www.ricuc.cl
LinkedIn Revista Ingeniería de Construcción

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

CO_2 mineralization in the production of sustainable concrete

Mineralización de CO2 en la producción de hormigón sostenible

De la Varga, Igor *; Sargam, Yogiraj ** [1]; Alexio, Daniel Martins ***

* Director of Applied Customer Solutions, CarbonCure Technologies, Florida, USA.
** Director of Research - Science, CarbonCure Technologies, Dartmouth, NS, Canada.
*** Latin America Business Director, CarbonCure Technologies, Sao Paulo, Brazil.

Fecha de Recepción: 11/09/2024
Fecha de Aceptación: 16/12/2024
Fecha de Publicación: 30/12/2024
PAG: 1-9

Abstract

As the concrete industry continues to grapple with the challenge of reducing its carbon footprint, CO_2 mineralization technologies offer a practical and scalable solution. These technologies enable the integration of CO_2 as a valuable raw material, transforming waste emissions into durable mineral compounds during the concrete production process. This study investigates the implementation of CO_2 mineralization in fresh concrete, analyzing its effects on key material properties such as strength and durability. Experimental results reveal that the process not only ensures equivalent compressive strength of concrete with a reduced cement content, but also contributes to reductions in embodied carbon compared to traditional methods. Furthermore, the study underscores the role of this approach in supporting the industry's decarbonization efforts, aligning with global sustainability goals. The findings highlight CO_2 mineralization as a pivotal step toward the creation of more sustainable construction materials, offering both environmental and economic benefits. These conclusions demonstrate the transformative potential of this technology in advancing the sustainability of concrete production while addressing the pressing demand for eco-friendly construction practices.

Keywords: Carbon Dioxide (CO_2); Mineralization; Concrete Decarbonization; Mineralization Technology; Concrete Properties.

Resumen

A medida que la industria del concreto enfrenta el desafío de reducir su huella de carbono, las tecnologías de mineralización de CO_2 ofrecen una solución práctica y escalable. Estas tecnologías permiten la integración del CO_2 como un valioso material primo, transformando las emisiones residuales en compuestos minerales duraderos durante el proceso de producción de concreto. Este estudio investiga la implementación de la mineralización de CO_2 en hormigón fresco, analizando sus efectos en propiedades clave del material como la resistencia y la durabilidad. Los resultados experimentales revelan que el proceso no sólo garantiza una resistencia a la compresión equivalente del hormigón con un contenido reducido de cemento, sino que también contribuye a reducir el carbono incorporado en comparación con los métodos tradicionales. Además, el estudio destaca el papel de este enfoque en el apoyo a los esfuerzos de descarbonización de la industria, alineándose con los objetivos de sostenibilidad globales. Los hallazgos subrayan la mineralización de CO_2 como un paso fundamental hacia la creación de materiales de construcción más sostenibles, ofreciendo beneficios tanto ambientales como económicos. Estas conclusiones demuestran el potencial transformador de esta tecnología para avanzar en la sostenibilidad de la producción de concreto mientras se aborda la creciente demanda de prácticas de construcción ecológicas.

Keywords: Dióxido de Carbono (CO_2); Mineralización; Descarbonización concreta; Tecnología de Mineralización; Propiedades del hormigón.

Corresponding author: ysargam@carboncure.com
Director of Research - Science, CarbonCure Technologies, Dartmouth, NS, Canada

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

1. Introduction

The global concrete industry is a cornerstone of modern infrastructure, contributing significantly to the construction of buildings, bridges, roads, and other critical structures. However, it is also one of the largest contributors to global carbon dioxide (CO_2) emissions, given that cement, its main constituent, accounts for approximately 7-8% of total anthropogenic CO_2 emissions (Chatham House, 2018). The production of cement is particularly carbon-intensive largely due to the calcination process, which releases large amounts of CO_2 (Schneider, 2012). As the demand for concrete continues to grow, particularly in developing countries undergoing rapid urbanization and infrastructure development, the industry's environmental impact has become a significant global concern.

In response to the urgent need to mitigate climate change, the concrete industry has embarked on several decarbonization initiatives. Many industry stakeholders are now committed to reducing their carbon footprints through a variety of approaches, including improving energy efficiency, adopting alternative fuels, and utilizing supplementary cementitious materials (SCMs) such as fly ash and slag. (Miller et al., 2018); (Marceauet al., 2007).

