REVIEW

CO$_2$ Capture in Construction Materials: Review of Uptake Approaches and Energy Considerations

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ABSTRACT: The construction industry is a significant contributor to global CO$_2$ emissions, and urgent innovation is needed to mitigate its environmental impact. This paper provides a comprehensive review of scalable approaches for CO$_2$ uptake in construction materials, including the injection of CO$_2$ into fresh concrete, the CO$_2$ curing of precast concrete, and the use of ceramics as CO$_2$ sinks. Among these three approaches, CO$_2$ curing methods for concrete represent the most advanced and widely adopted strategies within industrial practice, with substantial research supporting their effectiveness and scalability. The comparison of carbonation mineralisation across three distinct material groups reveals that the direct injection of CO$_2$ into fresh concrete mixes results in CO$_2$ uptake of less than 3 kg/m^3. For the precast concrete elements, the CO$_2$ uptake ranges from 30 to 350 kg/m^3, while ceramics can achieve uptake efficiencies up to 23 wt.% under pilot-scale conditions. Achieving efficient CO$_2$ uptake in fresh and precast concrete without compromising mechanical properties relies on precise control over the CO$_2$ dose, a tailored mix design, and optimised curing conditions, while avoiding excessive carbonation that could reduce alkalinity or durability. Valorisation of carbonated materials as supplementary cementitious components or aggregates is identified as an important circular solution, though further research is needed to address regeneration, performance, and standardisation. The review highlights ongoing gaps in life-cycle assessment and industrial-scale validation, and recommends future work on durability and techno-economic optimisation for robust decarbonisation in the cement and concrete industries.

KEYWORDS: CO$_2$ capture and storage; construction industry; cementitious materials; innovation in CO$_2$ uptake

1 Introduction

The cement industry accounts for approximately 8% of global anthropogenic CO$_2$ emissions, primarily due to limestone calcination (50%–60% of emissions), fossil fuel combustion for high-temperature processing (30%–40% of emissions), and electricity consumption ($\approx$20% of emissions). Meeting carbon-neutrality targets by 2050, in accordance with international climate commitments, requires emission reductions throughout the cement production chain from raw material extraction to the end-of-life of cement-based structures. In response, the cement industry has adopted multiple decarbonization strategies, including the partial substitution of clinker with alternative materials such as Supplementary Cementitious Materials (SCMs) [1,2], development of alternative binders such as Limestone Calcined Clay Cement (LC^3) [3,4], and

alkali-activated binders [5], and recycled cement [6]. Additional measures include the use of alternative fuels, the electrification of production processes [7,8], and the implementation of Carbon Capture and Utilisation (CCU) technologies [9]. Still, the urgent need highlights the demand for effective CO_2 sinks to mitigate carbon emissions from the cement industry. It is known that cementitious materials naturally absorb atmospheric CO_2 through slow carbonation reactions with hydrated cement phases [10]. The natural carbonation process starts at the exposed surface and gradually moves inward in a slow, diffusion-controlled manner [11]. Since the carbonated layer reduces CO_2 diffusion and limits the inherent carbonation potential of cement-based materials, the carbonation is initially restricted to a relatively thin layer near the exposed surface [12]. Therefore, the carbonation rate is insufficient to deliver a substantial reduction in emissions within the immediate timelines for achieving carbon neutrality [13]. Accelerated carbonation, by contrast, intentionally intensifies this reaction under controlled conditions, enabling rapid and considerable CO_2 uptake and positioning this approach as a practical short-term decarbonization pathway for the cement industry [14,15].

In this context, the present review aims to identify the most effective methods for CO_2 uptake using construction material, addressing the urgent need to reduce the cement industry's carbon footprint. CO_2 uptake using concrete with a specific focus on (i) CO_2 injection into fresh concrete and (ii) CO_2 curing of concrete will be evaluated. Additionally, the potential of ceramic waste materials as a considerable fraction of construction and demolition waste (CDW) in CO_2 sequestration will be assessed. Moreover, this review assesses the industrial adaptations required for each CO_2 capture technology, focusing on the process modifications needed for large-scale implementation while accounting for both technical and economic factors. The final goal and key innovation of this work is to identify sustainable, actionable strategies that can significantly reduce the environmental impact of cement production by integrating CO_2 absorption into the cementitious product throughout the value chain. It is worth noting that, among the three techniques evaluated in this review, the use of concrete for CO_2 capture is the most extensively investigated, whereas the other approaches are more recent and remain less explored.

2 Methodology of Literature Review

As mentioned previously, this work aims to identify the most effective methods for CO_2 uptake using construction materials, with a specific focus on CO_2 injection into fresh concrete, CO_2 curing of concrete, and CO_2 absorption by ceramic waste materials.

Therefore, first, the literature searches focused on the mechanism of CO_2 capture by cementitious materials. Then, advances in CO_2 capture using cementitious materials were explored to cover all innovative solutions in the field. Lastly, the industrial implementation of the three techniques was covered. The literature exploration was conducted using the Web of Science, Scopus, and Google Scholar databases, focusing on original research published between 2000 and 2025 that reported quantitative or qualitative data on CO_2 sequestration in cementitious materials, concrete, or ceramics. Search keywords included combinations of CO_2 capture, CO_2 curing, CO_2 uptake, CO_2 sequestration, CO_2 absorption mechanism, chemical absorption, CO_2 capture efficiency, cement industry, concrete industry, fresh mix, fresh concrete, concrete curing, and ceramic waste. As a result, a wide spectrum of references using CO_2 mineralisation methods has been retrieved for cementitious materials, including accelerated carbonation of aggregates, direct aqueous carbonation of industrial byproducts and waste, bio-mineralisation via microorganisms, end-of-life concrete carbonation, CO_2 capture and mineralisation by ceramics, especially via incorporating ceramic demolition waste into cementitious systems, and enforced carbonation during mixing. To follow the objective of this review, the inclusion criteria were studies that directly investigated cementitious or ceramic-based materials for CO_2 capture, sequestration, or curing. Exclusion criteria comprised works unrelated to

concrete/ceramics, unrelated to CO_2 capture, or lacking outcomes relevant to sequestration performance. After removing duplications, the initial search yielded a set of 350 documents linking to the subject. A two-step screening process was applied. First, titles, abstracts, and conclusions were screened for relevance. Second, an accurate classification process began, in which whole-text articles were assessed against the inclusion and exclusion criteria. A literature search using more specific keywords was repeated during the writing and revision processes whenever contradictory or unclear statements were encountered. This careful evaluation yielded a refined set of 129 research studies related to the topic; all published between 2000 and 2025. Of these, 62.5% were published between 2020 and 2025, 23% between 2015 and 2019, and only 7.5% between 2000 and 2014.

3 CO_2 Capture Using Concrete

As mentioned previously, cement and concrete can naturally absorb atmospheric CO_2 through slow carbonation reactions. CO_2 uptake by concrete over its service life contributes directly to the reduction of greenhouse gas emissions and, in theory, enhances material strength by decreasing porosity [10]. Nevertheless, according to research carried out in Nordic countries, it would take 100 years to store 33%–57% of the CO_2 emissions from cement production in the year 2003, by natural carbonation [16]. Therefore, forced carbonation technologies in which cementitious materials are exposed to elevated concentrations of CO_2 are considered a more viable approach to contribute to short-term climate change mitigation than natural carbonation and have a positive impact on reducing CO_2 emissions [17,18].
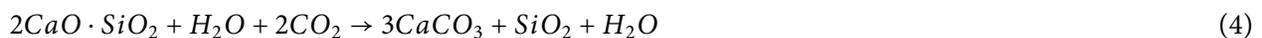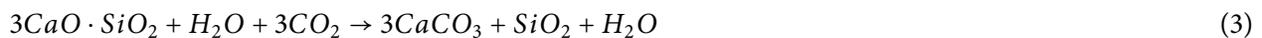
Two established pathways for utilising CO_2 as a feedstock in concrete are: (i) injection of CO_2 into fresh concrete during the mixing stage, and (ii) curing of precast concrete in a CO_2-rich atmosphere. In both processes, the gaseous CO_2 is diffused and dissolved into the alkaline pore solution. The dissolved CO_2 further hydrolyses to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, which then react with calcium ions (Ca^{2+}) released from hydrates into the pore solution and predominantly convert into solid calcium carbonate ($CaCO_3$). The carbonation of calcium hydroxide ($Ca(OH)_2$), which is generated during the hydration of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) phases in Portland cement shown in Eq. (1) [10].

$$CO_2 + Ca\left(OH\right)_2 \rightarrow CaCO_3 + H_2O \tag{1}$$
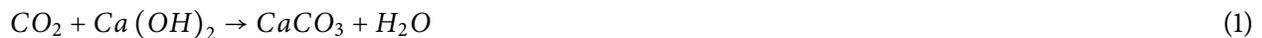
CO_2 can also react with calcium silicate hydrates (C–S–H), a primary product of cement hydration responsible for the strength and durability of concrete, forming silica gel according to Eq. (2) [16].

$$CO_2 + C - S - H \rightarrow CaCO_3 + SiO_2 + nH_2O \tag{2}$$

Likewise, CO_2 react with unhydrated C_3S and C_2S, resulting at formation of $CaCO_3$ and silica gel according to the Eqs. (3) and (4) [10].

$$3CaO \cdot SiO_2 + H_2O + 3CO_2 \rightarrow 3CaCO_3 + SiO_2 + H_2O \tag{3}$$
$$2CaO \cdot SiO_2 + H_2O + 2CO_2 \rightarrow 3CaCO_3 + SiO_2 + H_2O \tag{4}$$

