Journal of Building Engineering 97 (2024) 110904

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Innovative approaches, challenges, and future directions for utilizing carbon dioxide in sustainable concrete production

Dong Lu [a], Fulin Qu [b,*], Chao Zhang [a,**], Yipu Guo [b], Zhiyu Luo [c], Lei Xu [d], Wengui Li [b]

[a] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region*
[b] *Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, University of New South Wales, NSW, 2052, Australia*
[c] *Department of Civil and Environmental Engineering, National University of Singapore, 117576, Singapore*
[d] *Department of Civil Engineering, Tsinghua University, Beijing, 100084, PR China*

ARTICLE INFO

Keywords:
Carbon emission
Carbon capture, utilization, and storage (CCUS)
Carbonation
Low-carbon cement composites
Sustainable construction

ABSTRACT

Cement concrete presents a significant opportunity for carbon dioxide (CO_2) capture, utilization, and storage through carbonation treatment. This process involves carbonating binders, industrial waste materials, and recycled aggregate concrete, which can subsequently be integrated into fresh concrete mixtures. This review focuses on the current research landscape regarding the use of CO_2 in producing low-carbon and sustainable concrete, emphasizing developments over the past decade (2014–2024). The paper begins by outlining the properties of CO_2 and exploring its potential applications within the concrete industry. It then summarizes and compares the various carbonation methods applied to cement concrete and classifies the different approaches to CO_2 utilization in concrete production. Additionally, the review examines the carbonation mechanisms of binders and the development of low-carbon concrete, aiming to enhance the understanding of how carbonized components affect the performance of cement-based materials. Finally, the review explores typical commercialized technologies for CO_2 utilization in producing low-carbon concrete. The discussions and findings presented are anticipated to provide valuable insights into the application of CO_2 in the concrete industry, thereby facilitating the production of low-carbon and sustainable concrete.

1. Introduction

Amid burgeoning global industrialization and persistent dependence on fossil fuels, energy-related carbon dioxide (CO_2), a predominant greenhouse gas, has surged to over 370 billion tons, posing a formidable threat to global ecological equilibrium [1,2]. The adoption of Carbon Capture, Utilization, and Storage (CCUS) technologies emerges as a viable interim solution to curtail anthropogenic CO_2 emissions and to attain the ambitious target of carbon neutrality by 2050 [3–5]. Cement-based materials, the most extensively utilized man-made substances (e.g., cast-in-place concrete and precast concrete) [6,7], embody a substantial carbon footprint throughout their production and application processes [8–10]. Notably, cement manufacturing alone accounts for approximately 8 %

Abbreviations: CCUS, Carbon capture, utilization, and storage; SCMs, Supplementary cementitious materials; RCA, Recycled concrete aggregate; C-S-H, Calcium-silicate-hydrate; CH, Calcium hydroxide; RH, Relative humidity; CaO, Calcium oxide; MgO, Magnesium oxide; PC, Portland cement; NZE, Net-zero emissions; CUC, Carbon Utilization and Capture; ITZ, Interface transition zone.

* Corresponding author.

** Corresponding author.

E-mail addresses: Fulin.qu@unsw.edu.au (F. Qu), Chao-cee.zhang@polyu.edu.hk (C. Zhang).

https://doi.org/10.1016/j.jobe.2024.110904
Received 26 May 2024; Received in revised form 24 September 2024; Accepted 29 September 2024

of global CO_2 emissions [11,12]. Therefore, it is imperative to achieve substantial reductions in CO_2 emissions from concrete production.

Numerous tactics have been devised to reduce CO_2 emissions in the concrete sector [13,14]. To date, the most effective approach involves substituting cement clinker with supplementary cementitious materials (SCMs) [15–17], such as fly ash [18], silica fume [19], and slags [20] derived from industrial processes. This method is particularly impactful as CO_2 emissions from cement clinker production account for 70–85 % of the total CO_2 emissions in concrete manufacturing [11]. However, this strategy presents challenges, including diminished early-age strength of cement composites, certain durability issues, and the higher cost of some SCMs compared to cement worldwide, such as in China, America, Australia, etc., [21,22]. These limitations have hindered significant advancements in CO_2 reduction using this method. Moreover, the adoption of innovative cementitious binders, such as limestone calcined clay cement and alkali-activated cementitious materials, encounters obstacles related to raw material availability and cost [23–25]. Consequently, further research is imperative to overcome these barriers and to promote the widespread adoption of these techniques to reduce CO_2 emissions in the concrete industry.

Cement concrete presents a promising avenue for CCUS through carbonation treatment. This involves the carbonation of binders, industrial waste materials, and recycled aggregate concrete sourced from demolished structures, which can subsequently be incorporated into new concrete [26–29]. This technology has garnered substantial attention in recent decades due to its significant environmental benefits and can alleviate the depletion of natural aggregate resources [30,31]. The mineral CO_2 sequestration process involves a CCUS method, where CO_2 reacts with calcium-containing materials to produce calcium carbonates ($CaCO_3$) [32,33]. Naturally, due to the slow kinetics of carbonation reactions, the ability of cement composites to carbonate over their service life is typically limited [12,34,35]. To improve CO_2 sequestration efficiency, accelerated carbonation techniques have been developed and have seen substantial progress [36,37]. Optimal applications of accelerated carbonation include the pre-carbonation of industrial solid wastes before mixing and the early-age carbonation curing of cement composites post-mixing [38,39]. It is important to note that the hydration and carbonation processes of cement composites occur concurrently at early stages, resulting in a coupling effect between the two processes [40,41]. However, there remains a lack of comprehensive understanding and discussion concerning the carbonation process of various cement concrete components, the CCUS potential of different carbonation methods, and a detailed comparison of their impact on the performance of cement composites, particularly recycled aggregate concrete.

It is imperative to review and critically discuss the current knowledge regarding the utilization of CO_2 in low-carbon concrete production and to accelerate its practical application. The gaps in this field primarily stem from an insufficient exploration of two key challenges: a comprehensive and profound understanding of the carbonation mechanisms of CO_2 with concrete components; and the effects of carbonation treatment on waste materials, particularly the performance of recycled aggregate concrete. In this context, the review begins by introducing the characteristics of CO_2 and its potential applications in the concrete industry. It then summarizes and compares the different types of cement concrete carbonation and classifies the various approaches to CO_2 utilization in concrete production. Following this, the review delves into the carbonation mechanisms of binders and the development of low-carbon concrete to elucidate the impact of incorporating carbonized components on the performance of cement-based materials. Finally, it examines the typical commercialized technologies for CO_2 utilization in the preparation of low-carbon concrete. The discussions and conclusions in this work are anticipated to provide valuable insights into the use of CCUS in the concrete industry, thereby enabling the manufacturing of sustainable and low-carbon concrete.

2. Characteristics of CO2 and its potential utilization in sustainable concrete industry

The density of CO_2 is 0.00198 g per cubic centimetre, approximately 1.53 times that of air [42,43]. While CO_2 is indispensable for life, excessive accumulation poses severe threats to the Earth's climate [4,9]. As illustrated in Fig. 1, CO_2 is predominantly emitted through industrial activities such as power generation, transportation, and combustion processes in the mining and fossil fuel industries. Consequently, reducing CO_2 emissions from factories and enterprises through energy-saving and pollution-reduction technologies has emerged as one of the most pressing environmental challenges of the 21st century.

At moderate pressures (typically below 100 bar), CO_2 readily dissolves in water at molar concentrations, swiftly forming bicarbonate ions, hydrogen ions, and carbonate ions (HCO_3^-, CO_3^{2-} and H^+) [2]. As the pH decreases, this chemical process initiates optimal reactions and may interact with other phases in cement concrete, such as binders or aggregates, leading to the formation of various hydrates [44,45], which will be elucidated in the subsequent sections. This capability enables cementitious materials to act as a foundational medium for the absorption and utilization of CO_2.

Geological formations offer a vital avenue for the permanent storage of CO_2; however, achieving thorough decarbonization necessitates the full deployment of CO_2 capture technologies [40,46]. The rising interest among various stakeholders in utilizing CO_2 for diverse applications underscores a growing public fascination with this gas [47,48]. The first approach, non-conversion of CO_2, involves the storage of CO_2 in other materials and carbon capture/storage. The second approach, CO_2 conversion, utilizes CO_2 as a feedstock to create new products, effectively transforming it into versatile resources [3,4]. The potential products and services from CO_2 conversion mainly fall into five categories: fuels, chemicals, enhanced biological processes, extraction of construction materials from minerals, and carbonized waste [49,50]. Specifically, the use of CO_2 in the concrete industry not only achieves environmental protection but also generates economic benefits. The application of CO_2 in concrete production offers significant carbon sequestration potential and showcases a vast market opportunity estimated to be worth $400 billion [4,45,51]. Therefore, this review predominantly concentrates on exploring the latter two categories of CO_2 applications within the sustainable concrete industry.

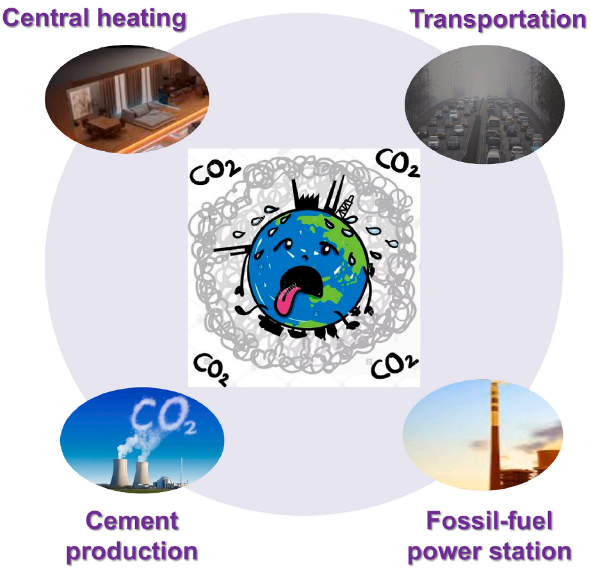


Fig. 1. CO_2 from industrially produced sources.

