

CARBON DIOXIDE SEQUESTRATION FROM THE CONSTRUCTION INDUSTRY: A REVIEW OF TECHNOLOGIES, MATERIALS, AND PATHWAYS TO CARBON-NEGATIVE INFRASTRUCTURE

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Abstract

About 8% of the world's carbon dioxide released from the construction sector, mostly from the manufacturing of cement. With an emphasis on CO₂ mineralization in structural concrete, biochar-based enhancement materials, and alternate cement-based mechanisms, this paper summarizes current developments in carbon capture, utilization, and storage (CCUS) strategies across the construction industry. This analysis investigates the technological principles, performance consequences, economic viability, and environmental consequences of carbon sequestration solutions in structure materials using scientific research reported between 2020 and 2025.

1. INTRODUCTION

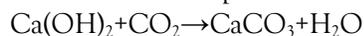
One of the industries with the highest carbon emissions worldwide is the building sector. The main binding component in construction, Portland cement, is responsible for around 8% of global anthropogenic CO₂ production; if the cement manufacturing sector were a nation, it would be the third most significant emitter after the United States and China [2-4]. With almost a global population of lacking suitable housing globally, the industry is under increasing pressure to decarbonize whereas satisfying expanding infrastructural requirements [5]. Three main approaches to CO₂ sequestration in construction are examined in this article: (1) CO₂ mineralization techniques for construction production; (2) the use of biochar as a carbon-free addition; and (3) the use of substitute cement-based substances and industrial by-products. Modern technical advancements, material performance attributes, and techno-economic evaluations are all included in the research.

2. CO₂ Mineralization in Concrete

2.1 Fundamental Mechanisms

One biomimetic method that speeds up natural weathering procedures is CO₂ mineralization. Stable calcium carbonate (CaCO₃) crystals are created when CO₂ is added to fresh concrete and interacts with calcium-based substances, mainly calcium hydroxide and calcium silicate hydrates (C-S-H) [6, 7]. In contrast to natural the carbonation process, which takes place in hardened concrete throughout long periods of time, mineralization happens at the fresh phase and is controllable [8, 9].

The chemical compound route could be summed up as follows:



According to Zajac et al. (2022), this procedure successfully functions as a nanoparticle's augmentation without the need for specific dispersing processes by producing in situ nano-calcite nanoparticles that act as nucleation sites for hydrated cement. In addition, strength enhancement can be achieved by these nanomaterials reacting with alumina-containing constituents to create carbo-aluminates [10].

2.2 Technological Implementation

2.2.1 Fresh Concrete Mineralization

CO₂ may now be injected completely into mixer vehicles or while mixed concrete at batch facilities through commercially available methods [11, 12]. Pressurized liquid CO₂ storage, controlled measurement and injection valves, and interaction with current batch control mechanisms are all components of the current framework. When liquid CO₂ is injected, it quickly grows to the surrounding air pressure, forming a substance that resembles snow and spreads throughout the mixture. According to carbon-sulfur analyser methods, capture of carbon performance approaches about 90% [13, 14]. According to De la Varga et al. [15], through improved cement hydration performance, this method allows for cement utilization decreases of up to 6% while keeping similar compressive strength. Increased hydration kinetics are confirmed by isothermal calorimetry, which shows improvements in heat released of 3-10% in mineralized mixtures.

2.2.2 Curing and Post-Curing Applications

Beyond the mineralization associated with fresh concrete, CO₂ could be added to reused concrete aggregate or throughout the rapid curing of precast pieces. According to Skocek et al. [16], mineralization of fines made from reused concrete offers a practical technique to sequester CO₂ while also enhancing the material's qualities. For periods longer than a millennium, the procedure produces strong minerals made of carbonate that effectively embed CO₂ inside the concrete composition.

2.3 Performance Implications

CO₂ mineralization improves several characteristics of concrete, according to the latest study: Mechanical Performance: Because of the microstructure's development and the creation of novel binding stages, carbonated concrete has a higher compressive strength. The interfacial transition zone is strengthened and capillary pores are filled by the nano-calcite materials.

Durability Features: By obstructing pore networks with calcium carbonate precipitation, carbonation lowers permeability. This improves resistance to freeze-thaw cycles, sulphate assault, and chloride intrusion. On the other hand, steel-reinforced buildings, high carbonation depth needs to be managed to avoid corrosion of the reinforcement.

Rheological Properties: Although dosage modification is necessary to avoid premature stiffening, the incorporation of small carbonate grains might enhance the workability and cohesiveness of fresh concrete.

2.4 Global Decarbonization Potential

A thorough evaluation of CO₂ mineralization capability in the concrete industry was carried out by Driver et al. [17], who came to the conclusion that broad adoption might considerably aid in worldwide

decarbonization endeavours. This strategy differs from transient carbon storage techniques in that mineralized carbon storage is permanent, lasting more than 100,000 years. The research investigation highlighted that stable calcium carbonate at Earth's surface circumstances guarantees long-term sequestration without requiring geological CCS inspection.

3. Biochar as a Carbon-Negative Construction Material

3.1 Production and Properties

According to oxygen-limited circumstances, biomass is thermochemically converted (pyrolysis or gasification) to form biochar. Organic waste is turned into a highly porous, carbon-rich substance with remarkable stability by this method. The feedstock type and temperature of pyrolysis have a major impact on the physical characteristics, which include specific surface area, pore volume, and size of particles distribution.

Important characteristics that are pertinent to use in building contain:

- Significant carbon concentration: long-term storage of 70–90% fixed carbon [18, 19].
- Alkaline pH: 6.5–10, suitable for cement-based construction [20, 21].
- Porous structure: Promotes nucleation sites and internal cures.
- Thermal stability: impervious to deterioration when exposed to the environment.