One of the most notable efforts is the development of industry-specific decarbonization roadmaps. For instance, the Global Cement and Concrete Association (GCCA) has launched the "2050 Net Zero Roadmap" (GCCA, 2020), which outlines a comprehensive plan for reducing carbon emissions across the cement and concrete value chain. This roadmap includes targets for reducing the clinker factor, increasing the use of SCMs, and implementing carbon capture, storage, and utilization (CCSU) technologies. Similarly, the European Cement Association (CEMBUREAU) has released its own "Carbon Neutrality Roadmap" (CEMBUREAU, 2020), which sets out ambitious goals for achieving carbon neutrality by 2050, emphasizing the need for innovation, collaboration, and policy support.

Among the various strategies to decarbonize the concrete industry, CO_2 mineralization presents a promising opportunity as a carbon utilization solution. CO_2 mineralization involves the chemical reaction of CO_2 with minerals in concrete to form stable carbonates (U.S. Geological Survey, 2024). This process not only reduces the amount of CO_2 released into the atmosphere but can also enhance certain properties of the concrete, such as its strength and durability. (Akerele and Aguayo, 2024); (Renforth and Campbell, 2023).

Several companies are developing materials and technologies that leverage CO_2 mineralization in concrete. In fact, a fully scaled technology already exists that mineralizes small amounts of CO_2 by injecting captured CO_2 into fresh concrete during mixing (CarbonCure Technologies, 2023). The injected CO_2 reacts with calcium ions in the cement to form nano-sized calcium carbonate minerals (Monkman et al., 2016). This not only sequesters CO_2 permanently within the concrete but also improves the cement hydration reaction efficiency, allowing for a slight reduction in cement content without compromising performance. The primary goal of the technology is to utilize CO_2 in concrete as a viable solution to decarbonize the industry, contributing to the broader effort to reduce global carbon emissions.

2. CO_2 mineralization

The interaction between CO_2 and mature (hardened) concrete has been a subject of study for several decades (Qiu, 2020); (Von Greve-Dierfeld et al., 2020); (Šavija and Luković, 2016); (Ashraf, 2016). It is widely recognized that CO_2 predominantly reacts with calcium hydroxide (or portlandite), one of the primary hydration products of cement, to produce calcium carbonate, typically in the form of calcite. This chemical reaction, commonly known as carbonation, differs somewhat from 'early carbonation', where CO_2 primarily reacts with calcium-containing compounds in the cement while the concrete is still in its fresh stage, rather than with hydration products like portlandite (Zajac et al., 2023). Carbonation occurring in concrete during the fresh stage is often referred to as mineralization, as CO_2 reacts to form calcium carbonate minerals that can positively influence the cement hydration process.

CO_2 mineralization in concrete has emerged as a focal point within the concrete research community and is increasingly garnering attention within the concrete industry (Zajac et al., 2022); (Driver et al., 2024). It is recognized as a fundamental method to reduce the carbon footprint associated with concrete production. The main effect of CO_2 mineralization in fresh concrete is the creation of in-situ nanoparticles of calcite much like adding any other nanotechnology in concrete. The primary advantage of producing in-situ nanoparticles is their superior dispersion throughout the concrete material. This contrasts with ex-situ nanoparticles, which necessitate special dispersion techniques to achieve similar dispersion levels (Monkman et al., 2022). The type of nanotechnology caused by CO_2 mineralization offers several beneficial effects in fresh concrete, the main one being the provision of additional nucleation sites for a better cement hydration reaction. In the case of calcite nanoparticles, which are

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

the main product formed when injecting CO_2 into fresh concrete, these nanoparticles can also react with alumina-based components to form additional hydration products, such as carbo-aluminates (Briki et al., 2021); (Lothenbach et al., 2008).