3. Carbonation treatment of cement concrete

3.1. Natural carbonation

Carbonation of cement concrete refers to a chemical process that can impact its structural integrity. When CO_2 infiltrates the concrete, it reacts with the alkaline substances present, forming carbonates and water [52–54]. This process, known as concrete carbonation or neutralization, results in a reduction of the concrete's alkalinity. If carbonation penetrates beyond the protective layer of the concrete and is exposed to water and air, the concrete loses its ability to shield the steel reinforcement, leading to the initiation of rusting. Concrete carbonation typically does not directly diminish its performance [55]. In fact, for plain concrete, carbonation can even enhance durability [56]. However, for reinforced concrete, carbonation lowers the alkalinity of the cement pore solution and increases hydrogen ion concentration, which compromises the protective effect on the steel reinforcement [57].

Following the hydration of cement grains, the primary strength-enhancing phase is the formation of calcium-silicate-hydrate (C-S-H), which constitutes approximately 60 % of the hydration products [58,59]. In the presence of CO_2, as depicted in Fig. 2a, the carbonation mechanism of C-S-H unfolds in three stages: 1) dissolution, 2) diffusion, and 3) a slowly ongoing reaction. Recently, Liu et al. [8] utilized a C-S-H@ZIF-8 (C-S-Z) sorbent for ultra-high CO_2 adsorption, as shown in Fig. 2b. Their findings indicated that C-S-Z possesses abundant pyrrolic nitrogen and an exceptionally high surface area of 577.18 m^2/g, enabling it to absorb CO_2 up to 293.6 mg/g.

Another crucial hydration product is calcium hydroxide (CH), which comprises about 20 % of the hydrates [60,61]. CH plays a vital role in maintaining the pH of the cement pore solution around 12.5, thus preventing the corrosion of low-carbon steel reinforcement [62,63]. Additionally, CH can react with CO_2 to form calcium carbonate, which can crystallize as calcite, vaterite, aragonite, or

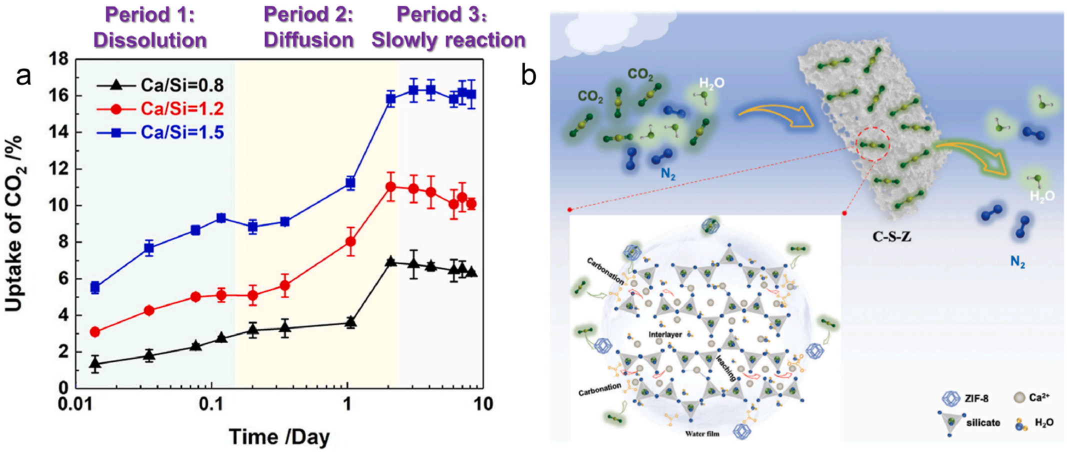


Fig. 2. Illustration of (a) changes of C-S-H during carbonation and (b) selective adsorption of CO_2 using C-S-Z adsorbent [8].

amorphous $CaCO_3$, reducing the pH of the system to around 9 [64]. More critically, continuous carbonation can lead to changes in other hydrates within the concrete, such as the partial decalcification of C-S-H gel. Furthermore, the calcium aluminate sulfate hydrate ettringite (AFt) undergoes decomposition. Ultimately, the fully carbonated paste is primarily composed of silica gel, calcite, and alumina gel, which are the main constituents of the carbonation phase [14,65]. Therefore, the focus of future research should be on controlling and optimizing the carbonation parameters of cementitious composites.

The degree of carbonation in cement concrete is influenced by several factors, including CO_2 concentration, relative humidity (RH), and the permeability of cement-based materials [66]. Thermodynamic modelling, using tools such as the cement-specific web-based code CemGEMS, can be employed to calculate phase changes resulting from carbonation in hydrated cement pastes. As illustrated in Fig. 3, these simulation processes provide a profound understanding of the carbonation reaction mechanisms in cementitious materials [67].

Over time, the carbonation front advances from the surface of the concrete towards its interior, leading to a decrease in pH. The alkaline environment that protects the steel reinforcement is disrupted when the carbonation front reaches it, leaving the steel vulnerable to corrosion [68,69]. This can accelerate the deterioration of the concrete protective layer, particularly in humid environments. Consequently, natural carbonation is undesirable, and concrete mix designs typically aim to minimize or control carbonation as much as possible. Switzerland has proposed estimating CO_2 absorption by cement during its usage and recycling stages [55], as shown in Fig. 4. It is estimated that around 25 % of CO_2 will be absorbed within 100 years, with the potential for this CO_2 to be chemically bound. The majority of CO_2 absorption occurs in the latter period [70,71]. While concrete can absorb a significant amount of CO_2, the rate of natural carbonation is too slow. According to previous studies, the estimated negative contribution of natural carbonation of building materials in the construction environment is only 51 kg of CO_2 per ton of cement [14,72]. Conversely, CCUS (including mineral carbonation) is expected to result in the sequestration of 280 kg of CO_2 per ton of cement, thereby facilitating the achievement of net-zero emissions goals.

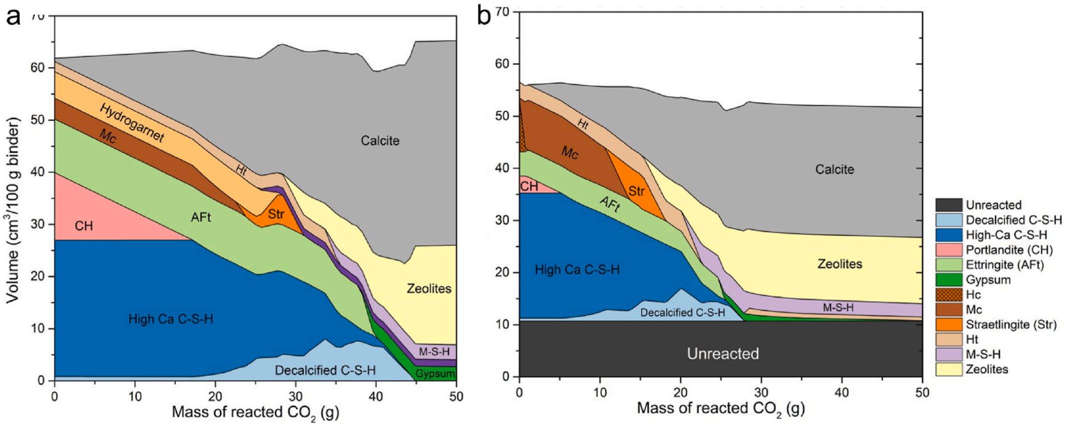


Fig. 3. The evolution of phase assemblage and pH value in the pore solution of (a) cement and (b) accelerated carbonation of cement-slag during carbonation [67].

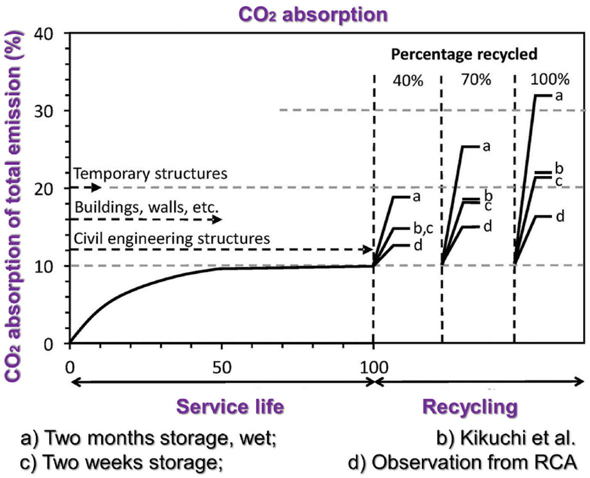


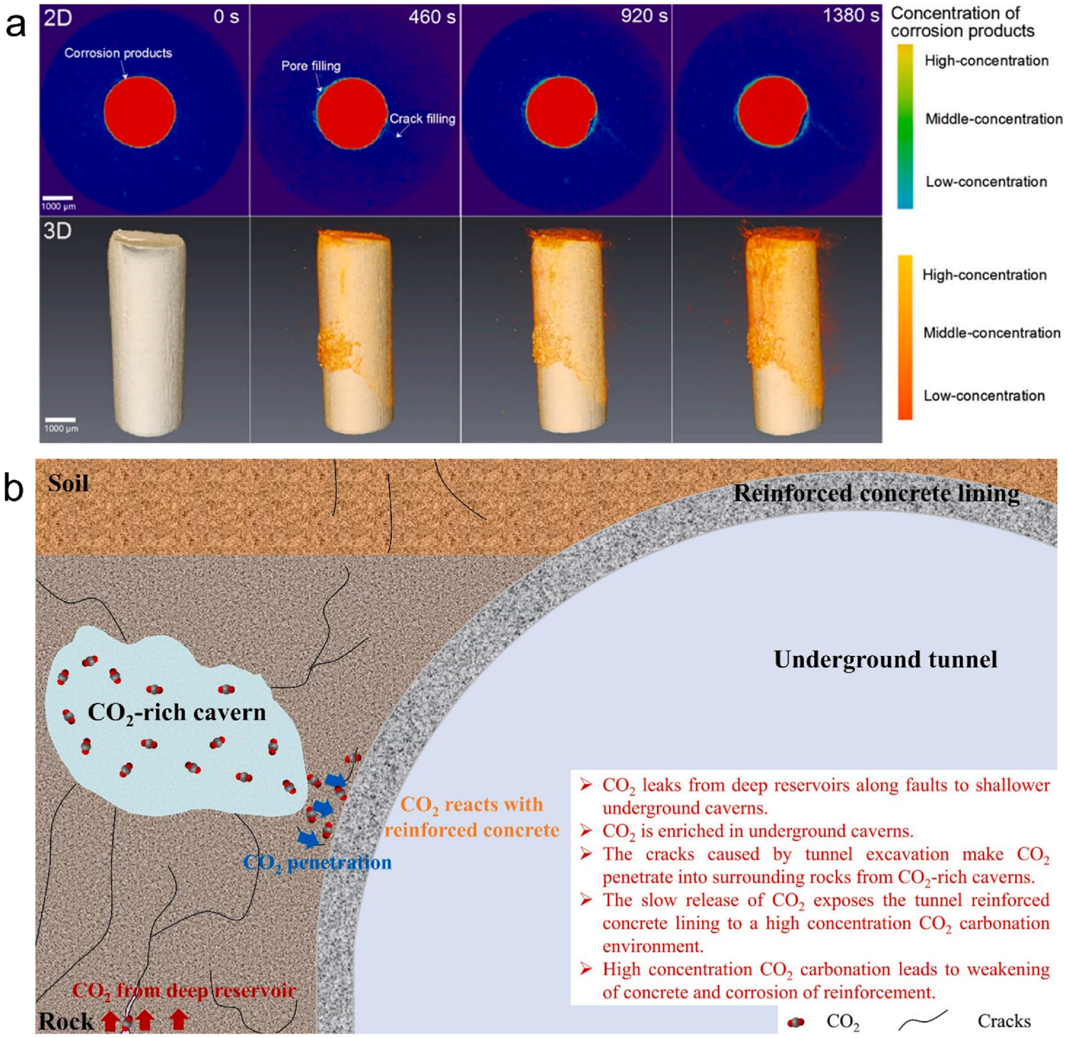
Fig. 4. Estimation of CO_2 absorption by cement during its usage and recycling stages [55].