It is worth mentioning that the reactions described by Eqs. (2)–(4) may adversely affect the mechanical properties of concrete, as the excessive precipitation of $CaCO_3$ within the pore structure may increase porosity or provoke the formation of microcracks. Moreover, early-age exposure to CO_2, when hydration is still in progress, can disrupt matrix development, restrict the formation of essential hydration products such as C–S–H, and lead to incomplete microstructural development [19,20]. Thus, precise control of parameters such as CO_2 partial pressure, temperature, relative humidity, exposure duration, and timing relative to

hydration is crucial to balance CO_2 uptake with material quality. The influence of these parameters will be addressed in detail in the following chapters, providing a framework for optimising CO_2 curing to maximise both environmental and mechanical benefits. Fig. 1 shows the schematic representation of the carbonation reaction in cementitious materials.
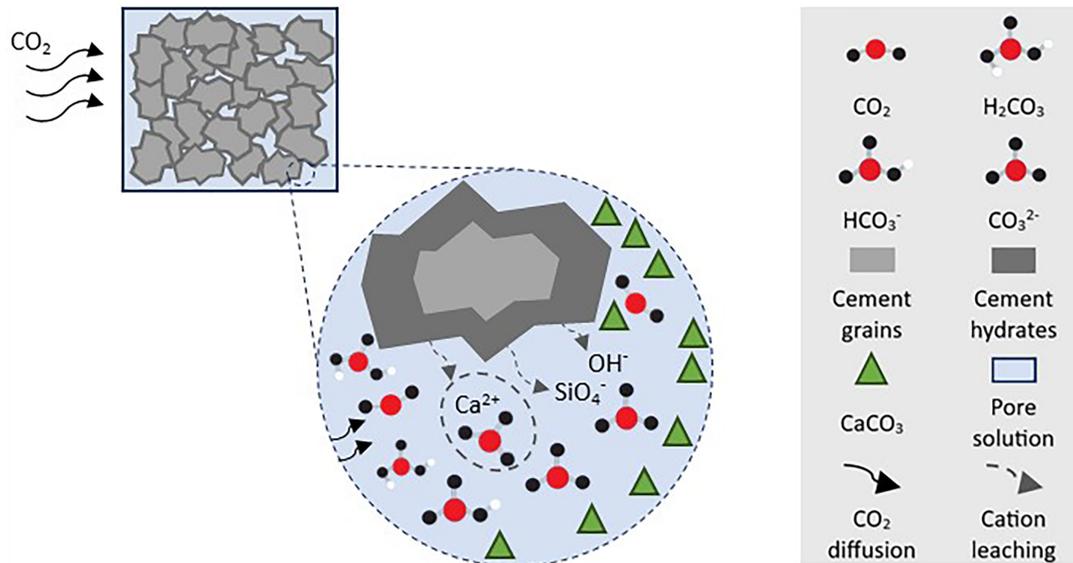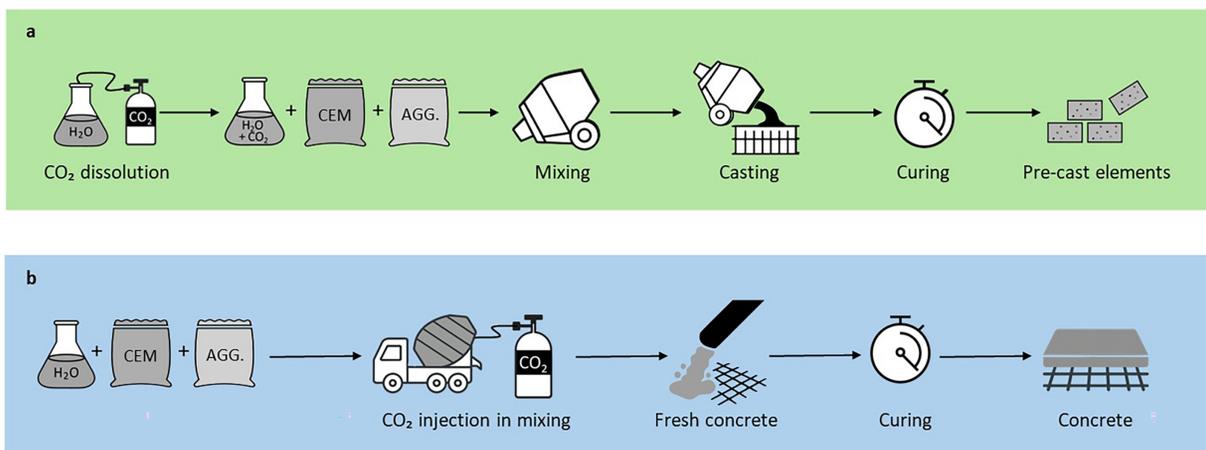

Figure 1: Schematic representation of carbonation mechanism in cementitious materials

3.1 CO₂ Injection into Fresh Concrete

CO$_2$ injection into fresh concrete or mortar during mixing creates a carbonating environment for cementitious materials. Continuous stirring of the fresh mix in the mixer enhances reagent interaction, facilitating more efficient CO_2 diffusion by eliminating porous solid barriers that form during $CaCO_3$ precipitation, thereby increasing the rate of CO_2 absorption [14]. To inject CO_2 into freshly mixed cement-based materials, the literature reports the use of carbonated water (Fig. 2a), in which CO_2 is initially dissolved in water, and then used to prepare the cementitious mixture [21,22]. Nevertheless, since CO_2 is poorly soluble in water, the expected CO_2 uptake by concrete is low, limiting the contribution of this approach to the cement industry's carbon neutrality. To compensate for the low CO_2 uptake by water, Kwasny et al. [22] and Fu et al. [23] added an extra CO_2 injection step, such as injecting CO_2 into a cement suspension or a concrete mix. However, the most common method involves injecting CO_2 directly into the cementitious mixture during the mixing stage (Fig. 2b) [24,25], resulting in the formation of amorphous nanocrystalline $CaCO_3$ [26].

The formation of these amorphous $CaCO_3$ accelerates the hydration reaction and increases the compressive strength [23,25]. The acceleration of the hydration reaction during CO_2 injection into fresh concrete has been explained through three key mechanisms: (i) the filler effect, (ii) the nucleation effect, and (iii) the chemical effect [26]. The filler effect involves rapid CO_2 mineralisation, producing fine $CaCO_3$ particles that occupy nano-scale pores in the concrete mix, improving microstructural density and potentially increasing durability. The nucleation effect occurs as these $CaCO_3$ particles provide additional nucleation sites for hydration products, such as C–S–H, thereby accelerating the development of early-age strength and hydration kinetics. The chemical effect involves CO_3^{2-} ions participating in cement hydration reactions, which results in a reduced calcium-to-silicon (Ca/Si) ratio within the C–S–H gel. Additionally, these CO_3^{2-} ions

promote the formation of carboaluminate phases through their reaction with aluminate-bearing components in the cement matrix [27]. When CO_2 dosage and timing are carefully optimised, these mechanisms collectively improve hydration efficiency, microstructural quality, and early strength, while reducing the overall carbon footprint of concrete production [26]. According to Zajac et al. [28] while only a small amount of CO_2 is stored in concrete (0.1–1 wt.%), the increased strength allows for a reduction in cement content [23,24,26], which indirectly reduces the carbon footprint of concrete production. Nevertheless, some contradictory results have been reported regarding the reduction in strength after CO_2 injection [29]. According to Zajac et al. [28] and Silva et al. [30], the carbonation of fresh concrete should sequester less than 1 wt.% of CO_2, as higher CO_2 uptake would negatively impact the hydraulic reactivity and performance of the hardened concrete [28,30]. The reasons for the low CO_2 uptake and negative effect on the mechanical properties in such technology have been discussed recently by Silva et al. [30]. Based on this study, low CO_2 absorption during mixing is attributed to the fact that, at this initial stage, the primary cement hydration products, particularly $Ca(OH)_2$, which is the most reactive with CO_2, are not yet formed in significant quantities. As a result, freshly mixed concrete primarily contains unhydrated clinker phases with limited direct reactivity toward CO_2. The same authors explain that the reduction in mechanical properties observed when CO_2 is injected into fresh concrete is related to changes in cement hydration and particle morphology. Exposure of anhydrous cement to CO_2 in the presence of water accelerates the dissolution of small unhydrated particles (mostly C_2S), resulting in the complete consumption of a larger portion of the finer particles. This particle redistribution produces a coarser pore structure, which compromises the paste's early-age mechanical performance, although partial strength recovery can occur at later curing stages [30]. Therefore, the low CO_2 absorption of CO_2 injection into the fresh mix is the major drawback of this strategy.

Figure 2: Schematic representation of CO_2 injection into fresh concrete: (**a**) dissolution of CO_2 in water, and (**b**) direct injection of CO_2 into the fresh mix

Winnefeld et al. [31] reported the possibility of using the same approach to storing CO_2 in the concrete slurry waste. Concrete slurry waste generated during the cleaning of concrete mixers and trucks contains high levels of reactive calcium-bearing phases such as $Ca(OH)_2$ and partially hydrated cement, making it a suitable feedstock for mineral carbonation. This composition enables 12% CO_2 storage per solid content in concrete slurry waste ($\approx$0.8% CO_2 absorption in the liquid slurry) by converting these phases into stable $CaCO_3$. Winnefeld et al. [31] also reported that the carbonated concrete slurry waste was reused as a SCM, partially replacing Portland cement in new mixes and delivering dual benefits of permanent CO_2 immobilisation and reduced clinker demand, while also offering some improvements in hydration and early strength. Sim

et al. [32] reported that the supercritical CO_2 process demonstrated that near-complete carbonation of concrete slurry waste can be achieved rapidly ($\leq$30 min) at a solids content of approximately 5%, producing a stable, carbon-rich sludge that can be dried and blended into fresh concrete. Despite these advantages, both studies highlight a critical limitation: concrete slurry waste accounts for only 1%–3% of total ready-mix output, so while the process is technically viable and aligns with carbon-neutrality goals, its large-scale impact on cement-sector decarbonisation is constrained by limited feedstock availability [31,32]. Despite the low CO_2 uptake of CO_2 injection into the fresh mix as a major drawback of this strategy, commercialised technologies for this approach have been reported by CarbonCure [24,26].