(Figure 1) shows a calcite nanoparticle created in a cement paste sample after injecting CO_2 as well as evidence of enhanced cement hydration from an isothermal calorimetry experiment where the heat released from the cement hydration reaction is significantly increased when CO_2 is added to a cement paste sample. The isothermal calorimetry test was performed with a Calmetrix iCal 8000 calorimeter. Fifty-gram samples of cement paste were placed in the calorimeter within 60 seconds of the conclusion of the mixing, and the temperature was set to 20 °C and the data was collected for up to 24 hours. The measured rate of heat (normalized to sample's cement content) was integrated to calculate the cumulative heat and is presented as the energy in (Figure 1b). Similarly, Scanning Electron Microscopy (SEM) images were obtained using a Hitachi S4800 field emission equipped with Si (Li) detector and ATW detector window. Before imaging, a dried cement paste sample was attached with double-sided conductive glue tape on an aluminum sample holder without any further conductive coating. The imaging was performed in secondary electron (SE) mode at 1.0-2.0 kV accelerating voltage.

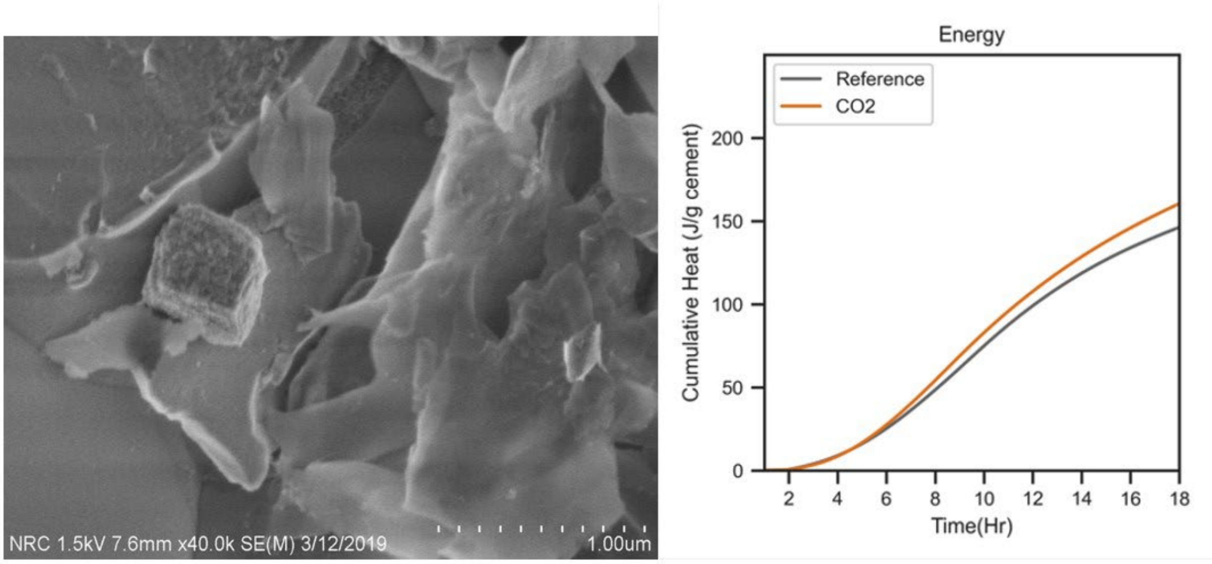

Figure 1. (a) Calcite nanoparticle formed from the CO_2 mineralization reaction within a cement paste sample, and (b) cumulative heat release measured using isothermal calorimetry means to evidence increased heat in a cement paste sample with CO_2.

3. Effect on concrete properties

As explained above, the main effect of CO2 mineralization is the enhancement of cement hydration efficiency (that is, improving the cement reaction with water). which is evidenced by the slight increase in heat being released in an isothermal calorimetry test. Heat increases of about 3 to 10% are commonly observed. This reaction not only permanently sequesters CO2 within the concrete material, but also allows for a safe, slight reduction in cement content in concrete mixes (i.e., up to 6%, based on actual numbers from concrete producers using an available CO2 mineralization technology in fresh concrete), further lowering the material's carbon footprint. From a strength standpoint, this cement hydration efficiency improvement guarantees an equivalent performance even with lower cement content, as conceptualized in (Figure 2). As observed, both CO2 doses 2 and 3 ensure equivalent strength performance in the mixes containing CO2 and a 3% cement reduction compared to the control. The 3% cement reduction was selected based on a slight increase in the measured heat release from the cement reaction and extensive field experience which indicates that this level of cement reduction does not compromise overall performance due to the enhancement in the cement reaction.