3.2. Accelerated carbonation

As previously mentioned, cement concrete holds significant potential for CO_2 storage and consumption through the carbonation process [42,43]. This method involves carbonating the calcium and magnesium-containing components of cement concrete to create new concrete [73]. As a result, the carbon footprint of concrete can be mitigated, and in some cases, even achieve negative CO_2 emissions for building materials [74]. In this section, the latest research advancements in storing CO_2 in cement concrete through accelerated carbonation methods will be discussed [75].

For short-term climate change mitigation, accelerated carbonation of cement concrete outperforms natural carbonation. Concrete can undergo carbonation to store CO_2 at various points during its service life [76,77]. Amorphous $CaCO_3$ can be formed during the fresh concrete stage by adding CO_2 during the mixing and batching process, presumably in the form of nanocrystals, which accelerate cement hydration and enhance the concrete's strength [78]. A comparable method involves storing CO_2 in the concrete paste produced when concrete plants clean their mixers and transport trucks; this carbonated slurry can then be added to freshly mixed concrete. However, this type of CO_2 storage has a limited capacity, and the supply of these materials constitutes only 1 %–3 % of precast concrete production [71].

Strength is usually increased, pore structure densification occurs, and chemical erosion is lessened as a result of carbonation curing, mostly because of decreased permeability [69]. Nevertheless, concerns may arise regarding the decrease in alkalinity and the potential for inducing corrosion of reinforcement. For instance, Dong et al. [79] studied structural changes induced by corrosion in reinforced concrete, as depicted in Fig. 5a. When reinforced concrete is exposed to the environment over the long term, CO_2 can infiltrate the concrete, leading to corrosion of the steel reinforcement, ultimately compromising structural performance and safety [80]. The corrosion problem of reinforced concrete can be mitigated through carbonation treatment. As evident in Fig. 5b, following carbona-



- ➢ CO_2 leaks from deep reservoirs along faults to shallower underground caverns.
- ➢ CO_2 is enriched in underground caverns.
- ➢ The cracks caused by tunnel excavation make CO_2 penetrate into surrounding rocks from CO_2-rich caverns.
- ➢ The slow release of CO_2 exposes the tunnel reinforced concrete lining to a high concentration CO_2 carbonation environment.
- ➢ High concentration CO_2 carbonation leads to weakening of concrete and corrosion of reinforcement.

Fig. 5. (a) The reconstruction of corrosion products and the formation of products within the concrete [80] and (b) illustration of concrete and steel reinforcement exposed to CO_2 [79].

tion treatment, a layer of carbonation product forms on the surface of the steel reinforcement within the concrete. This layer effectively shields the steel from direct exposure to corrosive agents, thereby providing protection to the reinforced concrete [79]. However, it is important to note that extremely high partial pressure of CO_2 (i.e., 1 MPa or higher) can lead to significant damage to the reinforced concrete due to excessive carbonation, as reported by Xue et al. [81] and Zhang et al. [82]. Therefore, the pressure of CO_2 should be carefully controlled and selected to achieve optimal carbonation treatment for the reinforced concrete. Further research is necessary to screen and optimize suitable carbonation procedures (e.g., CO_2 pressure, concentration, and duration, etc.) for efficient protection of reinforced concrete.

The chemical composition of raw materials, RH, temperature, CO_2 concentration, and other factors all influence the effectiveness of concrete carbonation [52,66]. For instance, under high RH conditions, the carbonation rate of cement is the fastest. For larger specimens or concrete blocks, factors such as porosity, permeability, relative humidity, and dryness play crucial roles in the carbonation process [67,71]. Utilizing accelerated carbonation methods can sequester significant amounts of CO_2. Conversely, the amount of calcium oxide (CaO) in the cement, typically produced by burning calcium carbonate, significantly impacts CO_2 binding capacity [79]. Therefore, reducing cement usage through carbonation curing helps mitigate global warming by preventing the manufacturing of additional concrete.

A significant hurdle lies in the global adoption of carbonated curing cement and its potential to reduce CO_2 emissions [14]. Pressurized carbonation is a typical technique employed to enhance the carbonation reaction of materials [69]. In this method, CO_2 concentration is typically maintained around 20 % [83–86], as indicated in Table 1. Moderately high gas pressure aids in the diffusion of CO_2 into other components, enhancing carbonation effectiveness. However, excessive gas pressure can increase the load on the reaction chamber and may even lead to material cracking. Therefore, a balance must be struck when setting gas pressure to ensure efficient carbonation without causing detrimental effects on the material structure.

3.3. Mineral carbonation

In addition to RCA, other potential sources in waste streams for easy carbonation include calcium compounds, such as cement kiln dust, and various process-generated slags and ashes, including steel slag [44]. Other materials suitable for mineral carbonation include natural calcium or magnesium minerals. The generated magnesite can serve as a permanent carbon sink or as a raw material for magnesium oxide production [41]. During the processes of carbonation and subsequent calcination, magnesium silicates and magnesium-rich brines do not release fossil-derived CO_2. Thus, the possibility of producing binder materials from magnesium oxide extracted from magnesium silicates offers the potential for binder production while reducing the carbon footprint [40]. Magnesium oxide (MaO) can serve as a raw material for various magnesium-based binders [93]. Formerly known as Novacem, the magnesium binder is the first attempt at making “negative carbon” cement using a low-carbon raw material production process.

In comparison to natural carbonation, accelerated carbonation of the cement phase in concrete offers significantly greater potential in the short term for mitigating climate change [46]. This technique can be applied at various stages and even beyond the service life of concrete, effectively sequestering CO_2 within the material. Early-age carbonation treatment, which includes the use of accelerated carbonation for curing freshly mixed concrete, has recently garnered considerable attention [94]. However, the process of early-age carbonation curing is more intricate than that of accelerated carbonation for industrial waste. Cement-based composite materials comprise various chemical components and possess a micro-porous structure, adding complexity to the carbonation conditions [93]. Additionally, during the early stages, these materials undergo simultaneous carbonation and hydration reactions, resulting in coupling effects between these processes [94,95]. It is now commonly acknowledged that early-age carbonation curing affects the performance of cement-based composite materials in the short- and long-term. In practice, the use of accelerated carbonation in concrete holds substantial promise, particularly since precast concrete elements account for approximately 10 % of global concrete consumption annually [36].

Table 1
The commonly used methods for accelerated carbonation of concrete.

Types	Applications	CO_2 content (%)	CO_2 partial pressure (MPa)	Time (h)	Notes	Ref.
Typical fast carbonation	Cement powder wastes	20 ± 3	0.1	72	Extended carbonation time; 2) Low effectiveness of carbonation.	[83]
	Cement powder wastes	20	0.1	24		[84]
	RCA	20 ± 3	0.1	72		[85]
	RCA	20	0.1	672		[86]
Pressurized accelerated carbonation	Cement powder wastes	100	0.01	24	1) High carbonation efficacy; 2) Need for a sealed reactor with pure CO_2. 3) Discontinuous process of carbonation	[87]
	Cement powder wastes	99	0.05	72		[88]
	RCA	95	0.01	72		[89]
	RCA	100	0.01	24		[90]
Carbonation increased by flow-through	Cement powder wastes	25	0.1	5	1) Enhanced efficiency of carbonation; 2) Well suited for low CO_2 levels.	[91]
	RCA	100	0.1	24		[26]
	RCA	20	0.1	238		[92]

Mineral carbonation offers a viable option for sequestering substantial amounts of CO_2 within basic calcium and magnesium compounds. Potential sources include fresh concrete (using carbonation curing), RCA from demolished buildings, industrial byproducts like steel slags and cement kiln dust, residues from burning municipal waste, and naturally occurring rocks [14]. By incorporating carbonated materials into building supplies such as cement and concrete, carbon emissions can be significantly reduced, and the circularity of their constituent parts is improved, providing a substantial reservoir for storing CO_2 [40,93]. The long-term stability of CO_2 storage via mineral carbonation is demonstrated by the millions of years that carbonatic rocks have been present on Earth [96]. Accelerated carbonation is far more beneficial for combating climate change quickly than the natural weathering of materials like rocks or concrete [46,97]. At the moment, various technologies utilizing different materials and procedures are being increasingly investigated. The most promising techniques include direct aqueous carbonation, carbonation mixing, and carbonation curing [14]. A holistic approach to various carbonation technologies and recycling concrete within the context of a circular economy is emphasized. In the long run, this integrated method could serve as a significant carbon sink. Therefore, thorough life cycle assessments (from cradle to grave or cradle to cradle) and cost-benefit analyses of the different technologies are crucial.

4. Classification of CO_2 utilization in concrete production

As summarized in Fig. 6, the integration of accelerated carbonation with cement composite manufacturing encompasses three primary methods: 1) pre-carbonation of concrete ingredients, 2) carbonation curing, and 3) CO_2 mixing.