CarbonCure ready-mix technology injects a precise amount of recycled CO_2 (captured from industrial operations) into fresh concrete during mixing, after approximately half of the cement and water contents have been discharged. The liquified CO_2, when injected into the mix, reacts with the cement compounds, forming nano-sized $CaCO_3$ particles that become permanently bound within cementitious material, allowing it to mineralise while preserving its properties [26]. Both CO_2 dosage control and the timing of CO_2 injection are key factors in CarbonCure's success in CO_2 injection into the fresh mix, without compromising the mechanical properties or negatively affecting the high alkalinity required for steel reinforcement protection [26,33]. Using CarbonCure technology, the CO_2 uptake based on cement mass was approximately 1.4 wt.%. Overall, the technology is reported to save 7–11 kg of CO_2 per cubic meter (kg/m^3) of ready-mix concrete, 12–18 kg/m^3 of precast concrete, and 0.5 kg of CO_2 per 30 standard masonry blocks [34]. Additionally, Zhang et al. [16] and Monkman et al. [35] have been claimed that upon carbonation, the fast formation of nano-$CaCO_3$ results in the shorter initial setting of concrete by 40% and improves the 1- and 3-day strength by 14% and 10%, respectively. Nonetheless, at 28 days, CO_2 curing can reduce the compressive strength of concrete compared with conventional curing, as reported by Ravikumar et al. [36]. Therefore, this technology requires further in-depth investigation.

Monkman et al. [15] investigated the use of CO_2 injection into fresh-mix concrete (CarbonCure technology) with reduced binder content. Compared to a standard mix, the binder-reduced mixture exhibited lower compressive strength; however, this loss was offset when CO_2 was introduced during curing. The approach demonstrated that binder content can be lowered while preserving mechanical performance. In a large-scale implementation spanning over ten months, CO_2 was injected into approximately 130,000 m^3 of concrete, resulting in a 5% reduction in cement consumption. This reduction corresponds to savings of about 600 tonnes of cement and 530 tonnes of CO_2 emissions, without compromising performance.

There are also other commercialised solutions that use CO_2 in fresh concrete, such as Concrete 4 Change (C4C) [37]. C4C has developed an innovative technology for CO_2 uptake in cementitious materials by mineralising captured CO_2 from industrial flue gases using abundant waste calcium sources to create a reactive $CaCO_3$ additive. A low-cost, porous, granular absorbent material derived from waste streams such as recycled wood, glass, ceramics, and plastics is used as a CO_2 carrier. The CO_2 carrier is placed in an autoclave and loaded with CO_2, where the gases are absorbed. This approach turns waste into value, promotes a circular economy, and minimises the carbon footprint. These carriers are then added as an additive into fresh concrete mixes, without altering conventional production processes, resulting in a well-controlled carbonation of the concrete. The carrier slowly releases CO_2 inside the concrete for permanent mineralisation. This approach, which results in permanent CO_2 sequestration, increases concrete strength and reduces cement content by 20%–50%. Recent pilot projects and ongoing commercial development indicate strong scalability and cost-effectiveness. The technology distinguishes itself by enabling superior CO_2 uptake efficiency, broad compatibility with existing concrete types, and a circular production model, positioning it as a key industrial pathway to achieving net-zero targets in the construction sector. This technology is currently in the pilot trial phase and is expected to undergo a full-scale rollout by 2026–2027. The total emission savings are 50 kg of

CO_2 per cubic meter of concrete, while the concrete CO_2 emission (of this technology) of C4C concrete is 230.63 kg CO_2/m^3 [38]. It is worth mentioning that recently NEG8 Carbon, a company specialising in direct air capture, reported successful CO_2 uptake in wet mix concrete by injecting captured atmospheric CO_2 directly into fresh concrete during batching [39]. Table 1 summarises the main features of the CarbonCure and C4C technologies, including their TRL, key advantages and limitations, and commercial status.

Table 1: Summary of main features of the CarbonCure and C4C technologies (information extracted from references [35,39]

Technology / Aspect	CarbonCure	Concrete 4 change (C4C)
Technology readiness level	TRL 9 (fully commercial)	TRL 6–7 (pilot trials)
CO_2 savings per m^3 concrete	7–11 kg/m^3 (ready-mix)	≈50 kg/m^3 total emission savings
Cement reduction potential	≈5% demonstrated	20%–50%
Injection method	Direct injection during batching	CO_2-loaded porous carrier added as an additive
Key advantages	Precise dosage control; no process change	Circular economy model (waste-derived carriers); high compatibility
Key limitations	Limited CO_2 uptake (≈1.4 wt.%); requires further investigation	Not yet commercially proven; limited published durability data
Commercial status	Globally deployed; 130,000 m^3 (over 10 months)	Full-scale rollout targeted 2026–2027

3.2 CO_2 Curing of Pre-Cast Concrete

Carbonation curing of precast concrete under a CO_2-rich atmosphere is another approach to decreasing carbon footprint that has attracted the attention of the cement and concrete industries. The approach of CO_2 curing precast concrete is reported as a promising method for permanently storing CO_2 in concrete [24,28]. To date, carbonation curing of non-reinforced precast concrete under a CO_2-rich atmosphere is recommended [40]. In this approach, after mixing and casting, CO_2 is introduced into the concrete to accelerate curing (Fig. 3). It allows for rapid strength gain and has been shown to enhance product density and durability [16,41]. The rapid strength gain also enables the precast industries to achieve a high production turnover [42]. It is worth noting that carbonation curing is self-limiting, as the formation of a dense carbonated layer restricts further reaction. Even so, studies consistently report significant early-age benefits of CO_2-curing, compared to non-carbonated samples, although values typically converge by 28 days [40]. Similarly, another study reported strength improvements upon the CO_2 curing, ranging from 20%–100% at early ages and 5%–20% after subsequent 28-day water curing [28].
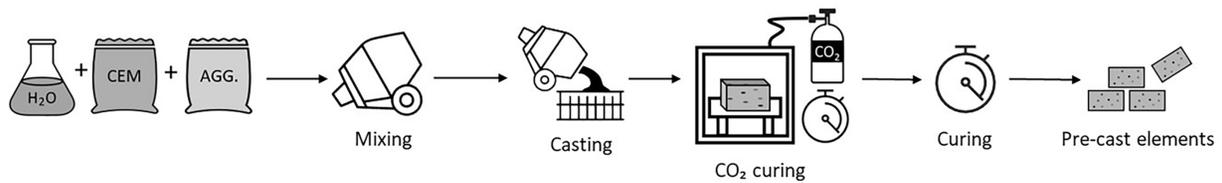
Figure 3: Schematic representation of CO_2 curing of pre-cast concrete elements

The CO_2 curing process can be performed in a closed chamber or flow-through system, where temperature, humidity, CO_2 concentration, and curing time need to be precisely controlled to maximise the carbonation reaction and ensure the quality of the final product [43]. The concrete mix design, e.g., water-to-binder ratio (w/b) [44] and aggregate particle size, is a crucial factor in the success of CO_2 curing [45,46]. In this respect, two types of precast materials, dry-mix and wet-mix, can be subjected to CO_2 curing. The carbonation curing process for precast concrete typically involves three stages: pre-conditioning, carbonation, and post-conditioning [47]. The pre-conditioning stage aims to reduce pore water content, thereby optimising CO_2 diffusion through the concrete matrix during carbonation, as saturated pores may hinder CO_2 penetration [17]. This step is usually performed at 20°C–25°C and 40%–60% relative humidity (RH) [17]. While pre-conditioning is a crucial step for wet-mix concrete to achieve optimum humidity and to balance hydration and carbonation reactions, it should be avoided for dry-mix concrete, as over-drying may cause water starvation, which inhibits the hydration process [16]. The low humidity level during carbonation is also a critical parameter, as the literature reports its negative effect on CO_2 uptake and carbonation rate in cementitious materials [16]. Additionally, pre-conditioning time is an essential parameter for the CO_2 curing of cement-based materials. As such, a wide range of curing conditions (wet, in mould, off mould, open air, and steam curing) and various curing durations (3–72 h) have been investigated in the literature [47,48]. Nevertheless, evidence suggests that CO_2 absorption is primarily governed by the degree of moisture loss, rather than by the duration of pre-conditioning [16].

During the carbonation stage, to accelerate hydration and promote early-age strength development, concrete is exposed to CO_2 under controlled conditions [47]. CO_2 concentration, curing time and temperature, RH, and pressure are crucial parameters that affect the CO_2 uptake of cement-based materials [49,50]. Literature reported on 25%–100% CO_2 concentration [44,51], 4–96 h of curing time, 23°C–95°C of curing temperature, 30%–90% RH [40,44], and 0.1–13.9 bar of CO_2 pressure [52] to maximise the CO_2 uptake by concrete. It is worth mentioning that, based on the literature, 50%–60% RH and room temperature are optimum conditions, which maximise carbonation efficiency [47,53]. In the post-conditioning stage, concrete is stored under controlled environmental conditions at 20°C–25°C and RH of 40%–95%, which allows further hydration of unreacted cement particles by consuming the remaining free water in the concrete, thereby stabilising concrete properties [51]. Nevertheless, most experimental studies kept the carbonated samples in a humidity-controlled chamber at 25°C and 95% RH for 27 days [51,54]. The study by Ravikumar et al. [36] reveals that the CO_2 uptake potential in CO_2 curing for precast concrete applications is significantly higher than that in CO_2 injection into fresh-mix concrete. For this reason, commercialised technologies for this approach have been reported by several companies, namely Solidia Technologies [55], Carbostone® [56], CO_2-SUICOM [57], CarbiCrete [58], Neustark [59], Carboclave [60], and Blue Planet [61]. These successful cases applied CO_2 curing technology in non-reinforced concrete prefabricated elements.

Solidia Technologies, headquartered in the United States, offers a patented process in which concrete is cured using CO_2 rather than conventional water/air curing. This technology has been applied to concrete masonry and paving units, enabling the permanent storage of CO_2 within precast products [16]. The

proprietary mix design and dedicated curing strategy have led to notable environmental and performance improvements. Specifically, the process enables lower production temperatures and approximately 30% less limestone usage, resulting in a 30% reduction in CO_2 emissions and a decrease in the overall carbon footprint of up to 50% [16].