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

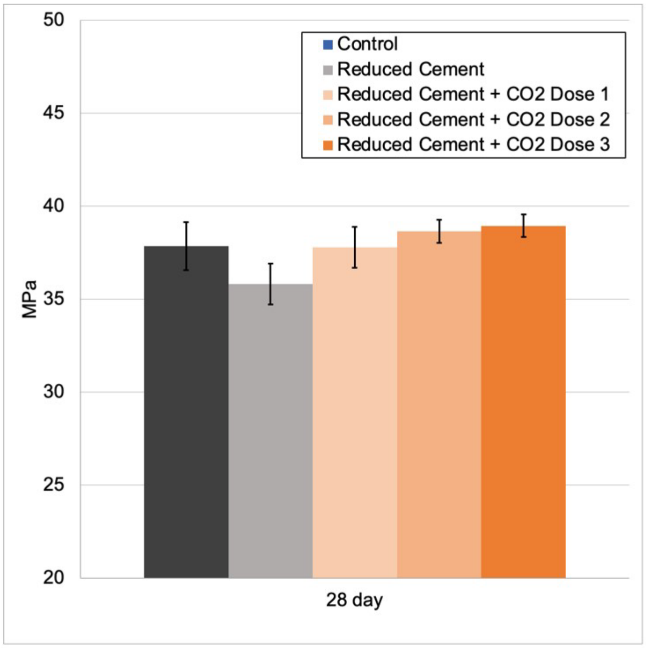

Figure 2. Equivalent strength obtained in a concrete mix with 3% less cement and mineralized CO_2 as compared to the same control concrete mix without CO_2 and cement reduction.

The introduction of CO2 into fresh concrete often raises concerns among producers and other stakeholders regarding its impact on various concrete properties, particularly durability. The following sections summarize the effects on key properties that directly influence the durability of the concrete material.

4.1 Effect on early age chemistry of pore solution

CO_2 mineralization in cementitious systems primarily involves the reaction of CO_2 with calcium-containing compounds in the cement, which can influence the pH and chemistry of the pore solution. These effects were evaluated by analyzing pore solutions extracted from both a reference cement paste, and a CO_2-mineralized cement paste during the first 3 hours of hydration. As shown in (Figure 3a), the pH of the CO_2-mineralized solution was approximately half a percentage point lower than that of the reference solution during the first 30 minutes of hydration. Afterward, the pH values became comparable. For reference, pH levels must drop significantly below 9 to pose any corrosion risk in steel reinforcement (Mehta, 2014). Similarly, the concentrations of calcium (Ca) and sulfur (S) were affected for the first 30 minutes (Figure 3b), while no significant impact was observed on the concentrations of alkalis (Na and K). These early-age effects of CO_2 mineralization are likely due to various multi-step dissociation processes (e.g., formation of carbonic acid, release of CO_3^{2-}, etc.) and cement dissolution-precipitation reactions, as detailed in this publication (Monkman et al., 2022). Overall, it can be concluded that CO_2 mineralization influences the pH and pore solution chemistry of the cementitious system only during the very early stages of hydration, with no long-term effects.

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

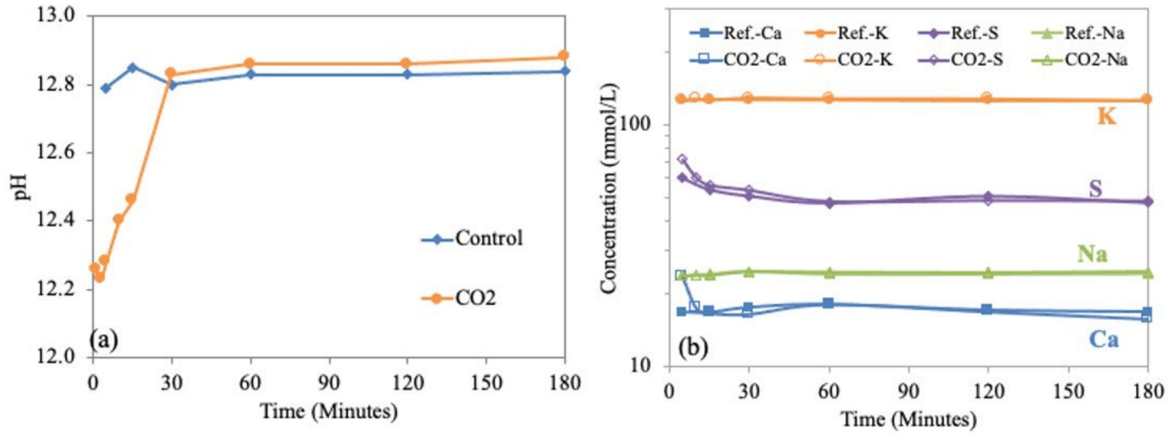

Figure 3. Effect of CO2 mineralization on early-age (a) pH and (b) elemental concentration of pore solution.

