniaxial compressive stress-strain relation of recycled aggregate concrete. *Construction and Building Materials*, *188*, 956-965.

Meng, D., Unluer, C., Yang, E.-H., & Qian, S. 2022. Carbon sequestration and utilization in cement-based materials and potential impacts on durability of structural concrete. *Construction and Building Materials*, *361*, 129610.

Milanova, I., & Kearsley, E. 2021. Potential for carbon dioxide sequestration in wet concrete mixes.

Mo, L., Yang, S., Huang, B., Xu, L., Feng, S., & Deng, M. 2020. Preparation, microstructure and property of carbonated artificial steel slag aggregate used in concrete. *Cement and Concrete Composites*, *113*, 103715.

Molahid, V. L. M., Kusin, F. M., Kamal, N. M. A., Hasan, S. N. M. S., Ramli, N. A. A., Abdullah, A. M., & Ashaari, Z. H. (2021). Carbon sequestration of limestone mine waste through mineral carbonation and utilization as supplementary cementitious material. *International Journal of Integrated Engineering*, *13*(1): 311-320.

Monkman, S., & MacDonald, M. (2017). On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete. *Journal of Cleaner Production*, *167*, 365-375.

Monkman, S., & Shao, Y. (2010). Integration of carbon sequestration into curing process of precast concrete. *Canadian Journal of Civil Engineering*, *37*(2): 302-310.

Mushtaq, F., Maqbool, W., Mat, R., & Ani, F. N. (2013). *Fossil fuel energy scenario in Malaysia-prospect of indigenous renewable biomass and coal resources* 2013 IEEE Conference on Clean Energy and Technology (CEAT):

Nath, S. K., & Dutta, R. K. (2010). Fluoride removal from water using crushed limestone.

Nedunuri, A. S. S. S., yar Mohammed, A., & Muhammad, S. (2021). Carbonation potential of concrete debris fines and its valorisation through mineral carbonation. *Construction and Building Materials*, *310*, 125162.

Nidheesh, P., & Kumar, M. S. (2019). An overview of environmental sustainability in cement and steel production. *Journal of Cleaner Production*, *231*, 856-871.

Owais, M., Järvinen, M., Taskinen, P., & Said, A. (2019). Experimental study on the extraction of calcium, magnesium, vanadium and silicon from steelmaking slags for improved mineral carbonation of CO2. *Journal of CO2 Utilization*, *31*, 1-7.

Owuamanam, S., & Cree, D. (2020). Progress of bio-calcium carbonate waste eggshell and seashell fillers in polymer composites: a review. *Journal of Composites Science*, *4*(2): 70.

Pan, X., Shi, C., Farzadnia, N., Hu, X., & Zheng, J. (2019). Properties and microstructure of CO2 surface treated cement mortars with subsequent lime-saturated water curing. *Cement and Concrete Composites*, *99*, 89-99.

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.

Qian, X. (2017). *In-situ production of calcium carbonate nanoparticles in fresh concrete using pre-carbonation method*. The University of Alabama.

Ramakrishna, C., Thenepalli, T., & Ahn, J. W. (2017). A brief review of aragonite precipitated calcium carbonate (PCC) synthesis methods and its applications. *Korean Chemical Engineering Research*, *55*(4): 443-455.

Ren, P., Ling, T.-C., & Mo, K. H. (2021). Recent advances in artificial aggregate production. *Journal of Cleaner Production*, *291*, 125215.

Russo, N., & Lollini, F. (2022). Effect of carbonated recycled coarse aggregates on the mechanical and durability properties of concrete. *Journal of Building Engineering*, *51*, 104290.

Ryu, H.-k., Heo, S.-s., & Kim, S.-c. (2017). Effect of carbonated water manufactured by a soda carbonator on etched or sealed enamel. *The Korean Journal of Orthodontics*, *48*(1): 48-56.

Salehi, S., Khattak, M., Ali, N., & Rizvi, H. (2016). Development of geopolymer-based cement slurries with enhanced thickening time, compressive and shear bond strength and durability. IADC/SPE Drilling Conference and Exhibition,

Shen, L., Gao, T., Zhao, J., Wang, L., Wang, L., Liu, L., Chen, F., & Xue, J. (2014). Factory-level measurements on CO2 emission factors of cement production in China. *Renewable and Sustainable Energy Reviews*, *34*, 337-349.

Shoji, M., Higuchi, T., Morioka, M., & Yokozeki, K. (2015). Inhibitory effect of alkali-silica reaction by the carbonation reaction. *Cem. Sci. Concr. Technol*, *69*(1): 504-510.

Shukla, P. R., Skea, J., Slade, R., Khourdajie, A. A., Diemen, R. v., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., & Malley, J. (2022). *Climate Change 2022: Mitigation of Climate Change* (Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Issue. I. P. o. C. C. (IPCC).