3.2 Carbon Sequestration Mechanisms

Biochar helps sequester carbon in a number of ways:

Direct Sequestration: For every tonne of biochar added to concrete, up to three tons of CO₂-equivalent that would otherwise be released due to burning or biomass breakdown are prevented. In the concrete base material, the carbon is still trapped in solid aromatic compounds.

Accelerated Carbonation: By facilitating carbonation processes, biochar-modified building material exhibits increased CO₂ absorption throughout curing. While preserving the alkalinity that propels the carbonation process, the porous biochar composition offers more surface area for carbonate formation.

Cement substitution: By substituting 5–10% of the Portland cement used by weight, biochar can lower the binder structure's carbon content.

3.3 Economic and Environmental Assessment

Commercial feasibility is demonstrated by Holcim's recent installation of the Climate Drive [22]. According to economic research, carbon credit schemes may compensate for costs even if the present cost of producing biochar is higher than that of traditional cement. For every tonne of biochar utilized, or three tons of CO₂ reduction, Canada's carbon credit scheme gives CA\$770. Biochar concrete can reach net-zero embodied carbon (cradle-to-gate) when properly made using recycled aggregates, according to life cycle studies.

Biochar during construction has a technology readiness level (TRL) of 9 (proved in an operating setting), where puts it ahead of several designed carbon dioxide extraction methods like accelerated weathering and direct air capture, that normally run at TRL 4–6 [23, 24]. At around \$179/t CO₂, price competitiveness is advantageous in comparison to the average of \$388/t for all CDR techniques.

4. Alternative Cementitious and Carbon-Negative Materials

4.1 Supplementary Cementitious Materials (SCMs)

An established decarbonization approach with growing sequestration capability is the partial substitution of industrial/agricultural products for Portland cement [25-28]:

Ground Granulated Blast Furnace Slag (GGBS): Superior pozzolanic response is provided by a substantial calcium silicate concentration, which also sequesters CO₂ via carbonation processes. Recent research shows that via improved mineralization, slag-based binders may absorb more CO₂ than Portland cement.

Agricultural Ashes: Using waste biomass streams, bagasse ash [29-31], wood waste ash, maize cob ash [32] and bamboo leaf ash have significant silica levels that promote pozzolanic reactions. When substituted for 20–30% of cement, these components can lower net CO₂ emissions by 15–20%.

Calcined Clays: In contrast to clinker generation, metakaolin [33-36] and calcined clay-limestone systems (LC³) provide 30–50% substitute for cement capability with lower calcination energy needs.

4.2 Alkali-Activated Materials (AAMs)

Fly ash, slag, and metakaolin are examples of waste from industries components that are activated by alkaline solutions to create alkali-activated products, such as geopolymers which makes geopolymer concrete [37-39] to produce sustainable environment. These mechanisms provide:

- A 60–80% decrease in embodied carbon as when compared to Portland cement.
- Improved durability and resilience to chemicals.
- The possibility of sequestering CO₂ by carbonating phases that include calcium Alkali-silica response vulnerability and long-lasting efficiency validation in field settings, however, continue to provide difficulties.

4.3 Magnesium-Based Binders

Developing options with inherent carbon sequestration potential include magnesium oxide (MgO) cements and magnesium silicate hydrate (M-S-H) structures. Compared to calcium-based mechanisms, the carbonation of magnesium hydroxide yields durable magnesium carbonate minerals with a greater CO₂ binding capability.

5. Techno-Economic and Environmental Assessment

5.1 Comparative Analysis of Sequestration Pathways

A thorough techno-economic analysis of CO₂ mineralization methods used the building industry was carried out by Abdelshafy et al. [40]. Three main methods were assessed in the analysis: (1) mineralization of concrete waste/recycled aggregates; (2) CO₂ curing of precast parts; and (3) CO₂ integrating in freshly mixed concrete. Significant findings show that:

- **CO₂ mixing** provides the maximum scalability with the least amount of capital expenditure.
- **CO₂ curing** required special curing chambers but offers higher sequestration efficiencies per unit of material.
- **Waste mineralization** produces added-value products while addressing end-of-life emissions.

5.2 CO₂ Source Considerations

The properties of the CO₂ feedstock are crucial for the environmental advantage of mineralization methods. The purification energy needs have a substantial influence on net sequestration advantages, according to life cycle evaluations comparing CO₂ from steel mill flue gas, biogas production, and ammonia manufacturing waste streams. Although it takes longer reactivity durations, direct use of diluted CO₂ streams (10–20% concentration) eliminates energy-intensive purification.

7. Conclusions

Over the recent past five decades, CO₂ sequestration from the building sector has developed from an experimental notion to a commercially viable technique. While biochar inclusion offers long-lasting elimination of carbon with complementary advantages for material characteristics, CO₂ mineralization in

concrete enables instant scalability with shown performance benefits. The toolset for decarbonization is expanded by the use of industrial byproducts and other cementitious approaches.

Opportunities for producing genuinely carbon-negative building components are presented by the confluence of several technologies: CO₂ mineralization, biochar inclusion, and sophisticated SCM compositions. Although in order to overcome standards gaps, financial obstacles, and scale-up hurdles, concerted activity across academic, policy, and industry sectors is necessary to realize this promise.

The building sector is at a turning point when the materials used to produce the contemporary world may be rethought as carbon sinks rather than sources. Technical answers are available, as the literature shows; the current challenge is to deploy them at the size and pace required by environmental goals.

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