4.2 Effect on pore structure

CO_2 mineralization leading to the formation of calcium carbonate nanoparticles can alter the pore structure of cementitious systems, potentially affecting their mechanical properties and durability. To evaluate this effect, a mercury intrusion porosimetry (MIP) testing was conducted, (AutoPore V from Micromeritics), with the findings summarized in (Table 1). The results indicate that CO_2 mineralization leads to an approximate 2% reduction in total penetrable pore volume and a 14% decrease in average pore diameter, accompanied by an increase in pore surface area. These observations suggest a general trend of reduced porosity and refined pore structure due to CO_2 mineralization.

Table 1. Effect of CO2 mineralization on pore structure.

Cementitious System	Pore volume (%)	Avg. pore diameter (nm)	Pore surface area (m^2/g)
Reference	20.56	37.89	13.24
CO_2	18.45	32.73	14.78

4.3 Effect of durability

Durability of concrete is primarily dependent on its permeability and the alkalinity of the pore solution (Mehta, 2014). In this regard, a study was conducted to determine the effect of CO2 mineralization on durability of concrete through indirect test methods such as electrical resistivity and rapid chloride ion permeability (RCPT) on 56-day concrete samples. The results, presented in (Table 2), indicate that the pore solution pH of CO2-mineralized concrete is similar to that of the reference concrete. This suggests that CO2 mineralization does not increase the risk of depassivation of reinforcement bars and hence the risk of corrosion. Furthermore, the surface resistivity, bulk resistivity, and RCPT results demonstrate that CO2 mineralization does not significantly affect these properties, placing CO2-mineralized concrete in the same moderate permeability class as the reference concrete. For a detailed assessment of other durability aspects, such as shrinkage and freeze-thaw resistance, please refer to additional literature (Monkman et al., 2016), (Monkman et al., 2023).

Table 2. Effect of CO_2 mineralization on 56-day pore solution pH, electrical resistivity, and RCPT.

Cementitious System	Pore solution pH	Surface resistivity (kΩ.cm)	Bulk resistivity (kΩ.cm)	RCPT (Coulombs)	RCPT rating
Reference	13.83	11.43	6.48	2403	Moderate
CO_2	13.79	11.00	6.28	2785	Moderate

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

4. CO_2 mineralization technology

One of the main requirements demanded in new, sustainable materials and technologies is their cost and scalability. In this regard, a technology has been successfully scaled to offer CO_2 mineralization for industrial concrete production. It involves injecting small dosages of captured CO_2 into fresh concrete during mixing at the concrete plant, either into the central mixer or directly to the mixer truck, and without impacting the mixing cycle time. The technology is integrated with the existing batch operation system, just like any other chemical admixture for concrete; in this case, the technology acts as a dispenser for CO_2 automatically injecting the precise amount of CO_2 required for any given load. The CO_2 is dosed by weight of cement, which means that the actual amount of CO_2 that goes into any particular load can vary. This process is fully automated thanks to a pressurized CO_2 vessel installed right in the facility, a valve box that meters and controls the input of CO_2 into the mix and a control box in the plant's central command center. There is also a telemetry system that tracks data for reporting to allow the concrete producer to monitor and improve operations. (Figure 4) shows a schematic of the technology set up at the concrete plant.