4.1. Pre-carbonation of concrete ingredients

In the carbonation of concrete ingredients approach, the concrete ingredients undergo pre-treatment with CO_2 before mixing to initiate the carbonation reactions [98,99]. As previously mentioned, this method leads to the creation of carbonated SCMs, fillers, and aggregates [72]. The $CaCO_3$ precipitated during this process can be incorporated into various binder systems. This innovative technique not only helps reduce the carbon footprint of cement composites but also promotes the sustainable utilization of materials in diverse cementitious applications.

4.2. CO_2 mixing

In the CO_2 mixing method, carbonation is promoted by directly introducing CO_2 during the concrete mixing process [100]. This results in the generation of nano-sized $CaCO_3$ as nucleation sites, catalyzing early-age hydration. Compared to the addition of pre-manufactured nano-sized $CaCO_3$ in Portland cement (PC), ground limestone, or precipitated calcium carbonate, the direct introduction of CO_2 to form $CaCO_3$ in situ allows for more uniform dispersion of nanoparticles [101,102]. This process significantly influences the chemical properties and hydration heat of cement paste during the early-age period. However, the overall reactivity of clinkers in the PC remains essentially unchanged, with the optimal range for CO_2 absorption reported to be only 0.05–0.3 % of the cement mass [103,104]. Extending carbonation beyond this range would reduce workability, posing challenges to concrete mixing and forming. When the amount of absorbed CO_2 during the mixing process exceeds 3.4 %, the mechanical strength of concrete may decrease [100,105]. This decrease in strength is due to the formation of a thick layer of $CaCO_3$ on the surface of the unreacted cement, which prevents further hydration.

As indicated in Fig. 7, the compressive strength of cement composites made by CO_2 mixing typically decreased compared to those made by air mixing, with a maximum reduction of about 80 % [27,28,106–111]. This decrease is primarily because the carbonation coating on the cement particle surface can obstruct the hydration reaction, resulting in reduced compressive strength [104]. Additionally, the compressive strength may have decreased due to the reduction in the C-S-H gel [112]. At the microstructure level, the carbonation reaction has been observed to have a favorable effect on the hydration reaction [73]. To fully understand the advantages and disadvantages of CO_2 curing on the development of concrete strength, more research is required. It is crucial to identify the specific CO_2 parameters (e.g., age of curing, curing time, and CO_2 concentration) that influence these strength differences.

4.3. Carbonation curing

In the carbonation curing method, concrete specimens are exposed to CO_2 during the curing process to stimulate carbonation reactions and reduce the carbon footprint of the final product [113]. Accelerated curing is widely used in the precast concrete industry to speed up production and ease equipment turnover [114,115]. This is typically achieved through steam curing, which requires both heat and moisture. Recent research suggests that CO_2 may accelerate reactions in the PC, potentially replacing steam in the curing process of concrete. Materials produced using carbonation curing exhibit higher early-age strength and improved durability under various exposure conditions, including sulfates, acids, and freeze-thaw environments [102]. Carbonation curing methods are essential for activating the hardening process of non-hydraulic binders. Currently, these methods are primarily used in precast applica-

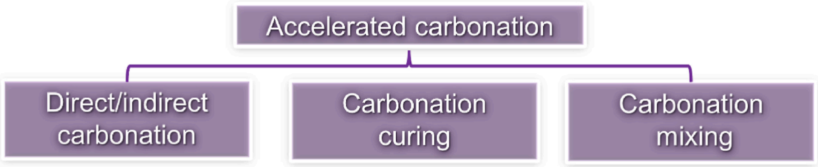


Fig. 6. Typical approaches are widely used to accelerate carbonized cement concrete.

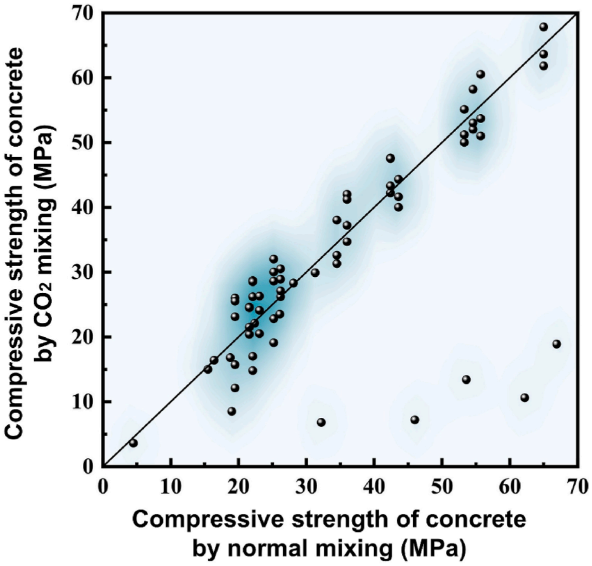


Fig. 7. Compressive strength of concrete by normal mixing relative to carbonation mixing [27,28,106–111].

tions, as they necessitate a closed reactor system to maintain materials in a carbon-rich environment for an extended period (typically several hours).

The process of carbonation curing includes semi-dry carbonation, which involves intentionally drying the concrete before exposing it to CO_2. This creates a carbonate gradient across the material's depth due to the decreasing rate of CO_2 absorption [104]. Carbonation activation is primarily suitable for thin layers or porous materials that can undergo complete carbonation. In reinforced concrete structures, the application of carbonation curing may potentially elevate the risk of reinforcing steel corrosion [115]. However, there is an ongoing debate about whether carbonation curing actually intensifies corrosion, as carbonated concrete surfaces tend to become denser and more resistant to corrosive elements.

This section emphasizes the challenges faced by the concrete industry in achieving net-zero emissions (NZE) when implementing the Carbon Utilization and Capture (CUC) approach. These challenges may arise from factors such as insufficient market capacity for certain products or limitations in the absorption of CO_2 by specific processes. To address these challenges and make significant progress towards NZE, a comprehensive strategy integrating various carbon utilization methods must be adopted. By tailoring these approaches to specific products, a more substantial reduction in CO_2 emissions can be achieved.

Table 2 outlines how the effective reduction of carbon emissions can be achieved through the integrated use of various CUC technologies. One prominent approach highlighted is the combination of pre-carbonation of concrete components with carbonation curing to produce fully carbonated prefabricated elements [3,9,34,44]. This combined strategy enhances the carbonation of concrete elements, positioning it as a leading solution for the concrete industry to achieve NZE. By leveraging multiple CUC approaches and customizing them for specific products, the industry has the potential to significantly reduce its carbon footprint and advance environmental objectives.

In the concrete industry, studies into the mineral CO_2 sequestration of industrial waste materials such as fly ash, slag, and RCA are frequently conducted [116]. These materials contain calcium phases that help generate carbonate compounds, aiding in the sequestration of CO_2. Early-age carbonation treatment has garnered significant attention as it uses rapid carbonation to cure fresh concrete [117]. However, the early-age carbonation curing of cement composites is a more involved procedure than the accelerated carbonation treatment of industrial waste materials [96]. Variations in chemical compositions and microporous structures among cement composites with different constituents pose challenges in effectively managing carbonation conditions.

Table 2
Combining different CO_2 consumption strategies to produce NZE concrete [3,9,34,44].

Product	Approaches			Readiness for NZE
	Precarbonation of concrete	CO2 mixing	Carbonation curing	
Cast-in-situ, normal/heavy weight	✓	✓		Low
Cast-in-situ, lightweight	✓	✓		Moderate
Precast, lightweight, carbonated fully	✓	✓	✓	High
Precast, lightweight, carbonated partially	✓	✓	✓	Moderate

5. Carbonation mechanism of binders and the preparation of low-carbon concrete

5.1. Early-age carbonation of binders

Because of the delayed carbonation process, cement concrete has a relatively limited natural capacity to sequester CO_2 throughout its service life [14,71]. As outlined in Section 3, significant advancements have been made in recent years to increase CO_2 sequestration efficiency through accelerated carbonation treatment [52,65]. As illustrated in Fig. 8, the key applications of accelerated carbonation in cement composites are primarily centred around two methods: 1) industrial wastes should be pre-carbonated before being mixed, and 2) cement composites' early-stage carbonation curing after mixing.

5.1.1. Principles of cement clinker carbonation

Cement hydration and carbonation processes work together as a linked mechanism during the early carbonation curing process of cement composites [118,119]. This section will delve into the reaction mechanism between CO_2 and cement clinkers to elucidate the interactions and chemical processes occurring during this process [14,96].

Fig. 9 illustrates the reactivity of different components in cement clinker with CO_2 [110]. Specifically, calcium silicates (such as C_3S and C_2S) undergo an immediate chemical reaction with fresh cement upon contact with CO_2 to produce C-S-H gel and CH [23]. The latter is the primary carbonation product of cement composites [120]. The hydration rate of tricalcium aluminate (C_3A) is no-

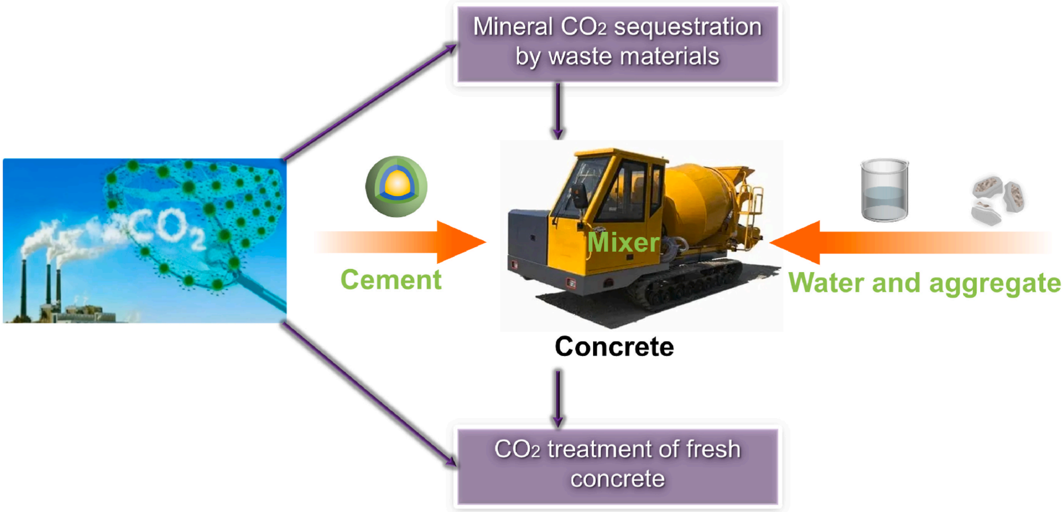


Fig. 8. Two mineral CO_2 sequestration methods are used in concrete production.