Demonstrations and industrial-scale applications have shown that at least 0.2 tonnes of CO_2 can be absorbed per tonne of Solidia Cement, which is formulated with wollastonite and rankinite as principal alternatives to Portland cement, when used in precast concrete. For industrial deployment, Solidia has developed curing chambers with dimensions of 3.0 m × 6.0 m × 23.0 m [40]. The curing protocol involves exposing ground clinker and gypsum compositions to a controlled CO_2 atmosphere within these chambers. During the process, water is removed, and CO_2 is incorporated, facilitating strength development in less than 24 h and resulting in a significant improvement over the conventional 28-day hydration period [62]. The CO_2MENT project, a collaboration between LafargeHolcim, Solidia Technologies, and Svante, has established a demonstration unit at the Richmond Cement Plant in British Columbia. Using Svante's capture technology, CO_2 is removed from flue gas and injected into Solidia's curing chambers for mineralisation within precast concrete. Industrial pilots based on this process are underway in Canada [62], USA [60,61], Germany [59,62,63], France [62], and the UK [62], representing a significant advancement in CCU for cement production.

Carbstone®, developed through collaborative research initiated by VITO in Belgium in 2007, represents a leading example of industrial-scale CO_2 mineralisation for sustainable construction. The technology converts calcium-rich steel slag into cement-free building blocks [56,64]. Production involves compacting the slag into shaped products and curing them in autoclaves under elevated CO_2 pressure and temperature. During curing, reactive oxides convert into stable carbonates, permanently uptaking CO_2 and producing high-performance construction materials [56]. The resulting masonry products offer strength and durability comparable to conventional concrete. Carbstone® blocks are certified CO_2-negative and fully recyclable, and their commercial deployment with Environmental Product Declaration (EPD) validation demonstrates their suitability as an alternative to cement-based materials. Each block captures about 2 kg of CO_2, with an additional 2 kg avoided by eliminating cement-related emissions; a full truckload saves 6–7 tonnes of CO_2 compared to standard blocks, making the products carbon-negative over their lifetime. Steel slag feedstock is also widely available, with more than 40 million tonnes produced annually in the EU and several hundred thousand tonnes in Portugal [65,66].

In CO_2-SUICOM technology, an advanced concrete formulation enabling net zero or carbon-negative performance through the synergistic use of clinker substitution and accelerated carbonation curing [57,67,68]. In this process, Portland cement is replaced by more than 30 wt.% with a blend of industrial byproducts, such as ground granulated blast furnace slag (GGBFS) and a gamma dicalcium silicate (γ-C_2S) admixture, the latter synthesised from waste calcium hydroxide, which is calcined at significantly lower temperatures to substantially reduce process CO_2 emissions. The reactivity of γ-C_2S enables hardening through a direct reaction with CO_2 under controlled conditions. Under controlled CO_2-rich curing conditions, γ-C_2S rapidly reacts with CO_2 to form stable $CaCO_3$ phases, achieving approximately 50% conversion within 24 h. It is worth noting that C_3S exhibits a much lower affinity for direct carbonation, while it is primarily responsible for early strength development under standard hydration conditions in Portland cement [69]. Carbonation curing is conducted in chambers where temperature, RH, and CO_2 can be precisely regulated. Often, CO_2 is sourced from the exhaust of thermal power plants or generated by direct air capture technologies, with concentrations typically ranging from 10% to 20%. CO_2-SUICOM reported a mean CO_2 emissions reduction of 306–324 kg CO_2/m³ of concrete, resulting from both reduced cement usage and CO_2 uptake during curing, equivalent to a reduction of 18 kg CO_2/m³. CO_2-SUICOM exhibits

compaction and porosity characteristics comparable to those of conventional concrete and can meet the required flexural strength and durability specifications for infrastructure applications. Further enhancements in cost efficiency and scalability depend on optimising carbonation chamber operation and the logistics of high-purity CO_2 supply, with demonstration projects and life-cycle assessments indicating promising results for large-scale deployment across both precast and cast-in-place segments [57,68].

Another commercialised technology for CO_2 uptake using precast products is CarbiCrete [58]. It is a cement-free concrete technology in which steel slag serves as the binder once again. After mixing with aggregates and water, the fresh precast products are placed in curing chambers, where CO_2 at high concentration (often up to 100% CO_2 by volume) is introduced, reacting with the slag to form stable carbonates and driving strength development without the need for hydraulic cement. This process avoids the significant CO_2 emissions associated with Portland cement production and permanently mineralises up to 1 kg of CO_2 per standard block, resulting in overall reductions in global warming potential of 150 kg CO_2 per metric tonne of concrete. EPDs indicate that utilising CarbiCrete technology for masonry production results in carbon footprint values up to 20 times lower than those of conventional concrete masonry units. CarbiCrete's technology is already in commercial use at several North American and European precast facilities, demonstrating robust mechanical properties and durability while enabling scalable, permanent carbon sequestration in construction materials [58].

Carboclave, founded in Canada in 2016, has developed and commercialised an advanced CO_2 curing system for precast concrete products, including masonry and paving units [60]. The technology supports both retrofitting of existing low-pressure curing chambers and the construction of purpose-built autoclaves for high-pressure CO_2 curing. The system is fully automated, ensuring precise control of gas distribution, pressure, and safety for both adapting conventional installations and installing new high-efficiency units. Carboclave's technology enables up to a 50% replacement of cement with supplementary cementitious materials, resulting in a carbon footprint reduction of up to 70% compared to conventional units. It can durably sequester up to 250 g of CO_2 per standard 19 cm $\times$ 19 cm $\times$ 39 cm masonry block. Products fabricated with this system exhibit higher early-age compressive strength, enhanced resistance to freeze-thaw, sulfate attack, and efflorescence, as well as improved durability and reduced permeability [70]. Recent industrial deployments have confirmed Carboclave's commercial readiness, with ongoing full-scale operations and planned participation in the voluntary carbon credit marketplace through a verified third-party life-cycle assessment. User reports highlight consistent product quality, rapid curing, cost savings, and the successful 100% replacement of virgin aggregates with recycled materials in masonry units, all of which support the industry's shift toward low-carbon, resilient construction materials [16,60,71].

Recently, the properties and roles associated with the reuse of recycled aggregates, including carbonated recycled aggregates, have been extensively investigated and reviewed in the literature [72–74]. A comprehensive synthesis of these findings falls outside the scope of the present review and can be found in dedicated sources [75–77]. Nonetheless, it should be noted that, to date, two commercialised technologies have been reported for CO_2-curing recycled aggregates to mitigate CO_2 emissions in the construction industry.

As the most recent technology, Neustark has developed a commercial solution for CO_2 mineralisation in recycled concrete aggregates sourced from construction and demolition waste sites [63,78]. The company captures and liquefies CO_2 from regional biogas facilities and distributes it to nearby aggregate plants. At these locations, CO_2 is injected directly into recycled aggregates through a controlled, accelerated mineralisation process. This technique permanently binds CO_2 within the aggregate matrix, enabling its subsequent use in concrete production. Industrial trials and recent field deployments have demonstrated that this approach enables the permanent sequestration of up to 10 kg of CO_2 per cubic meter of produced concrete. In addition to this direct storage, further reductions in cement content are achieved, resulting

in total avoided emissions of approximately 20 kg CO_2/m^3 compared to conventional concrete mixtures. Performance monitoring and life-cycle assessments have demonstrated that this process produces durable, strong masonry products while reducing carbon emissions. Neustark is now expanding its technology across Europe, and it works well both for factory-made (precast) and site-made (ready-mix) concrete products [59].

In line with the Neustart technology, Blue Planet Systems (a US-based company) has developed a patented technology that captures CO_2 from a wide range of sources, including flue gases and direct air capture, and mineralises it into synthetic limestone aggregate for use in concrete. The Geomimetic$^{®}$ process permanently sequestrates CO_2 by combining it with calcium-rich industrial waste, such as cement kiln dust, steel slag, demolition concrete, and fly ash, producing durable construction materials. Unlike conventional CCU approaches that rely on purification, Blue Planet's method directly incorporates CO_2 into aggregate, making the process cost-effective and scalable. Concrete produced with this aggregate is certified as carbon-negative, and the CO_2 remains secured in the mineral structure even after demolition. Commercial deployment is underway, with facilities validating large-scale production and successfully integrating it into conventional concrete supply chains, thereby helping drive progress toward net-zero targets within the built environment [61,79].

It is worth mentioning that the influence of carbonation on the long-term durability of CO_2-cured concrete remains a subject of debate. Cai et al. [80] demonstrated that CO_2 curing can reduce drying shrinkage by 49%–53% in alkali-activated slag concrete through pore refinement and $CaCO_3$ precipitation. Similarly, Liu et al. [81] observed that carbonation curing not only reduces early-age shrinkage but also enhances long-term mechanical strength and durability in manufactured concrete. In contrast, Zhu et al. [82] and Xian et al. [83] reported that carbonation curing can increase dry shrinkage due to water consumption during CO_2 injection and the development of heterogeneous moisture gradients, which was attributed to the non-uniform distribution of carbonation products within the material. Additionally, Humad et al. [84] linked increased creep in carbonated alkali-activated systems to microcracking and decalcification of C–S–H gel, which coarsens the pore structure and reduces long-term dimensional stability. These divergent outcomes underscore that the net effects on shrinkage and creep are highly sensitive to curing parameters (pre-curing duration, curing temperature, relative humidity), water-to-binder ratio, binder composition (including activator type and MgO content), and the extent of carbonation. Accelerated carbonation generally improves resistance to chloride ingress and sulfate attack by densifying pores and forming a carbonate-rich surface layer that reduces permeability and pore connectivity. Rostami et al. [85] demonstrated that carbonation-cured concrete exhibited superior resistance to chloride permeability, sulfate attack, and freeze-thaw damage compared to conventional curing methods, while Su et al. [86] confirmed enhanced sulfate resistance through microstructure refinement. However, Mi et al. [87] identified a competing mechanism: carbonation releases previously bound chloride ions by decomposing chloride-bearing hydration products (Friedel's salt), thereby increasing the concentration of free chlorides available to initiate steel corrosion. This effect is particularly pronounced when carbonation penetrates beyond the protective surface layer into the bulk matrix. Additionally, prolonged or excessive carbonation that causes C–S–H decalcification can degrade sulfate resistance, as reported by Zhang et al. [88] in studies of fly ash concrete exposed to combined carbonation and sulfate attack. Nevertheless, the main durability challenge for carbonation-cured reinforced concrete is the rapid drop in pore solution pH from ≈13 to 8.5–9.5, which compromises the passive oxide film protecting the steel. Depassivation typically occurs at pH 9.4–10.0, depending on carbonate ion concentration and moisture conditions. Importantly, early-age carbonation applied only to the concrete surface (as in precast applications) can maintain core alkalinity above the threshold required for passivation, provided adequate cover depth is specified. Wu et al. [89] demonstrated that steel slag incorporation delays passive film formation but may sustain long-term passivity through controlled carbonation depth.