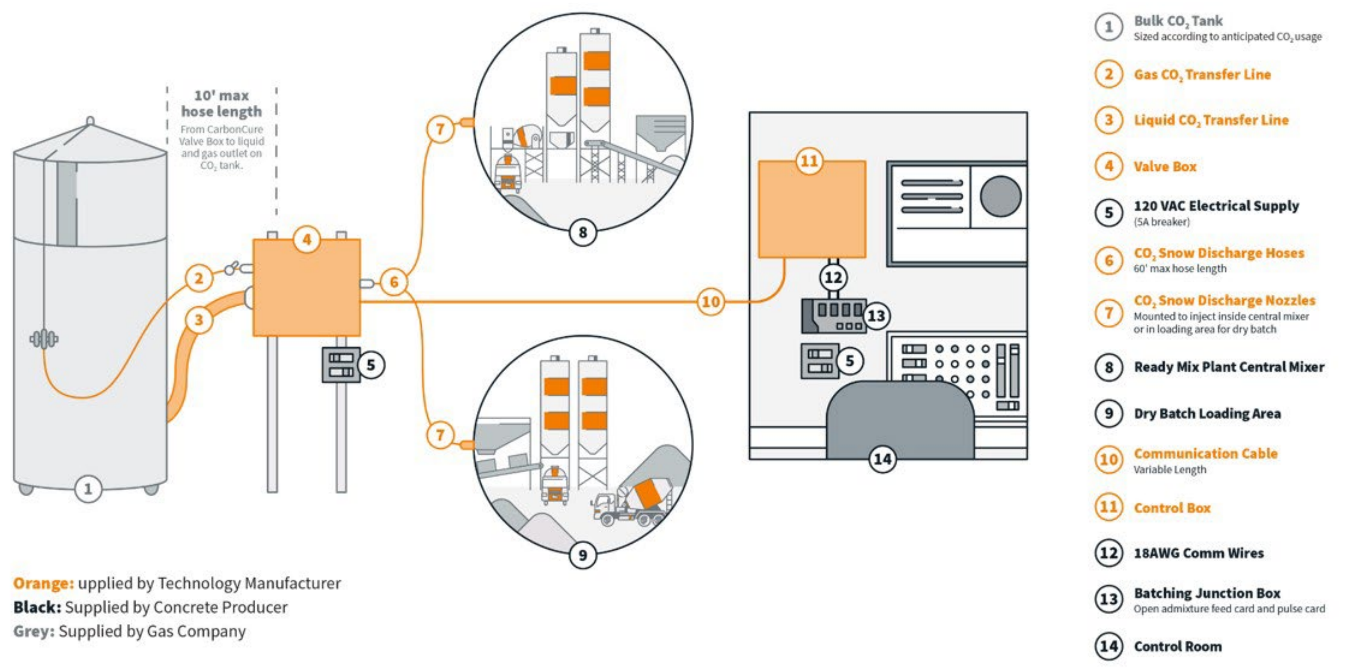

Figure 4. Schematic of CO_2 mineralization equipment setup at a concrete plant. In orange color, parts supplied by the technology manufacturer.

The CO_2 used by the technology is captured and commercialized by gas suppliers and consists of purified waste, biogenic CO_2, similar to what is commonly used in the carbonated beverage industry. It is typically transported in a liquid state. At the concrete plant, a pressurized tank stores the liquid CO_2. When injected, the CO_2 rapidly expands to atmospheric pressure, transforming into a snow-like material that settles into the concrete and mixes thoroughly. Carbon uptake efficiency values have been measured in concrete samples to be around 90% using a carbon-sulfur analyzer, where the total carbon content is measured and compared to a control sample without CO_2 mineralization (Figure 5).

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

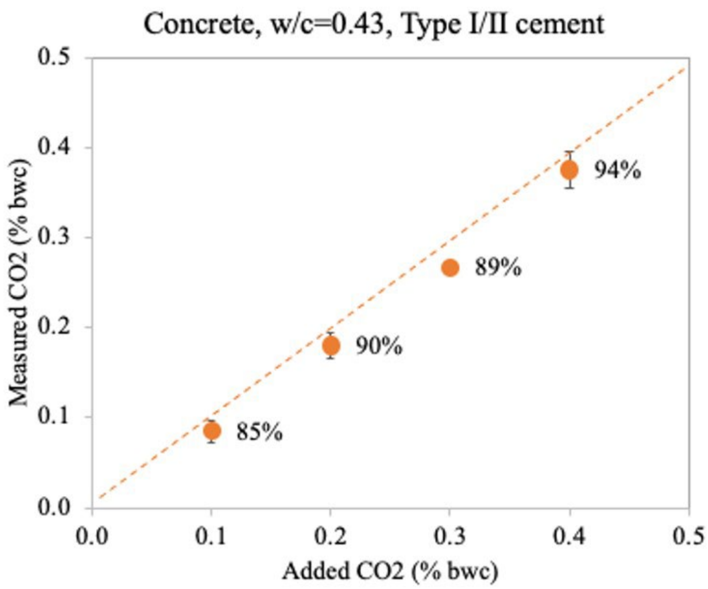

Figure 5. Carbon uptake efficiency measured using a carbon-sulfur analyzer methodology.