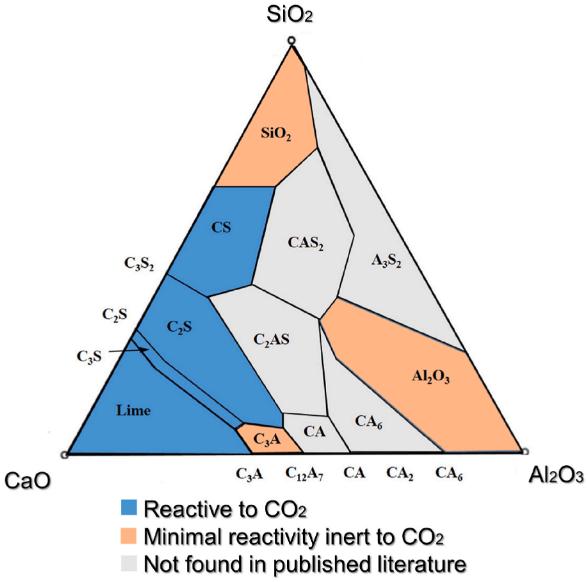


Fig. 9. The CO_2 reaction activity with cement clinkers [110].

tably rapid, leading to the formation of AFt and AFm [65]. The reaction of aluminous cement grain with water causes C_3A to interact with CO_2, producing ($CaCO_3$ and aluminum hydroxide, as depicted in equation (1):

$$3CaO{\cdot}Al_2O_3+3CO_2+3H_2O\rightarrow 2\ A\ l(OH)_3+3CaCO_3 \tag{1}$$

Before engaging in carbonation reactions, calcium silicate is enveloped by a layer of cement hydrates. During these reactions, the exothermic leaching of Ca^{2+} occurs, accompanied by the partial evaporation of mixing water [96]. The loosely bound layer of hydrated gel on the calcium silicate surface rapidly dissolves, releasing Ca^{2+}, SiO_4^{2-}, and $HSiO_4^{-}$. After the dissolved CO_2 ions cross the hydration product layer and interact with the calcium silicate, $CaCO_3$ precipitates are created, which build up on the surface of the calcium silicate [40]. The initial space filled by calcium silicate is eventually replaced by $CaCO_3$ precipitates as the carbonation process advances. Previous research indicates that $CaCO_3$ and calcium-modified silica gel are the end products of carbonation curing. Subsequent studies ought to concentrate on examining the mineralization kinetics of C_3S and β-C_2S in order to clarify the kinds, compositions, and processes of the final mineralization products [46].

5.1.2. Principles of cement hydrates carbonation

In the reaction of CO_2 with cement hydrates, C-S-H gel and CH are the primary cement hydrates that also undergo reactions with injected CO_2 [121,122]. The reaction process can be illustrated by equations (2) and (3):

$$Ca(OH)_2 + CO_2\rightarrow CaCO_3+H_2O \tag{2}$$

$$C\text{-}S\text{-}H + CO_2\rightarrow CaCO_3+SiO_2+H_2O \tag{3}$$

Carbonation reactions have the potential to release bound water from CH and C-S-H gel, thereby stimulating further hydration of cement. This phenomenon can enhance the strength of the concrete material [71]. Simultaneously, the reaction of CO_2 with C-S-H gel can modify the microstructure of fresh cement composites, potentially affecting their performance and influencing the properties of hardened concrete [50]. Moreover, the reaction of CO_2 with CH can decrease the pH value of the cement composite system, which might pose a risk to the reinforcement in concrete production [103,118]. C-S-H, as a key component of cementitious materials, is susceptible to carbonation, thereby offering significant potential for CO_2 capture [35,50]. For example, Liu et al. [35] conducted a study on the carbonation kinetics of C-S-H with different calcium-to-silica ratios (Ca/Si). The results of this study provide valuable insights into CO_2 capture using C-S-H, which is abundantly present in cementitious materials [35]. Understanding the carbonation behavior of C-S-H with different Ca/Si ratios can contribute to the development of more effective strategies for CO_2 capture and utilization in the construction industry. Furthermore, in 2023, Liu et al. [8] introduced a super C-S-H material designed for ultra-high CO_2 adsorption and storage. This innovative super C-S-H material exhibits an exceptional CO_2 capture capacity, achieving up to 293.6 mg/g, which represents a significant advancement in CO_2 capture technology [8].

Carbonation reactions and CO_2 sequestration are ongoing processes throughout the entire lifecycle of concrete structures, persisting even after demolition, and can be further enhanced. Different researchers have reported varying potentials for carbonation in concrete [123]. In traditional concrete made with OPC, carbonation has been viewed negatively due to its potential to deteriorate the passive layer around reinforcement, leading to corrosion [91]. However, recent literature suggests that cement hydrate carbonation, especially early carbonation, can enhance the mechanical strengths of cement composites without compromising durability [108]. Additionally, the carbonation of AFt can generate $CaCO_3$, aluminum hydroxide gel, and gypsum, offering further potential for CO_2 sequestration. It is essential to recognize that the formation of $CaCO_3$ competes with the hydration process [87]. The chemical processes involved in these reactions and their effects on the properties of cementitious materials can be better understood by examining a schematic diagram of the hydration and carbonation processes that occur on the surface of cement particles and within the network of interacting cement particles [118], as shown in Fig. 10a.

Additionally, once the accelerated hydration stage of cement paste commences, leading to the generation of CH and C-S-H gel, cementitious materials become suitable for carbonation [118], as shown in Fig. 10b. As a result, carbonation curing is usually carried out following a predetermined amount of time for conventional curing. The effectiveness of subsequent carbonation curing and the mechanical strengths of cementitious materials can be significantly impacted by the length of the conventional curing [124]. The rate of subsequent carbonation treatment and the capacity to absorb CO_2 can both be reduced by extending the standard curing period after casting, whereas an excessively short conventional curing time can impede the strength development of cementitious materials [99]. Effective carbonation curing contributes to achieving higher early strength and rapid strength enhancement in cementitious materials, primarily due to the pore-filling effect of calcite particles formed during the carbonation process, which enhances microstructure densification [110]. However, prolonged or overly intense carbonation curing may have detrimental effects on early compressive strength development. These negative impacts could result from: 1) carbonation curing delaying cement hydration, 2) decalcification of C-S-H gel, 3) microstructural cracking due to carbonation shrinkage, and 4) consumption of C_2S during the carbonation curing process, thereby slowing down the strength development of the cement paste in later stages [14].

Additionally, C-S-H has a high potential for CO_2 capture because it is the main component of cementitious materials and is subject to carbonation. Although some research has focused on the carbonation behaviors of C-S-H in relation to the durability of concrete, the kinetics of C-S-H carbonation and the changes that occur during carbonation have not been thoroughly investigated [35]. To promote sustainable building practices and improve concrete's performance in carbon capture applications, it is essential to comprehend the carbonation of C-S-H and its effects on concrete properties.

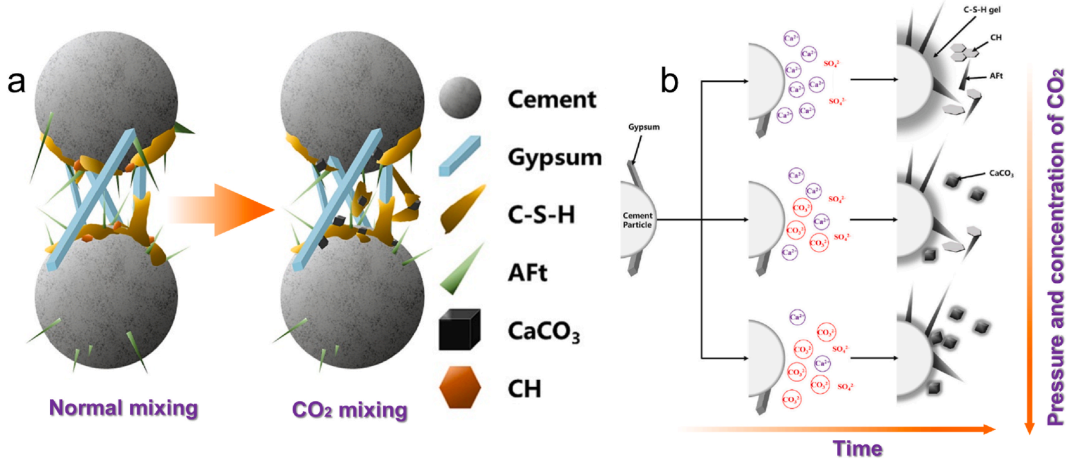


Fig. 10. (a) Illustration of hydration and carbonation products on the cement surface [118] and (b) a conceptual model illustrating the hydration and carbonation reactions of cement with CO_2 [118].

5.1.3. Principles of SCMs carbonation

The CO_2 emissions generated from the cement production process are substantial, contributing to approximately 7 % of the total CO_2 emissions [20,125]. To mitigate these emissions, substituting a portion of traditional cement clinker with SCMs is a viable strategy [15,126,127]. SCMs typically contain reactive silica components that can react with CH to form C-S-H gel through capillary action [21,128,129]. Consequently, SCMs are also anticipated to facilitate early carbonation curing [118,130,131]. Fly ash, a common SCM known for its favorable carbonation reactivity, can undergo a certain degree of hydration before engaging in early carbonation curing [132–134]. These reactions can be represented by equations (4) and (5):

$$xCa(OH)_2 + SiO_2 + m_1H_2O \rightarrow xCO_3{\cdot}SiO_2{\cdot}n_1H_2O \tag{4}$$

$$xCa(OH)_2 + Al_2O_3 + m_2H_2O \rightarrow yCaO{\cdot}Al_2O_3{\cdot}n_2H_2O \tag{5}$$

Additionally, in fly ash, CH, calcium silicate hydrate, and MgO are involved in subsequent carbonation reactions of cement composites [16,135,136]. The carbonation reactions of CH, C-S-H, and MgO can be depicted by equations (6)–(9):

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

$$Mg(OH)_2 + CO_2 + H_2O \rightarrow MgCO_3{\cdot}3H_2O \tag{7}$$

$$5\ Mg(OH)_2 + 4CO_2 \rightarrow 4MgCO_3 + Mg(OH)_2{\cdot}4H_2O \tag{8}$$

$$5\ Mg(OH)_2 + 4CO_2 + H_2O \rightarrow 4MgCO_3 + Mg(OH)_2{\cdot}5H_2O \tag{9}$$

The carbonation of fly ash competes with the cementitious reactions, indicating that the level of carbonation in fly ash is inversely related to the degree of cementitious reaction [125,137,138]. Nevertheless, the early-age strength of the composites can be guaranteed by carbonation by keeping the early carbonation curing time within a certain range, and the pozzolanic reaction can provide sufficient later mechanical strength [139,140].