Xian et al. [54] reported that ambient-pressure CO_2-curing reduces rebar mass loss by approximately 60% and improves chloride resistance vs. conventional curing, attributed to the dense carbonate-rich surface layer that restricts ingress. Despite promising short-term results (typically <5 years), the long-term durability (>10 years) of carbonation-cured reinforced concrete under real-world exposure conditions remains insufficiently documented. Key uncertainties include: (i) the interaction between early-age accelerated carbonation and subsequent atmospheric carbonation over service life; (ii) performance under combined degradation mechanisms (carbonation + chloride ingress + freeze-thaw cycling); (iii) optimal carbonation parameters (depth, CO_2 pressure, curing duration) that maximize CO_2 uptake and mechanical performance while preserving adequate alkalinity for reinforcement protection; and (iv) the influence of SCMs on long-term alkalinity buffering capacity in carbonation-cured systems [81,90]. Field trials and accelerated aging tests that simulate long-term exposure are essential to validate laboratory durability predictions and develop performance-based guidelines for carbonation-cured structural concrete.

Table 2 summarises the main features of Solidia, Carbstone®, CO_2-SUICOM, crCrete, Carboclave, Neustark, and Blue Planet technologies, including their TRL, key advantages and limitations, and commercial status.

Table 2: Summary of main features of the Solidia, Carbstone®, CO_2-SUICOM, CarbiCrete, Carboclave, Neustark, and Blue Planet technologies (information extracted from references [45,55–58,60,61,65,78]

Technology / Aspect	Solidia	Carbstone®	CO₂-SUICOM	CarbiCrete	Carboclave	Neustark	Blue planet
TRL	TRL 7–8 (industrial pilots)	TRL 9 (commercial)	TRL 6–7 (demonstration)	TRL 9 (commercial)	TRL 9 (commercial)	TRL 8–9 (field deployment)	TRL 8 (commercial)
CO₂ Uptake	0.2 t CO₂/t cement	≈4 kg CO₂/block	306–324 kg CO₂/m³ (18 kg/m³ uptake)	1 kg CO₂/block	250 g CO₂/block	10 kg CO₂/m³	NA
Key Advantages	30% less limestone; 50% carbon footprint reduction; <24 h strength	Cement-free; 100% recyclable; EPD-certified; abundant steel slag	>30% cement replacement; γ-C₂S admixture; CO₂ from power plants/DAC	Cement-free; 100% CO₂ curing; 20× lower carbon footprint	50% cement replacement; 70% carbon reduction; freeze-thaw/sulfate resistance	Recycled aggregate; biogas CO₂; precast & ready-mix; 20 kg CO₂/m³ avoided	Multi-source CO₂ (flue gas, DAC); cost-effective; carbon-negative
Key Limitations	Custom mix design; large curing chambers (3 × 6 × 23 m); limited scale	Masonry-only; regional slag availability; autoclaves required	Carbonation chambers required; CO₂ supply logistics; pilot stage	Precast-only; high-purity CO₂ (100%); limited scalability data	High equipment cost; autoclaves required; precast-focused	Recycled aggregate only; regional biogas source	Aggregate-only; requires waste feedstock; supply chain integration

(Continued)

Table 2 (continued)

Technology / Aspect	Solidia	Carbstone®	CO₂-SUICOM	CarbiCrete	Carboclave	Neustark	Blue planet
Commercial Status	Pilots: Canada, Germany, France, UK (CO_2MENT)	Commercially deployed; EPD-validated	Demonstration projects; LCA promising	N. American & European facilities operational	Full-scale operations; carbon credit marketplace	Expanding across Europe	Commercial deployment; integrated into supply chains

4 Ceramic Waste Materials as a CO₂ Sink

In recent years, ceramic materials have been investigated as potential CO_2 uptake materials due to their favourable chemical composition and structural characteristics. As discussed previously, CO_2, when dissolved in water, forms an acidic solution that can react with basic alkali and alkaline-earth ceramics to form stable carbonates [91].

Therefore, researchers hypothesise that the alkali and alkaline-earth ceramics could be a potential material for CO_2 uptake [92,93]. The most studied ceramics include calcium and magnesium oxides (CaO and MgO, respectively), lithium orthosilicate (Li_4SiO_4), lithium metazirconate (Li_2ZrO_3), and sodium metazirconate (Na_2ZrO_3), which have demonstrated a capacity to capture CO_2 through adsorption or chemisorption mechanisms [91]. In the chemisorption mechanism, materials tend to be densified due to the formation of carbonation product layers (e.g., Na_2CO_3, Li_2CO_3) at the surface or interface, which can affect further CO_2 diffusion and uptake kinetics [94]. Sodium zirconosilicate (Na_2ZrSiO_5) [95], lithium silicates (e.g., Li_4SiO_4), and Na_2ZrO_3 are some examples of ceramics with the capacity of CO_2 sequestration by chemisorption [96].

Eqs. (5)–(7) demonstrate the reactions of CO_2 uptake through chemisorption with Na_2ZrO_3, Na_2ZrSiO_5, and Li_4SiO_4, respectively. In these reactions, the acid properties of CO_2 enable the extraction of an oxygen anion (O^{2-}) from the ceramic, forming the CO_3^{2-} anion, which further reacts with the alkali or alkaline-earth cation (Na and Li) to form the corresponding carbonate salt. It is worth noting that the temperature ranges for the CO_2 uptake of Na_2ZrO_3, Na_2ZrSiO_5, and Li_4SiO_4 are reported to be 400°C–800°C, 1000°C–1100°C, and 500°C–600°C, respectively [97,98].

$$Na_2ZrO_3 + CO_2 \rightarrow Na_2CO_3 + ZrO_2 \tag{5}$$

$$Na_2ZrSiO_5 + CO_2 \rightarrow Na_2CO_3 + ZrSiO_4 \tag{6}$$

$$Li_4SiO_4 + CO_2 \rightarrow Li_2SiO_3 + Li_2CO_3 \tag{7}$$

The process of CO_2 uptake begins at the ceramic material's surface, where CO_2 molecules chemically react with the surface, forming strong chemical bonds (surface chemisorption).

Ida et al. [99] and Venegas et al. [100] explained the process of CO_2 chemisorption in ceramics using a dual-shell model, which accounts for the biphasic kinetic behaviour observed in ceramic CO_2 uptake. This model describes two sequential stages: (i) a rapid, chemically controlled surface chemisorption phase, and (ii) a slower, diffusion-controlled uptake phase. Based on this model, CO_2 absorption begins at the ceramic surface, where CO_2 molecules react chemically to form a layer of carbonate species (e.g., Li_2CO_3, Na_2CO_3) through direct surface chemisorption. This initial stage is characterised by fast reaction kinetics, driven by the strong chemical affinity between CO_2 and surface oxygen anions. Activation energies for this phase are typically in the range of 50–100 kJ/mol, depending on the cation type and particle size.

In the second phase, as the carbonate product layer thickens, the rate-limiting step shifts from surface reaction to solid-state diffusion of CO_2 through the increasingly dense product shell. During this diffusion-controlled stage, lithium ions (Li^+) and carbonate ions must migrate through the Li_2CO_3 product layer and any remaining intermediate silicate phases (e.g., Li_2SiO_3), which are generally less permeable than the original oxide precursor. Experimental and theoretical studies using TGA, XRD, and *in situ* FTIR confirm the formation of two distinct carbonate regions: an outer layer consisting primarily of surface carbonates (often mixed Li_2CO_3/Na_2CO_3) and an inner layer composed of residual unreacted oxide or mixed oxide–carbonate material. This structural evolution directly influences CO_2 diffusivity by creating pathways that facilitate or, in some cases, hinder ion transport.

It is worth noting that several factors, including the active surface area, particle size, composition, pressure, humidity, and gas mixture composition, affect the CO_2 uptake of ceramic materials. Calcium oxide (CaO) is considered to have a high potential due to its balance between its reactivity and industrial scalability. Additionally, other lithium- and sodium-based ceramic materials also demonstrate potential for CO_2 uptake [101].