5. Final remarks

CO_2 mineralization has proven to be a highly effective method for reducing the carbon footprint associated with concrete production. By integrating this advanced technology into the concrete manufacturing process, companies can significantly enhance their sustainability practices. The process not only serves as a vital tool in mitigating the environmental impact of concrete production but also aligns with broader global initiatives aimed at achieving net-zero carbon emissions. As the construction industry faces increasing pressure to reduce its environmental footprint, CO_2 mineralization in fresh concrete offers a practical and scalable solution that contributes directly to climate action goals, demonstrating its value in creating a more sustainable built environment.

Even with the relatively low dosages of CO_2 used in fresh concrete mineralization, the sheer scale of global concrete production presents a significant opportunity for carbon sequestration. When this technology is applied across the vast volumes of concrete produced worldwide, the cumulative impact can be substantial. The process can lead to meaningful reductions in global CO_2 emissions, highlighting its potential to effect widespread environmental change. This scalability is crucial, as it underscores the ability of CO_2 mineralization to make a positive impact on a global scale, offering a tangible solution to one of the most pressing environmental challenges of our time.

CO_2 mineralization can be utilized in various stages of the concrete manufacturing process, not just in fresh concrete. For example, it can be applied in the treatment of Recycled Concrete Aggregates (RCA), where CO_2 can be absorbed and stored in the aggregates before they are reused in new concrete. This application not only enhances the sustainability of RCA but also contributes to the overall carbon reduction of the final concrete product. Furthermore, the technology can be extended to the treatment of Recycled Water (RW) used in concrete production, where CO_2 can be dissolved, further enhancing the sustainability and efficiency of the process. Additionally, CO_2 mineralization can occur in hardened concrete, providing opportunities for retrofitting existing structures or enhancing the durability and lifespan of new constructions through improved carbonation processes. These varied applications demonstrate the versatility of CO_2 mineralization and its potential to revolutionize the way we think about concrete production and its environmental impact. (Monkman and MacDonald, 2017).

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

6. Notes on Contributors

Igor De la Varga, Director of Applied Customer Solutions, CarbonCure Technologies, Florida, USA. **ORCID** https://orcid.org/0000-0003-4374-212X	**Yogiraj Sargam,** Director of Research - Science, CarbonCure Technologies, Dartmouth, NS, Canada. **ORCID** https://orcid.org/0000-0001-9980-3038
Daniel Martins Axelio, Latin America Business Director, CarbonCure Technologies, Sao Paulo, Brazil. **ORCID** https://orcid.org/0009-0002-7319-6350	

7. References

Akerele, D. D.; Aguayo, F. (2024). Evaluating the impact of CO_2 on calcium sulphoaluminate (CSA) concrete. Buildings, 14(8), 2462. https://doi.org/10.3390/buildings14082462

Ashraf, W. (2016). Carbonation of cement-based materials: Challenges and opportunities. Construction and Building Materials, 120, 558-570. https://doi.org/10.1016/j.conbuildmat.2016.05.080

Briki, Y.; Zajac, M.; Haha, M. B.; Scrivener, K. (2021). Impact of limestone fineness on cement hydration at early age. Cement and Concrete Research, 147, 106515. https://doi.org/10.1016/j.cemconres.2021.106515

CarbonCure Technologies. (2023). CO2 Mineralization in Concrete: An Overview. Retrieved from https://www.carboncure.com/technology-overview

Chatham House. (2018). Making Concrete Change: Innovation in Low-carbon Cement and Concrete. Chatham House – International Affairs Think Tank. https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete

Driver, J. G.; Bernard, E.; Patrizio, P.; Fennell, P. S.; Scrivener, K.; Myers, R. J. (2024). Global decarbonization potential of CO2 mineralization in concrete materials. Proceedings of the National Academy of Sciences, 121(29), e2313475121.