Waste slag streams from the steel industry can also capture and sequestration CO_2. Compounds including C_3S, C_2S, hydroxides, and calcium-magnesium oxides are found in steel slag [67,141]. CH and calcium silicate present in steel slag can undergo reactions with CO_2 to produce CaO_3 [142,143]. Additionally, CaO and MaO in steel slag can directly react with CO_2 to form precipitates, with these compounds being prominent constituents in steel slag [15,138]. The proportions of CaO and MgO in steel slag are significant, as demonstrated in equations (10) and (11). Carbonation of waste slags is a promising technology for the treatment and management of industrial waste, this process can immobilize heavy metals and other contaminants within the waste slags, or convert certain contaminants into more stable forms that are less likely to be released into the environment, reducing the risk of contamination of soil, water, and air. However, it is important to carefully evaluate the specific waste materials and conditions to determine the most appropriate treatment method and ensure effective contaminant stabilization.

$$CaO + CO_2 \rightarrow CaO_3 \tag{10}$$

$$MgO + CO_2 \rightarrow MgO_3 \tag{11}$$

Certain elemental minerals, such as granulated blast furnace slag, silica fume, and limestone, show little reactivity towards CO_2 [144,145]. Nevertheless, throughout the carbonation process, limestone can act as a nucleation location for the creation of C-S-H, further increasing early-age mechanical strength. By adding SCMs, cementitious materials' porosity can be increased, which will aid in

CO_2 diffusion. A study performed by Qin et al. [43] revealed that compared to the control group, the incorporation of SCMs can lead to a higher rate of early strength enhancement, partially compensating for the reduced compressive strength. This compensation helps offset the decline in compressive strength resulting from the inclusion of SCMs [146,147]. For instance, as indicated by Liu et al. [67], notable insights have been obtained from the study of SEM-BSE pictures (at 750 × magnification) and matching EDX spectra of the BFS-50 % samples following spontaneous and accelerated carbonation (refer to Fig. 11). In the natural carbonation process, a heightened presence of silica gel (depicted in deep green areas) and alumina gel (observed in light blue areas) is evident. The decalcification of C-S-H results in the transformation of Ca-modified silica gel, leading to alterations in the structure of C-S-H and a substantial increase in porosity [35]. MgO exhibits a notable CO_2 absorption capacity (1.09 metric tons of CO_2 per ton of MaO), suggesting the potential development of a building material capable of absorbing more CO_2 than the quantity emitted during binder production [44]. However, the high costs of extraction, transportation, and further processing (heating and grinding) limit the use of these minerals in concrete and make it difficult to achieve meaningful CO_2 absorption.

Several factors influence the carbonation of cementitious materials, including the type of cementitious material, water-to-cement ratio, humidity, temperature, concentration of CO_2, CO_2 flow rate, and CO_2 pressure. For instance, the extent of carbonation is typically greater in aqueous solutions compared to dry conditions due to the leaching of calcium ions from the fractured concrete [104]. Despite the lower CO_2 absorption rates of certain binders, the economic and ecological advantages make the use of low-carbon binders more appealing.

5.2. *Utilizing CO_2 technologies for preparing recycled aggregate concrete*

Our world is currently grappling with significant environmental issues stemming from the overexploitation of natural resources and the substantial release of CO_2 into the atmosphere [29,70,148]. Additionally, the rapid pace of urbanization and redevelopment has led to the generation of substantial amounts of concrete waste [149–151]. As a typical solid waste, RCA possesses significant potential for sequestering carbon emissions. By utilizing carbonated RCA as an alternative material for natural aggregates, we can simultaneously address the challenge of managing concrete waste while also leveraging it as a carbon sink to mitigate CO_2 emissions [152–155]. This approach contributes to sustainable practices by reducing the environmental impact of concrete production and waste management in the construction industry [156–158]. The significance of CO_2 sequestration and the improvement of RCA and recycled aggregate concrete's performance through thorough reaction procedures have been underlined in recent studies

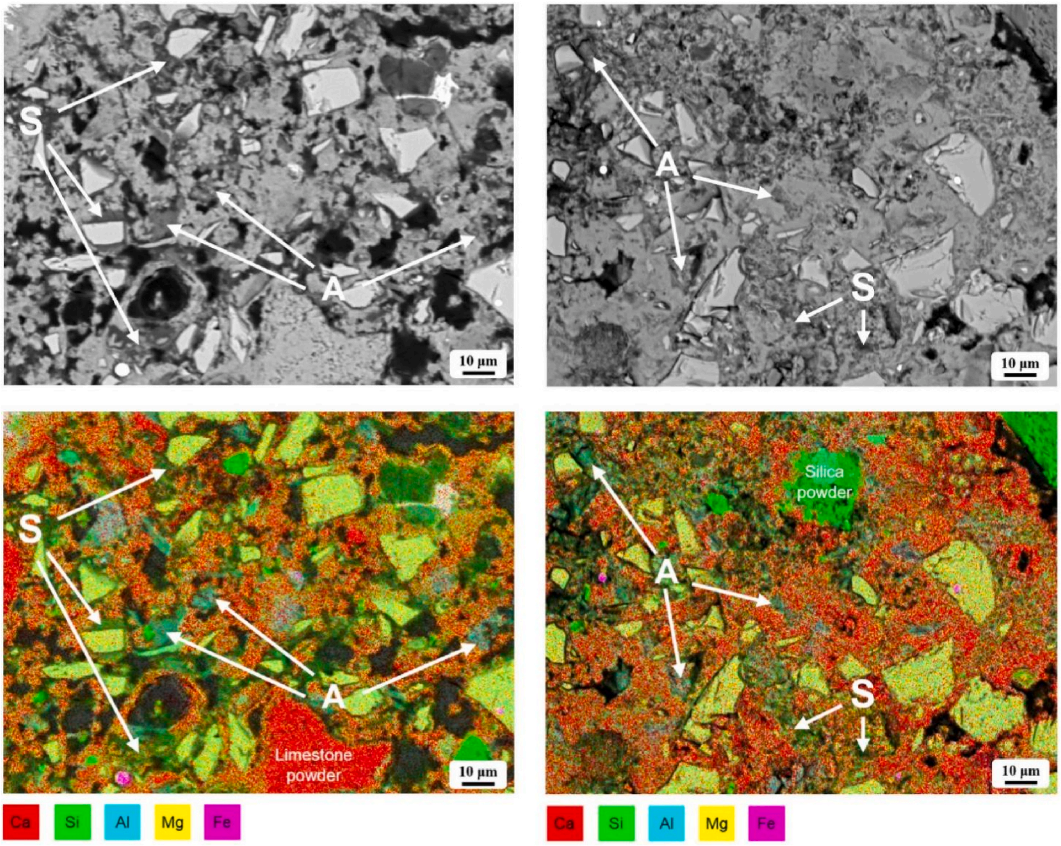


Fig. 11. SEM-BSE images of cement-slag composites after (a) natural and (b) accelerated carbonation with 2 % CO_2 (S: silica gel, A: alumina gel) [67].

[104,112,159]. As such, this section will introduce the roles of admixing CO_2 in the recycled aggregate concrete system and the admixing CO_2 on the performance of RCA and recycled aggregate concrete.

5.2.1. The roles of admixing CO_2 in the recycled aggregate concrete

The global annual production of demolished concrete can exceed 2.2 gigatons [160–162]. If this demolished concrete is fully recovered and utilized as aggregate, it could potentially reduce the need to extract approximately 13.5 gigatons, or 13 %, of the total volume of natural aggregates required for new concrete production [13,105,163]. However, as a result of attached old mortar, RCA often has features such as higher water absorption, lower density, and higher crushing values than NA [157,164]. It is widely acknowledged that the old mortar on the surface of RCA can react with CO_2 to produce $CaCO_3$, which ultimately precipitates in the pores and microcracks within cement composites [26,28,165]. Gaseous CO_2 penetrates loose mortar through pores, as shown in Fig. 12, and dissolves into the pore solution to generate carbonic acid [72]. Furthermore, Ca^{2+} precipitates from active calcium compounds, including cement hydrates like CH, C-S-H gel, and unhydrated cement clinkers to generate CaO_3 and silica gel [72]. Additionally, AFt can react with CO_2 to generate calcium carbonate, gypsum, and alumina gel. The formation and deposition of $CaCO_3$ in pores and microcracks can refine the microstructure of RCA, thereby enhancing its quality.

5.2.2. Commonly used methods for carbonizing recycled aggregate concrete

Carbonation adjustment and carbonation curing are two commonly employed treatments for recycled aggregate concrete [149]. The method of introducing CO_2 into RCA using a sealable carbonation chamber is known as carbonation adjustment. In contrast, carbonation curing involves the carbonation reaction between CO_2 and cement paste and is applied to the entire concrete block after mixing [152]. While carbonation of RCA can be conducted before concrete mixing, carbonation curing must be performed after mixing, limiting its application before casting [166]. Both methods yield favorable outcomes and aid in CO_2 sequestration, thus contributing to the reduction of greenhouse gas emissions. Among the two techniques, carbonation adjustment of RCA is often regarded as the most practical and effective approach for utilizing waste materials [152].

5.2.3. Performance improvement of carbonated recycled aggregate concrete

As previously discussed [116,167,168], with CO_2 treatment, RCA's water absorption and crushing value can be reduced by around 20–30 % and 5–25 %, respectively, while its apparent density can be increased by 0.6–5.6 %. Through the carbonation process, porous RCA produces calcium carbonate, thereby augmenting its solid volume [117,169,170]. Consequently, compared to untreated RCA, carbonation may result in decreased porosity and water absorption. One viable approach to enhance the use of leftover concrete in the CCUS industry is to produce high-strength, extensively processed, low-cost RCA products that also support sustainable CO_2 management. Improving RCA performance through innovative techniques like pre-soaking with CH can promote the utilization of waste materials in an eco-friendly manner and enhance the overall sustainability of the construction industry. For instance, in a recent study carried out by Zhu et al. [156], the application of pre-soaking with a CH solution was used to optimize the kinetics of the mineralization reaction, leading to RCA with stronger and more pliable pores. Notable improvements were observed, including a 28.8 % decrease in the crushing index and an 11.1 % reduction in the water absorption rate for RCA. In a study by Gao et al. [66], a highly efficient carbonation process was applied to RCA using a simple method, leading to notable improvements such as a 3.6 % reduction in water absorption rate and a 20 % decrease in porosity. EDS analysis revealed that silicon elements in the carbonation product were concentrated prominently in non-carbonated regions, while calcium elements tended to aggregate in more distant areas.