While chemisorption through ceramic materials has potential for CO_2 uptake, it is important to consider whether regeneration of the ceramic material is intended, as it requires significant energy due to the strength of the chemical bonds formed [91,102]. If regeneration is not intended, carbonated ceramics can be directly repurposed as functional additives, SCM, or aggregates in construction materials (Fig. 4). This valorisation pathway offers a practical and circular solution for carbon management in the construction sector [103,104].
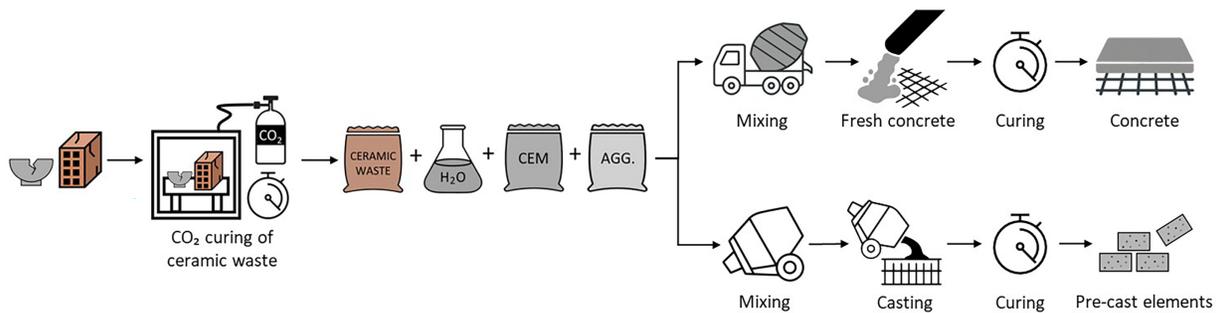
Figure 4: Schematic representation of CO_2 curing of ceramic waste and the possibility of re-utilising the carbonated waste in the construction industry
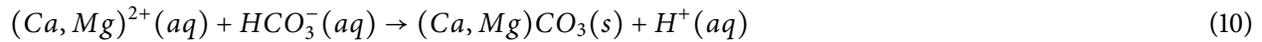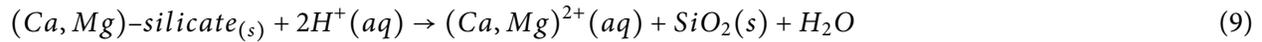
Ceramic materials can also capture CO_2 via adsorption. In this process, CO_2 molecules adhere to the surface of the ceramic material, forming weaker bonds such as Van der Waals or hydrogen bonds, making the process typically reversible. An example of this mechanism is represented in Eq. (8) [101].

$$Mg - O(s) + CO_2(g) \rightarrow Mg - O \ldots CO_2(ads) \tag{8}$$

Ramírez-Moreno et al. [101] reported that the adsorption temperature of CO_2 on ceramic materials is typically below 400°C for porous materials with a large surface area (e.g., Layered Double Hydroxides). In such a condition, a significant anion-exchange capacity of 2–3 milliequivalents per gram (meq/g) and optimal thermal stability can be achieved.

Recently, studies have focused on the potential of ceramic waste materials for CO_2 uptake. These ceramics contain a high concentration of calcium- and magnesium-silicates, which react with CO_2. The silicate framework facilitates ion exchange and carbonate formation. The ion exchange mechanism during

carbonation of silicate frameworks relies on the ability of the silicate mineral structure to release and replace cations. As mentioned previously, when CO_2 dissolves in water, it generates CO_3^{2-} and hydrogen ions (H^+). These ions can be replaced by divalent cations such as Ca^{2+} and Mg^{2+} within the silicate lattice. These released cations then react with CO_3^{2-} ions in solution to form stable mineral carbonates, such as $CaCO_3$ and $MgCO_3$ [105,106] (Eqs. (9)–(11)).

$$(Ca, Mg)-silicate_{(s)} + 2H^+(aq) \rightarrow (Ca, Mg)^{2+}(aq) + SiO_2(s) + H_2O \tag{9}$$

$$(Ca, Mg)^{2+}(aq) + HCO_3^-(aq) \rightarrow (Ca, Mg)CO_3(s) + H^+(aq) \tag{10}$$

$$(Ca, Mg)^{2+}(aq) + CO_3^{2-}(aq) \rightarrow (Ca, Mg)CO_3(s) \tag{11}$$

Martín et al. [107] investigated the carbonation of ceramic bricks surrounded by common clay (marl) in a hermetically sealed reactor. The experimental procedure involved maintaining a CO_2 pressure of 0.5 bar, a temperature of 23°C, and a solid-to-liquid ratio of 4:1 (wet carbonation) for 5 months. The results showed the formation of calcite as the main carbonated phase, with wollastonite and anhydrite as the principal phases transformed during the reaction. A maximum CO_2 sequestration of 10 wt.% was obtained under these conditions.

Afterwards, Martín et al. [108] conducted a similar study in a pilot-scale system to simulate the carbonation of ceramic waste bricks in a reclaimed quarry environment. The system was evaluated at 5, 7, 9, and 12 months, and the results showed a progressive increase in CO_2 uptake. After CO_2 exposure, CO_2 uptakes of 17 and 23 wt.% were reported at 5 and 12 months, respectively. Mineralogical analyses confirmed the transformation of wollastonite and the formation of calcite during the carbonation process. Microstructural characterisation indicated that macroporosity increased due to mineral dissolution by carbonic acid, while microporosity decreased due to the precipitation of carbonate phases. These findings demonstrate that ceramic brick waste is suitable for CO_2 uptake under the conditions examined [108]. No studies have been identified on the reuse of carbonated ceramic waste in cementitious materials. However, two notable projects in Italy have explored the material's potential for CCU within the ceramic industry.

The LIFE12 ENV/IT/000424 project, supported by the European Union and conducted in partnership with Ceramica Alta and the Department of Industrial Engineering at the University of Padova, aimed to mitigate CO_2 emissions from the ceramic firing process by implementing oxy-fuel combustion technology in place of traditional air combustion [109]. This modification altered the composition of exhaust gases, producing a stream of carbon dioxide and water vapour that facilitated the recovery and separation of CO_2. The recovered CO_2 was subsequently evaluated for reuse, including applications in greenhouse cultivation and the mineralisation of ceramic waste for recycling. The adoption of oxy-fuel combustion technology yielded notable benefits, including reductions in CO_2 and NOx emissions and lower energy consumption at the pilot scale. Additionally, tiles produced from recycled carbonated materials exhibited properties comparable to those of tiles produced by the conventional process [109]. A more recent project, Carbon Capture Storage and CO_2 Mineralisation for the Ceramic Industry (CCS4CER), launched in February 2024 and is coordinated by the Ceramic Centre of Italy [104]. The project objectives include developing approaches to separate CO_2 emissions and convert hazardous ceramic process wastes, such as spent lime, into carbonate-based products via mineralisation. The project also aims to optimise gas-liquid operating conditions to enhance the production of materials such as $CaCO_3$, CaF_2, and $CaSO_4$. CCS4CER further intends to validate the use of these synthesised materials in carbon-negative mortars and eco-cements, thereby supporting circular economy practices, while ensuring that all solutions are both energy- and cost-efficient to facilitate the transition of the ceramic tile industry toward climate neutrality. The CCS4CER project is investigating three primary approaches for CO_2 uptake in ceramic manufacturing: oxy-fuel combustion, which generates

a concentrated CO_2 and water vapor stream to facilitate separation; post-combustion chemical absorption, such as amine scrubbing, for removal of CO_2 from exhaust gases; and direct process integration, where captured CO_2 is utilized for mineralizing ceramic wastes through reactions that produce valuable carbonates and other compounds. To date, no specific outcomes have been reported from the project [104]. It is worth noting that, in addition to ceramic waste as an alkaline residue, other alkaline industrial by-products, such as air-pollution control residues, cement kiln dust, and municipal solid-waste incineration ashes, have also been utilised in CO_2 mineralisation processes, with some pathways already reaching commercial deployment. Among these, the most advanced is the accelerated carbonation technology developed by Carbon8 Systems (UK), which has achieved a Technology Readiness Level (TRL) of 8–9, signifying full commercial operation. In September 2020, Vicat implemented the first European cement-industry CO_2ntainer system at its Montalieu-Vercieu plant in France, where CO_2 from kiln exhaust gases is captured and reacted with bypass dust to produce a lightweight aggregate with thermal-insulating properties. This process permanently sequesters approximately 10–15 wt.% CO_2 as stable carbonates while simultaneously converting hazardous industrial residues into marketable construction materials. The technology is undergoing global scale-up following a 2021 partnership between Carbon8 Systems and FLSmidth, a major provider of cement-processing technologies. Notably, this pathway eliminates the energy penalty typically associated with sorbent regeneration, as the carbonated product serves as the final commercial material rather than an intermediate requiring thermal cycling [110]. This example illustrates that ceramic-based materials' carbonation technologies can successfully transition from laboratory research to commercial deployment through two principal innovations: (i) valorisation of carbonated products as SCMs or aggregates instead of regenerating sorbents, and (ii) seamless integration with existing kiln operations without the need for dedicated CO_2 capture infrastructure.

5 Cost of CO_2 Injection into Cementitious Materials

The costs associated with CO_2 injection in concrete production are highly variable and depend on several factors, including the scale of implementation, the origin and purity of CO_2, and the specific technology employed. A key cost component is CO_2 capture from industrial sources, which can be substantial and varies with the method used (e.g., amine scrubbing, membrane separation). Nevertheless, in line with legislative initiatives, near-term access to large volumes of captured CO_2 at reduced costs is expected to enhance the competitiveness of carbonation curing processes, thereby strengthening the competitive advantage of implementing them. Associated costs include capital investments for CO_2 injection equipment and retrofitting existing installations, as well as operational expenses related to CO_2 injection and system maintenance [16].

Additional expenses arise from CO_2 purification, compression, transportation, and storage [111]. Typically, pure CO_2 gas is used to accelerate diffusion. However, some studies aim to capture CO_2 directly from flue gas. The maximum CO_2 uptake will be strongly influenced by the CO_2 concentration (typically 20%–25% in cement plants) [112]. He et al. [113] investigated the carbonation of cementitious materials using flue gas. The lower reaction efficiency was observed due to reduced CO_2 concentration in flue gas. Nevertheless, the necessary strength was achieved in 5 h (using seven injection cycles), enabling CO_2 uptake of 5%–6%, with strength gains comparable to those achieved with pure CO_2 carbonation. Therefore, the study demonstrates the feasibility of connecting cement plants and concrete plants for effective CO_2 emission reduction through direct flue gas utilisation. It was not possible to obtain the specific investment and operating costs for CO_2 injection into fresh concrete. However, Monkman et al. [114] explored the use of CO_2 as an accelerating additive in the concrete mixing process, with CarbonCur*e*, comparing it to samples utilising a conventional accelerator (non-chloride accelerator). CO_2 injection expedites concrete setting

without compromising durability, offering a cost-effective alternative to chemical accelerators. In 2025, the escalated price of industrial CO_2 is approximately €508 per tonne, with per-truckload (8 m^3) expenses ranging from €0.64 to €3.76. By contrast, calcium nitrate costs €188 per tonne, and conventional non-chloride admixtures total €16.28-€32.56 per truckload. These findings confirm the economic advantage of CO_2-based acceleration under current market conditions.