European Cement Association (CEMBUREAU). (2020, May). CEMBUREAU carbon neutrality roadmap. CEMBUREAU. https://cembureau.eu/policies-issues/carbon-neutrality-roadmap/

Global Cement and Concrete Association. (2020). 2050 net zero roadmap. GCCA. https://gccassociation.org/2050-net-zero-roadmap/

Lothenbach, B.; Le Saout, G.; Gallucci, E.; Scrivener, K. (2008). Influence of limestone on the hydration of Portland cements. Cement and Concrete Research, 38(6), 848–860. https://doi.org/10.1016/j.cemconres.2008.01.002

Marceau, M. L.; Nisbet, M. A.; VanGeem, M. G. (2007). Life cycle inventory of Portland cement concrete. Portland Cement Association. Retrieved from https://www.cement.org/

Mehta, P. K. (with Monteiro, P. J. M.). (2014). Concrete: Microstructure, properties, and materials (Fourth edition). McGraw-Hill Education.

Miller, S. A.; John, V. M.; Pacca, S. A.; Horvath, A. (2018). Carbon dioxide reduction potential in the global cement industry by 2050. Cement and Concrete Research, 114, 115-124. https://doi.org/10.1016/j.cemconres.2018.08.026

Monkman, S.; Cialdella, R.; Pacheco, J. (2023). Performance, Durability, and Life Cycle Impacts of Concrete Produced with CO2 as Admixture. ACI Materials Journal, 120(1), 53–62. https://doi.org/10.14359/51734732

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. https://doi.org/10.1016/j.jclepro.2017.08.211

Monkman, S.; MacDonald, M.; Hooton, R. D.; Sandberg, P. (2016). Properties and durability of concrete produced using CO2 as an accelerating admixture. Cement and Concrete Composites, 74, 218–224. https://doi.org/10.1016/j.cemconcomp.2016.10.007

Monkman, S.; Sargam, Y.; Naboka, O.; Lothenbach, B. (2022). Early age impacts of CO2 activation on the tricalcium silicate and cement systems. Journal of CO2 Utilization, 65, 102254. https://doi.org/10.1016/j.jcou.2022.102254

Monkman, S.; Sargam, Y.; Raki, L. (2022). Comparing the effects of in-situ nano-calcite development and ex-situ nano-calcite addition on cement hydration. Construction and Building Materials, 321, 126369. https://doi.org/10.1016/j.conbuildmat.2022.126369

Qiu, Q. (2020). A state-of-the-art review on the carbonation process in cementitious materials: Fundamentals and characterization techniques. Construction and Building Materials, 247, 118503. https://doi.org/10.1016/j.conbuildmat.2020.118503

Renforth, P.; Campbell, J. S. (2023). The role of carbonation in cement-based materials. PNAS Nexus. https://doi.org/10.1073/pnasnexus.2023.01234

Šavija, B.; Luković, M. (2016). Carbonation of cement paste: Understanding, challenges, and opportunities. Construction and Building Materials, 117, 285-301. https://doi.org/10.1016/j.conbuildmat.2016.04.138

ISSN: 0718-5073

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00134.21

Schneider, M. (2012). Emissions from the cement industry. State of the Planet. Columbia University Earth Institute. https://news.climate.columbia.edu/2012/05/09/emissions-from-the-cement-industry/

U.S. Geological Survey. (2024). Carbon mineralization. Retrieved from https://www.usgs.gov/science/carbon-mineralization

Von Greve-Dierfeld, S.; Lothenbach, B.; Vollpracht, A., et al. (2020). Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC. Materials and Structures, 53(6), 136. https://doi.org/10.1617/s11527-020-01558-w

Zajac, M.; Skocek, J.; Ben Haha, M.; Deja, J. (2022). CO2 mineralization methods in cement and concrete industry. Energies, 15(10), 3597. https://doi.org/10.3390/en15103597

Zajac, M.; Maruyama, I.; Iizuka, A.; Skibsted, J. (2023). Enforced carbonation of cementitious materials. Cement and Concrete Research, 174, 107285. https://doi.org/10.1016/j.cemconres.2023.107285

ISSN: 0718-5073