The changes in the pore structure of RCA induced by carbonation-curing treatment are primarily due to the precipitation of $CaCO_3$ crystals within the aggregate pores, resulting in a reduction in pore volume [166]. Consequently, RCA cured by carbonation showed a decline in its crushing value. This reduction in crushing value was consistently observed across various studies, despite the different types of RCA utilized. Therefore, carbonation curing has the potential to improve the strength and durability of RCA, irrespective of the type [149].

Carbonating RCA or directly carbonating recycled aggregate concrete not only facilitates carbon sequestration but also improves the overall performance of concrete. Various techniques have been applied, enhancing the mechanical characteristics of concrete and

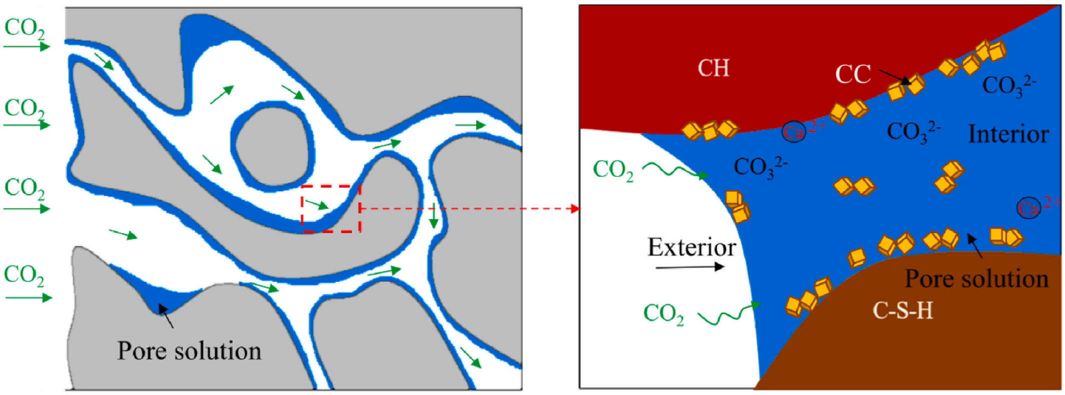


Fig. 12. The rapid process of RCA's carbonation: (a) mesoscopic; (b) microscopic [72].

accelerating its strength development. Table 3 showcases research findings related to the carbonation curing of recycled aggregate concrete [84,89,164,171]. As indicated in Table 3, most research findings suggest that concrete prepared using RCA after carbonation treatment exhibits improved compressive strength [36,168]. Furthermore, RCA's carbonation treatment can enhance their quality by increasing crushing indices and decreasing porosity, which may improve recycled aggregate concrete's durability performance metrics [172–175]. For example, Kaddah et al. [68] observed significant damage and cracking due to carbonation shrinkage and tensile strains in recycled aggregate concrete, along with increased gas permeability at the initial stage of carbonation. Leemann et al. [176] noted that regions in the cement paste with lower backscattering contrast on their surface result from the rapid carbonation of aggregates. Moreover, carbonation treatment can improve the interface transition zone (ITZ) between the cement matrix and carbonated RCA, thereby enhancing concrete performance and extending the service life of concrete structures [41]. In the study by Li et al. [78], the silicon (Si), aluminum (Al), and calcium (Ca) distribution in the ITZ in recycled aggregate concrete including carbonated RCA was more uniform. This finding suggested that an amorphous C-S-H gel was forming around the carbonated RCA particles. This finding suggested that an amorphous C-S-H gel was forming around the carbonated RCA particles. By densifying the ITZ, these C-S-H gels enhanced their binding capabilities and inhibited the development of big pores inside the ITZ.

In summary, the carbonation of RCA primarily leverages the residual CH within the adhered cement paste. The formation of $CaCO_3$ during carbonation can increase the overall solid volume by approximately 3 % and reduce the porosity of RCA by up to 30 % [116,175]. This reduction in porosity and the formation of $CaCO_3$ can improve the paste matrices attached to RCA and the aged ITZs within recycled aggregate concrete. As a result, water absorption is reduced, and both macro- and micro-mechanical properties of recycled aggregate concrete are enhanced. Consequently, concrete incorporating carbonated RCAs demonstrates improved mechanical strength and durability, including greater resistance to water, CO_2, chloride ion ingress, and other deleterious factors.

6. CO_2 utilization commercialized technologies in low-carbon concrete production

Impressively, there has been significant investment in developing patented products aimed at reducing carbon emissions in cement concrete production while promoting CO_2 utilization technologies in building materials. Over the past two decades, companies focusing on these initiatives have made substantial progress, with some successfully demonstrating carbon footprint reduction at pilot scale and transitioning to full-scale production. Table 4 outlines the various CO_2 utilization technologies employed in these endeavors [3,51,98,152,177]. Further exploration of these technologies and understanding their impact on the construction industry and environmental sustainability can be highly beneficial.

6.1. CarbonCure

Since 2007, CarbonCure, a company based in Nova Scotia, has been committed to lowering the carbon footprint of the concrete sector. The innovative technology developed by CarbonCure involves injecting a small amount of CO_2 directly into “green concrete mixes” during the production process, as illustrated in Fig. 13. This process accelerates the curing rate of concrete and enhances its strength. Additionally, CarbonCure's method reduces the amount of cement required, allowing for the production of more concrete. By injecting CO_2 into the concrete mix, the hydration process is expedited, leading to increased strength without compromising the final performance of the concrete. These improvements in strength and curing effects do not detract from the overall quality and dura-

Table 3
The effect of carbon-curing on the performance of recycled aggregate concrete.

RCA (%)	Carbonation duration (h)	Carbonation pressure (kPa)	Compressive strength (%)	Flexural strength (%)	Ref.
0	6	207	2	–	[171]
		345	14	–	
		414	5	–	
0	2	10	−17	−18	[84]
50	2	10	−25	−22	
100	2	10	−38	−27	
100	0	0	0	–	[164]
100	24	10	12	–	
50	6	10	15	–	[89]
	12	10	54	–	
	24	10	85	–	

Table 4
The commercialized technologies to reduce carbon emissions and prepare low-carbon concrete [3,51,98,152,177].

Company	Method	CO_2 reduction potential
CarbonCure	Injection of CO_2 in concrete	231,319 MT
Solidia	Cement concrete that cures with CO_2	1.5 gigatons of CO_2 sequestered annually
Novacerm	Creating superior composites by incorporating CO_2 into superior materials	180–200 g of CO_2 per kilogram of steel slag
Carbicrete	Steel slag carbonation as a cement substitute (cement-free concrete)	200 kg each day
Heidelberg	At lower burning temperatures (1150–1280 °C), turnover clinker	Decrease CO_2 emissions by 20–30 %

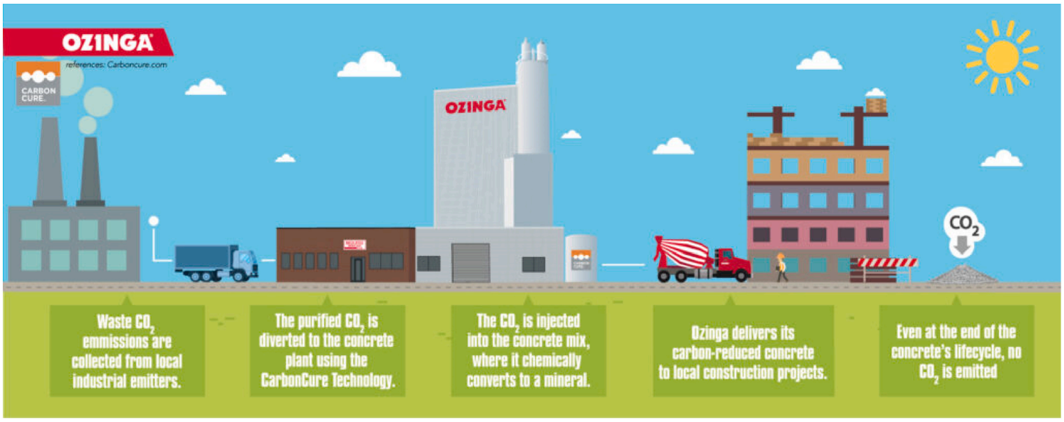


Fig. 13. The mission of CarbonCure for achieve low-carbon cement composites (https://www.carboncure.com/).

bility of the concrete. CarbonCure's approach represents an innovative solution for developing sustainable concrete, providing both environmental and economic benefits by optimizing the concrete production process and reducing its carbon footprint.

The concrete industry now has a very scalable way to turn CO_2 into products thanks to CarbonCure. With the help of CarbonCure's technology and their methods, more than 62 concrete companies have produced 1.16 million tons of cement composites [51]. In comparison to the production of regular concrete, CO_2 emissions have been reduced by over 15,000 tons [3]. The developers of the CarbonCure process project that by 2030, the technology could sequester 500 million tons of CO_2 annually, as indicated in Fig. 14. The technology has been installed and utilized in over 300 concrete plants globally, showcasing its extensive reach and industry impact.

CarbonCure has been at the forefront of industrial carbon mixing technology, utilizing high-purity CO_2 in fixed or transportable mixers through retrofitting centralized concrete facilities. During this process, a mixture of liquid and gaseous CO_2 is injected into the concrete mixer within 3 min of the start of mixing [178]. The mixing time varies from 10 s to 4 min, with CO_2 typically ranging from 0.01 % to 1 % of the cement mass in the concrete mixture. In addition to directly sequestering CO_2 (up to 1 % of the cement mass), CarbonCure technology enhances the efficiency of binders. Despite the relatively limited CO_2 absorption capacity, the implementation of this technology requires minimal modifications to equipment and material design. CarbonCure is a viable and sustainable solution for the concrete industry, as it can reduce cement usage without compromising concrete strength and is easy to integrate into existing equipment [51]. The widespread application and success of CarbonCure technology highlight its potential to significantly reduce carbon emissions in the concrete industry and promote future sustainability. By the end of 2020, the total amount of CO_2 saved by this technology exceeded 100,000 tons.