Regarding CO_2 curing of precast products, operational costs are primarily related to controlling curing conditions, particularly during the pre-curing phase, when energy is required to maintain the desired humidity for optimal carbonation efficiency. Compared with conventional steam curing, CO_2 curing typically requires only about one-fifth of the energy demand [48].

Fortunato et al. [40] conducted a feasibility study on the implementation of CO_2 curing in the Brazilian concrete block industry. The proposed curing chamber had internal dimensions of 4.0 m × 4.0 m × 4.0 m, corresponding to a total volume of 64.0 m^3. To achieve chamber saturation, 52.94 m^3 of CO_2 were injected per cycle, equivalent to approximately 109 kg. Based on a daily production rate of 5760 blocks, corresponding to 126,720 blocks per month, distributed across six curing chambers, the total CO_2 demand was estimated at 654 kg per day. Under these conditions, the cumulative CO_2 consumption amounted to approximately 14,388 tonnes per month, assuming three curing cycles per chamber operating over an 8-h daily schedule.

Fortunato et al. [40] reported that a 2 h CO_2 curing cycle enables the sequestration of approximately 6827 kg of CO_2 per month. Accounting for Chemical Engineering Plant Cost Index (CEPCI) escalation to 2025, the capital investment for a new curing chamber is estimated at €9383 and retrofitting an existing unit costs €10,342. The higher retrofit cost primarily results from increased labour, additional insulation, and technical upgrades required for airtight CO_2 curing, often making retrofits less cost-efficient than new installations. Monthly CO_2 supply expenses, dependent on supplier distance, range from €2537 to €8458, contributing to a 4%–14% increase in the unit price of blocks. Direct utilisation of flue gas from cement plants may present a more economical alternative for CO_2 supply.

At a commercial scale, Wang et al. [115] implemented a retrofitted CO_2 mineralisation curing system in China, achieving an annual CO_2 sequestration capacity of 11 kton. After over 72 h of continuous curing, the concrete specimens reached a CO_2 uptake of 5.3 wt.% and a conversion efficiency of 98.97%. The process yielded an adjusted economic benefit of €31.65 per tonne of CO_2 and reduced the product's carbon footprint by 178 kg CO_2-eq/m^3, with approximately 65% attributable to direct CO_2 sequestration.

Commercialisation costs and production economics for novel CO_2 mineralisation concrete technologies exhibit significant variability. Solidia reports production costs comparable to or lower than those of conventional Portland cement, owing to process efficiencies such as rapid curing, lower energy requirements, and the elimination of steam autoclaving. After adjustment for CEPCI escalation and currency conversion, capital investment for initial pilot and demonstration facilities is estimated at €1.13 million and €0.44 million, respectively [116].

Carbstone®, utilising stainless steel slag in a high-CO_2 environment, requires an initial investment of approximately €540,000 (accounting for CEPCI escalation from 2004 to 2025) for curing chamber retrofits. However, it subsequently achieves product costs comparable to those of standard blocks, with further savings realised through full recyclability and avoided landfill charges [56,117]. VITO and Orbix have built Carbstone® pilot plants and commercial demonstration lines in Flanders and Wallonia, Belgium. These sources discuss operational success and market penetration but do not provide installation costs. Industrial articles note that residual materials, CO_2, and labour are the main cost factors, and emphasise lower raw material and energy costs (compared to conventional cement blocks), but capital investment is not disclosed [118].

CO_2-SUICOM has reached industrial scale in Japan by employing waste-derived binders and carbon credit incentives, resulting in competitive cost parity for precast applications; however, the main operational expenses remain in carbonation equipment and CO_2 procurement. Although specific capital expenditure figures for CO_2-SUICOM carbonation equipment remain proprietary and undisclosed, the technology has demonstrated competitive cost parity for precast applications through carbon credit mechanisms and substantial cement replacement (>50%) with waste-derived binders, thereby reducing operational expenses and enhancing economic viability [68,119].

Carbicrete has secured investments exceeding €19.2 million for commercial-scale-up, with production costs reported to match those of conventional concrete blocks following precast chamber retrofits and savings from eliminating cement [58].

Carboclave retrofits pressure vessels for CO_2 curing and claims lower costs than autoclave-cured blocks, primarily driven by energy savings, while the final retail price is generally at or slightly below the standard block price [120]. Neustark's process, implemented in Europe, involves sizable infrastructure investment (secured approximately €61.4 million for expansion), yet its cost per ton of CO_2 removed remains favourable in carbon markets, with the process typically incurring only a slight premium over recycled aggregate but benefiting from carbon removal revenues and project-scale investment. In summary, all technologies can achieve cost parity or an advantage where supportive carbon markets or material incentives exist, and major costs are concentrated in the initial process adaptation, curing equipment, or CO_2 supply [121].

Recent techno-economic analyses of CO_2 mineralisation using ceramic wastes have clarified several critical factors that determine feasibility and scalability. The concentration of CO_2 in ceramic kiln exhausts is lower than that in traditional power plants, resulting in higher capture costs and lower process efficiencies. However, integrating waste heat recovery and energy management, such as utilising low-temperature heat from kiln operations, can partially offset these challenges, improving the energy profile of CO_2 capture systems installed in ceramics manufacturing. Indirect carbonation methods, especially those employing pH-swing mineralisation, have been found to offer carbon efficiencies approaching 95% when acid and base recycling are optimised, with reported process costs ranging from €445 to €712 per tonne CO_2 under the best scenarios. In less favourable setups that lack integrated recycling or employ more energy-intensive process steps, the cost can rise as high as €1602 per tonne CO_2; the carbonate precipitation stage consistently represents the largest expense in these workflows [122,123].

The proximity and availability of suitable ceramic wastes for mineralisation are essential to minimise transportation and handling costs and support viable circular economy models. Techno-economic models consistently emphasise the importance of valorising products generated, such as precipitated $CaCO_3$ and $MgCO_3$, which can be utilised in carbon-negative mortars or incorporated into eco-cement formulations, thereby generating economic returns and offsetting process expenses. Nevertheless, upfront capital costs for large-scale deployment of CO_2 mineralisation plants in ceramics remain substantial, and technical obstacles, including slow leaching kinetics, efficient process integration, and reliable supply of reactive alkalinity, must still be adequately addressed. Overall, while the utilisation of ceramic wastes for CO_2 mineralisation is increasingly supported by life cycle and cost-benefit assessments, widespread implementation will depend on continued advances in process optimisation, product market integration, and policy incentives to overcome both technical and economic barriers [123,124]. It is worth noting that the reported value in this chapter was updated to 2025 using the CEPCI using Eq. (12):

$$Updated\ CAPEX = Historical\ CAPEX \times \left(\frac{2025\ CEPCI}{Historical\ CEPCI} \right) \tag{12}$$

6 Summary of Potential Approaches for CO_2 Uptake Using Fresh Mix and Precast Concrete and Ceramic Waste Materials

In this work, potential approaches for CO_2 uptake using construction materials were reviewed. The specific attention was paid to those technologies that directly inject flue gas or CO_2 captured and stored for further re-use from the cement and concrete industry. Based on the literature, CarbonCure and C4C are the most advanced commercialised technologies for purifying CO_2, either directly or indirectly (via CO_2 carriers), in fresh mix concrete. As shown in Table 3, the CO_2 uptake is permanent but of low quantitative significance. In turn, the novel technologies that inject CO_2 into precast products reported higher CO_2 uptake in their products. It is crucial to note that the CO_2 uptake or CO_2 avoided in most of these technologies was reported as the sum of CO_2 uptake and CO_2 emission avoided through the substitution of some part of cement or natural aggregates with industry by-products, wastes, or recycled aggregates. CO_2 curing in precast concrete achieves substantially higher CO_2 uptake compared to CO_2 injection into fresh concrete mixtures. This increase results from the optimised reaction conditions and extended exposure during precast curing, which enhance the mineralisation efficiency and lead to greater permanent sequestration of CO_2 within the concrete matrix.

Table 3: A summary of the commercialised technologies discussed in this review

Technology	Country developed	Year developed	Material used	CO_2 uptake/Avoided per production (kg CO_2/m^3 Concrete)	Uptake type	Reference
CarbonCure	Canada	≈2012	Portland cement-based concrete + injected gas-phase CO_2	1.0–1.5	Permanent mineralisation in the concrete matrix	[34,125]
C4C	UK	≈2020	Reactive calcium waste carrier + gas-phase CO_2	Up to 3.0	Permanent mineralization	[38]
Solidia	USA	≈2010–2012	Low-lime Solidia cement, gas-phase CO_2 curing	Up to 70% CO_2 reduction; ≈30–50	Cement replacement + permanent uptake	[116]
Carbstone	Belgium	≈2015+	Steel slag or calcium-rich waste, autoclave carbonation	350	Permanent mineralisation (slags, blocks)	[56,117]

(Continued)

Table 3 (continued)

Technology	Country developed	Year developed	Material used	CO$_2$ uptake/Avoided per production (kg CO$_2$/m^3 Concrete)	Uptake type	Reference
CO$_2$-SUICOM	Japan	≈2010+	Cement replaced w/industry byproducts + admixtures + CO$_2$ curing	324	Permanent + avoided (binder + matrix)	[57]
Carbicrete	Canada	≈2017+	Steel slag binder + gas-phase CO$_2$ curing (precast only)	80–150	Permanent mineralization	[58]
Carboclave	Canada	≈2017	Portland cement-based concrete in a pressurised CO$_2$ autoclave	100–180	Permanent mineralization	[43,71]
Neustark	Switzerland	≈2020	Demolition concrete aggregates, mineralisation with liquefied biogenic CO$_2$	20–100	Permanent (aggregate recycling)	[63,78]
Blue Planet	USA	≈2012+	Carbonated aggregate-synthetic limestone via CO$_2$ mineralisation	Up to 440	Permanent (aggregate only)	[61]

Recent research on ceramics as promising materials for CO$_2$ uptake in construction applications was also assessed. According to the literature, alkali and alkaline-earth ceramics, particularly those containing calcium, magnesium, or lithium, exhibit favourable chemical reactivity, enabling them to form stable carbonates by chemisorption at elevated temperatures. Both laboratory and pilot-scale studies demonstrate the capacity of ceramic waste to capture significant amounts of CO$_2$ via mineral carbonation, with capture efficiencies reaching up to 23 wt.% under optimised conditions. It is worth mentioning that the CO$_2$ uptake values reported in this review use multiple units (kg/m^3, wt.%, and % of theoretical maximum) to accurately reflect the diversity of measurement conventions established in the source literature. This variation reflects

differences in material form, experimental methods, and the distinct reporting practices of the chemical engineering and civil engineering communities.