Soares, E. G., & Castro-Gomes, J. (2022). The role of biomass bottom ash in Carbonated Reactive Magnesia Cement (CRMC) for CO2 mineralisation. *Journal of Cleaner Production*, 135092.

Suescum-Morales, D., Fernández-Rodríguez, J. M., & Jiménez, J. R. (2022). Use of carbonated water to improve the mechanical properties and reduce the carbon footprint of cement-based materials with recycled aggregates. *Journal of CO2 Utilization*, *57*, 101886.

Summaries, M. C. (2021). Mineral commodity summaries. *US Geological Survey: Reston, VA, USA*, *200*.

Tang, B., Fan, M., Yang, Z., Sun, Y., & Yuan, L. (2023). A comparison study of aggregate carbonation and concrete carbonation for the enhancement of recycled aggregate pervious concrete. *Construction and Building Materials*, *371*, 130797.

Torrenti, J. M., Amiri, O., Barnes-Davin, L., Bougrain, F., Braymand, S., Cazacliu, B., Colin, J., Cudeville, A., Dangla, P., & Djerbi, A. (2022). The FastCarb project: Taking advantage of the accelerated carbonation of recycled concrete aggregates. *Case Studies in Construction Materials*, *17*, e01349.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British journal of management*, *14*(3): 207-222.

Wang, F., Dreisinger, D., Jarvis, M., & Hitchins, T. (2021). Kinetic evaluation of mineral carbonation of natural silicate samples. *Chemical Engineering Journal*, *404*, 126522.

Wang, T., Huang, H., Hu, X., Fang, M., Luo, Z., & Guo, R. (2017). Accelerated mineral carbonation curing of cement paste for CO2 sequestration and enhanced properties of blended calcium silicate. *Chemical Engineering Journal*, *323*, 320-329.

Winnefeld, F., Leemann, A., German, A., & Lothenbach, B. (2022). CO2 storage in cement and concrete by mineral carbonation. *Current Opinion in Green and Sustainable Chemistry*, 100672.

Wu, Y., Mehdizadeh, H., Mo, K. H., & Ling, T.-C. (2022). High-temperature CO2 for accelerating the carbonation of recycled concrete fines. *Journal of Building Engineering*, *52*, 104526.

Xian, X., Logan, C., & Shao, Y. (2022). Dimensional stability of cement paste and concrete subject to early-age carbonation curing. *Materials and Structures*, *55*(3): 94.

Xian, X., & Shao, Y. (2021). Carbonation curing of concretes in a flexible enclosure under ambient pressure. *Journal of Materials in Civil Engineering*, *33*(4): 04021025.

Xian, X., Zhang, D., Lin, H., & Shao, Y. (2022). Ambient pressure carbonation curing of reinforced concrete for CO2 utilization and corrosion resistance. *Journal of CO2 Utilization*, *56*, 101861.

Xian, X., Zhang, D., Shao, Y., & Zhang, S. (2023). Evaluation of corrosion resistance of precast reinforced concrete subjected to early-age ambient pressure carbonation curing by accelerated impressed current method. *Journal of Sustainable Cement-Based Materials*, *12*(5): 592-608.

Xiao, J., Zhang, H., Tang, Y., Deng, Q., Wang, D., & Poon, C.-s. (2022). Fully utilizing carbonated recycled aggregates in concrete: Strength, drying shrinkage and carbon emissions analysis. *Journal of Cleaner Production*, *377*, 134520.

Xuan, D., Zhan, B., & Poon, C. S. (2016). Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. *Cement and Concrete Composites*, *65*, 67-74.

Yang, H., He, z., & Shao, Y. (2015). Early carbonation behavior of high-volume dolomite powder-cement based materials. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, *30*(3): 541-549.

Zajac, M., Skibsted, J., Bullerjahn, F., & Skocek, J. (2022). Semi-dry carbonation of recycled concrete paste. *Journal of CO2 Utilization*, *63*, 102111.

Zhang, D., Cai, X., & Jaworska, B. (2020). Effect of pre-carbonation hydration on long-term hydration of carbonation-cured cement-based materials. *Construction and Building Materials*, *231*, 117122.

Zhang, D., Li, V. C., & Ellis, B. R. (2018). Optimal pre-hydration age for CO2 sequestration through portland cement carbonation. *ACS Sustainable Chemistry & Engineering*, *6*(12): 15976-15981.

Zhang, D., & Shao, Y. (2016). Early age carbonation curing for precast reinforced concretes. *Construction and Building Materials*, *113*, 134-143.

Zhang, X., Luo, Y., & Yao, W. (2022). Research on the carbonation resistance of concretes containing dolomite powder. *Fullerenes, Nanotubes and Carbon Nanostructures*, *30*(12): 1221-1232.