Table 4 presents the commercialisation status and estimated implementation costs of the technologies reported in Table 3. Implementation costs for carbon utilisation technologies are drawn from recent industry reports and published literature, with values reflecting direct investments, operating expenses, and funding sources. CarbonCure operates under a licensing model that entails no upfront capital expenditure (CAPEX), as the equipment is provided through retrofit installations with no purchase costs for the client. All recurring expenses, including the annual supply of CO_2 and related operational activities, are classified as operating expenditure (OPEX). Based on updated industry data and the CEPCI for 2025, typical CO_2 supply costs now range from approximately €4700 to €18,800 per year. The market rate for delivered CO_2 is currently between €470 and €560 per tonne, reflecting recent pricing trends and escalation factors from the current CEPCI, which has increased slightly over the past year.

Table 4: A summary of commercialisation and the cost of implementation of technologies discussed in this review

Technology	Commercialisation (Status)	Cost of implementation (Pilot/Industrial)	Reference
CarbonCure	>300 commercial plants, global, rapid install	No upfront capital cost; monthly licensing fee (undisclosed); CO_2 cost ≈ €470–560/tonne for bulk supply (Australia); CO_2 supply for typical plant €4700–€18,800/yr at ≈1 kg/m^3	[34,125]
C4C	Large demo/pilot, scaling, market entry 2027	Pilot plant and development funded by €2.8–5.1 million in seed and grant funding; scale-up round of €5.67–11.34 million (2025–2026)	[126]
Solidia	Multiple US/EU pilots, precast focus	U.S. pilot: ≈€1.98 million project budget; no commercial CAPEX disclosed; SCM production pilot line cost undisclosed	[116]
Carbicrete	Licensing to precast, commercial launch	Pilot commercialisation project ≈€5.89 million at Patio Drummond (Quebec, 2021); typical precast retrofit cost not disclosed; uses absorption chambers and a control system	[58]
Neustark	20 EU plants, 50+ planned, expanding	Large-scale expansion funded by €64.75 million for 1 million tonne CO_2 removal capacity (2025); cost per tonne CO_2 removed not yet published for individual plant	[121]

(Continued)

Table 4 (continued)

Technology	Commercialisation (Status)	Cost of implementation (Pilot/Industrial)	Reference
Carbstone	Demo/industrial pilot sites	Industrial scale partners; individual autoclave and plant retrofit cost not published publicly-budget typical for precast upgrades, expect hundreds of thousands EUR per line (estimate, no precise figure)	[56,117]
CO_2-SUICOM	Industry pilot, infra-scale, Japan	No unit cost published; carbon-negative panel implementation at civil works; cost reductions via cement replacement; uses proprietary admixture	[57]
Carboclave	Commercial/retrofit, licenses available	Turnkey retrofit solution cost not published; typically involves curing chamber and gas system installation (estimate: several hundred thousand USD/EUR per system)	[120]
Blue Planet	Several large industrial partnerships	Large CAPEX required for aggregate production facility; plant-level costs not public, but aggregate production is industrial-scale with multi-million-dollar investments	[61]

C4C secured approximately €2.8 million in seed funding in January 2024, bringing the total investment to €5.1 million, including €1.7 million in UK government grants. The seed round, led by Zacua Ventures and Counteract with strategic investment from Siam Cement Group and Goldbeck, positions C4C for pilot-to-commercial scale-up and a planned Series A round of €5.67–11.34 million 2025–2026.

Solidia secured €1.97 million from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) in May 2022.

CarbiCrete's commercial plant retrofit was funded at €5.89 million through a partnership between NGen (€2.5 million) and industry partners Patio Drummond and Innovobot Labs (€3.39 million).

Neustark's expansion to a projected one million tonne annual CO_2 removal capacity by 2030 is supported by €64.75 million raised in June 2024 from Decarbonization Partners (BlackRock-Temasek), Blume Equity, and strategic partners. Carbstone, CO2-SUICOM, Carboclave, and Blue Planet have reported large-scale installations or partnerships; however, exact per-plant costs remain unpublished. Available figures and budgets are consistent with sector norms for industrial retrofit and project-scale deployment.

It is worth mentioning that despite the recent advances in CO_2 capture technologies in construction materials, the deployment of such a technology faces critical barriers that must be overcome to transition from laboratory demonstrations to widespread industrial implementation, particularly for CO_2 injection in fresh concrete mixes, CO_2 uptake by precast elements, and CO_2 utilization in ceramic waste systems.

CO_2 injection in fresh concrete faces fundamental challenges related to reaction kinetics and durability trade-offs. Insufficient CO_2 volumes result in unstable carbonate polymorphs, vaterite and aragonite, which transform to calcite. This conversion causes volume changes and cracking, weakening the concrete's long-term compressive strength. Maintaining mechanical performance while integrating CO_2 injection into high-volume industrial mixing requires precise control of injection parameters (flow rate, pressure, duration), which adds energy and capital costs and complicates economic feasibility. Furthermore, CO_2-induced carbonation interacts unpredictably with SCMs such as slag or fly ash; while these materials can enhance CO_2 uptake and refine pore structures at later ages, they may also coarsen early-age porosity, reduce early strength development, and complicate quality control [23,127].

Precast concrete carbonation benefits from controlled factory environments that enable higher CO_2 uptake through optimized curing protocols, yet scalability challenges persist. Achieving uniform carbonation depth across larger or thicker precast elements remains difficult, as CO_2 penetration is limited by the interplay between moisture content, relative humidity, and pore connectivity. Additionally, extending CO_2 curing to structural elements demands rigorous validation of durability performance, including resistance to chloride ingress, sulfate attack, and alkali-silica reaction (ASR), under service conditions [36,47].

Ceramic waste as a CO_2-binding material presents opportunities for dual circularity but faces reactivity and standardization gaps. Variability in ceramic waste chemistry (calcium oxide and reactive silica content), particle size distributions, and pozzolanic activity directly influences both the rate and extent of CO_2 uptake, with optimal performance typically requiring milling to reduce the particle sizes [128].

Three key barriers limit the deployment of all three technologies. First, standardized protocols for measuring CO_2 uptake are missing, making it harder to compare results and gain regulatory approval. Second, LCA and TEA often reveal that the energy needed to capture, transport, compress, and heat CO_2, especially from distant sources or requiring cryogenic cooling, can cancel out the gains from carbon sequestration [34,129].

7 Conclusions

This review critically examines recent advancements in carbon dioxide uptake technologies for construction materials, with a particular emphasis on methods offering feasible implementation and scalability to substantially mitigate CO_2 emissions from the cement industry. Innovation in this field has accelerated to address the pressing need to reduce the carbon footprint associated with cement and concrete production. Special attention is given to technologies targeting CO_2 uptake in fresh concrete mixtures and precast concrete elements, as these approaches offer the greatest practical potential for industry-wide adoption and impact. Recent innovations are summarised in comparative tables, highlighting critical metrics such as country of origin, CO_2 uptake per cubic meter, uptake mechanism, commercialisation status, and detailed implementation costs for each technology. The CO_2 uptake values for each technology presented in this review are as follows: CarbonCure achieves 1.0–1.5 kg CO_2 per cubic meter of concrete, C4C up to 3.0 kg/m^3, Solidia approximately 30–50 kg/m^3, Carbstone 350 kg/m^3, CO_2-SUICOM 324 kg/m^3, Carbicrete between 80–150 kg/m^3, Carboclave 100–180 kg/m^3, Neustark 20–100 kg/m^3, and Blue Planet up to 440 kg/m^3. These data reflect permanent mineralisation capacities reported under optimised operational conditions. In ceramics, the formation of stable carbonates through mineral carbonation can reach up to 23 wt.% in optimised laboratory and pilot studies. Cost data and deployment scales are provided where available, illustrating investment requirements and the current commercial reach of leading technologies. Despite significant progress, notable gaps remain, particularly in standardised life cycle assessments, long-term durability studies, transparent cost benchmarks at industrial scale, and protocols for quantifying permanent CO_2 sequestration. Future research and innovation must prioritize the synergistic integration of CO_2 uptake

through advanced SCM blends and tailored mix designs that maximize CO_2 uptake without compromising mechanical or durability performance. Developing robust, industry-ready carbonation protocols with harmonized measurement standards is essential to enable regulatory acceptance and cross-comparison of technologies. Scale-up efforts should focus on pilot-to-industrial transitions, including optimized supply chains, process automation, and cost-reduction strategies that leverage co-location of CO_2 sources with production facilities. For ceramic and other solid waste materials, advancing mechanistic understanding of activation pathways and particle engineering will be critical to achieving higher reactivity and consistent performance. Additionally, comprehensive durability testing under realistic service conditions, spanning chloride and sulfate exposure, freeze-thaw cycling, and ASR susceptibility is imperative to ensure that CO_2-enhanced materials meet or exceed conventional concrete benchmarks over decades-long service lives. By addressing these challenges through interdisciplinary collaboration, standardization, and rigorous benchmarking of LCA and techno-economic metrics, the construction sector can translate the substantial theoretical potential of CO_2 capture technologies into reliable, scalable, and economically viable pathways for decarbonization.

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