CarbonCure has established itself as a global leader in carbon utilization solutions. By integrating CarbonCure's comprehensive suite of technologies, concrete producers can enhance the environmental performance of their operations and contribute to the industry's transition toward a more sustainable future. The continuous development of innovative technologies offers concrete producers additional benefits in performance, cost-effectiveness, logistics, and environmental impact. The ongoing advancement of carbon utilization technologies developed by CarbonCure underscores the industry's commitment to reducing CO_2 emissions and achieving sustainable cement concrete.

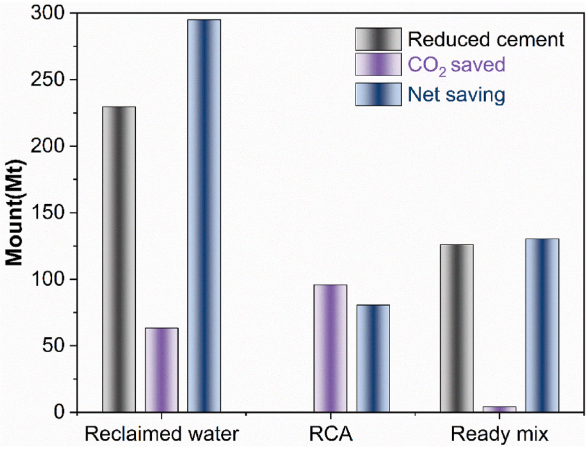


Fig. 14. CarbonCure goal by 2030 (https://www.carboncure.com/).

6.2. Solidia Technology

As shown in Fig. 15, Solidia Technology, established in Piscataway, United States, in 2008, offers green solutions for producing environmentally friendly building materials by utilizing CO_2 (https://www.solidiatech.com/). The company integrates low-carbon processes, carbon mineralization, and efficient operations to provide exceptional concrete performance, enhance supply chain resilience, and reduce the carbon intensity of concrete.

As depicted in Fig. 15b, Solidia Technology offers two products with lower net carbon emissions than traditional cement composites: Solidia Cement and Solidia Concrete. Solidia Concrete is cured with CO_2 instead of water, providing superior qualities compared to conventional concrete. Solidia Cement is a non-hydraulic cement that uses less energy than OPC [179]. Annually, Solidia Technology can save a minimum of 1.5 gigatons of CO_2, conserve 30 trillion liters of water, reduce energy consumption in the cement industry by 67 million tons of coal, and prevent the disposal of 100 million tons of concrete waste [3]. For the global $1 trillion concrete economy, these solutions continuously explore new product development and offer novel sustainable alternatives. Solidia Technologies received a $2.1 million grant from the US Department of Energy to create carbonated monolithic materials through the direct capture of CO_2 from flue gas. Recently, Solidia partnered with Matagorda Concrete in Bay City, Texas, to use Solidia SCM in concrete as a 35 % cement replacement. Construction workers were impressed by the usability of this material. The concrete pouring was smooth, the surface was even, and there were no issues with solidification. Even in windy conditions, there were no signs of cracking or delamination in the following days (Fig. 15c).

Using a technical platform developed by Solidia Technologies, new construction materials with remarkable physical qualities, affordable lifecycle costs, and minimal environmental impact can be produced. Preliminary research results indicate that the strength and performance of these materials significantly surpass those of traditional concrete. Additionally, the carbon sequestration technology employed in the production process provides carbon-neutral alternatives to conventional concrete.

6.3. CarbiCrete technology

CarbiCrete, headquartered in Montreal, specializes in developing building technology solutions aimed at reducing emissions in the construction environment and sequestering carbon (https://carbicrete.com/technology/). Their innovative process involves using an industrial by-product, blast furnace slag from steel mills, as a binder for concrete products instead of cement. By injecting CO_2 into freshly mixed concrete, this process not only enhances strength but also permanently sequesters CO_2 in the product.

CarbiCrete specializes in producing carbonized concrete blocks using recycled steel slag and advanced accelerated carbonation technology. The steel mill slag, rich in magnesium silicate and calcium silicate, reacts with captured CO_2 to yield premium-quality products [180]. The carbonization process involves three key steps: pre-treating the steel slag mixture, block molding, and diffusing CO_2 into the blocks. During this process, CO_2 and calcium silicate combine to generate $CaCO_3$, which permanently sequesters CO_2. Compared to conventional concrete, carbonized concrete can typically increase its mechanical strength by approximately 30 % [3]. CarbiCrete's technology can reduce CO_2 emissions by 150 kg per ton of concrete, potentially leading to an annual reduction of around 2.2 billion tons of CO_2 [181]. CarbiCrete was listed as one of the top ten construction startups in 2020 and has received recognition for its innovative approach. This accolade underscores the company's significant contribution to reducing carbon emissions and developing low-carbon concrete.

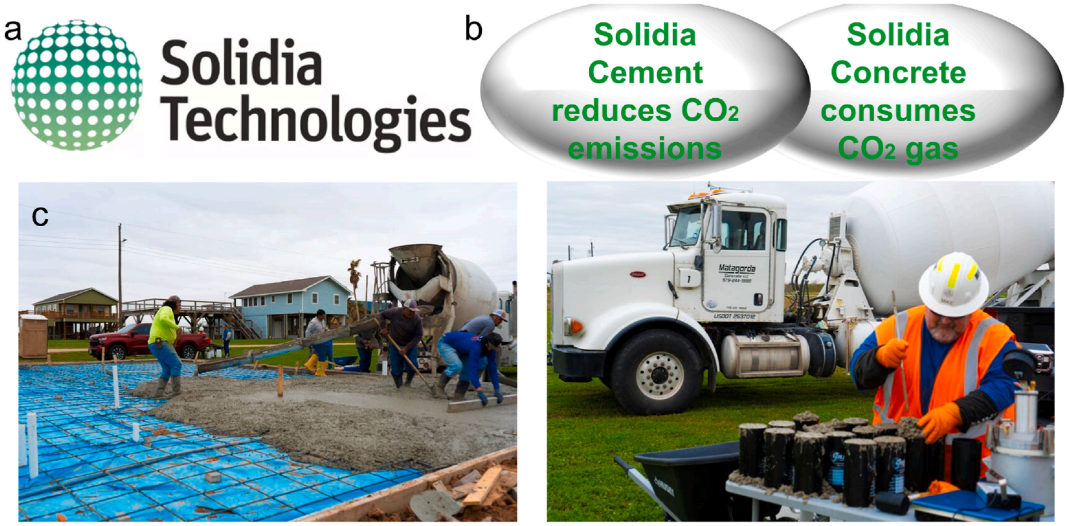


Fig. 15. (a) Company's logo; (b) two low-carbon products in this company; and (c) company's latest products utilizing SCM in low-carbon concrete (https://www.solidiatech.com/).

6.4. Heidelberg Materials

Headquartered in Heidelberg, Germany, Heidelberg Materials is an international building materials firm. In September 2022, the business, previously known as Heidelberg Cement, changed its name to Heidelberg Cement. Its core business includes the production and distribution of cement and aggregates. Its downstream operations primarily involve the production of ready-mix concrete, as well as asphalt and other construction products (https://www.heidelbergmaterials.com/en/investor-relations).

Heidelberg Materials aims to lead the industry in achieving carbon neutrality and developing new products with low carbon footprints and enhanced energy efficiency for construction. From 1990 to 2021, Heidelberg Materials reduced CO_2 emissions by approximately 25 %, reaching 565 kg of CO_2 per ton of cement composites [182]. By 2030, their goal is to reduce CO_2 emissions by an additional 10 million tons [3]. To achieve this, Heidelberg Materials is conducting extensive research on future-oriented technologies that can store CO_2 or utilize it as a raw material [183]. They have also developed various environmentally friendly alternatives to traditional cement, such as Ternocem. Ternocem cement offers high early-age strength and minimal shrinkage, making it an ideal choice for prefabricated applications [98].

Heidelberg Materials aims to lead the way in circular solutions and be at the forefront of efforts to achieve net zero emissions for cement and concrete. Their goal is to reach net zero emissions by 2050. The company collaborates with customers and partners to drive innovation and is dedicated to creating future-oriented building materials.

6.5. Novacem

Based in London, United Kingdom, Novacem is a pioneering company in sustainable cement production. Founded in 2007, Novacem is dedicated to developing negative carbon cement technology to significantly reduce the carbon footprint associated with traditional cement production processes (https://novacolor.sa/en/product/1618952077-ZYs-novacem). Magnesium silicate is the main raw ingredient used in their innovative cement production process, where more CO_2 is absorbed during the curing process than is emitted during production, resulting in a net carbon-negative effect. Novacem's technology provides a more environmentally friendly alternative to traditional cement production methods and has the potential to revolutionize the construction industry.

In 2008, Novacem developed an innovative magnesium oxide-based cement that replaces calcium carbonate with magnesium silicate, resulting in a negative carbon impact [184]. They employ an accelerated carbonation method to treat magnesium silicate, producing magnesium carbonate. The CO_2 generated in this process is captured and reused, creating a carbon-negative cement. Novacem's cement has a lower precursor production temperature and benefits from using biomass fuel, further reducing CO_2 emissions [185]. One ton of Novacem cement can absorb approximately 100 kg of CO_2, resulting in carbon-neutral products [3]. Recently, Novacem's “negative carbon cement” has garnered significant attention in the media as a pioneering “green” material.

Novacem's technology is based on magnesium silicate, rather than the limestone (calcium carbonate) used in traditional PC. It is estimated that global reserves of magnesium silicate exceed 100 trillion tons. The company's technology involves a low-carbon, low-temperature process to convert magnesium silicate into magnesium oxide, followed by the addition of special mineral additives to produce Novacem cement.

Table 5 outlines the advantages and disadvantages of various CO_2 utilization technologies, detailing their characteristics, development stages, and potential applications of carbonate products [3,14,51,65,69,152]. As summarized, diverse CO_2 utilization technologies have been developed, including the carbonation of industrial waste and RCA. The capability to capture CO_2 from the atmosphere holds the potential to create a global market worth billions of dollars for CO_2 utilization in the concrete industry. However, these technologies face numerous challenges, such as producing high-quality products, reducing CO_2 emissions throughout the entire lifecycle, and raising public awareness of CO_2 emissions in products. Additionally, significant challenges are associated with the commercialization of these technologies, including the high cost of CO_2 and strict requirements from various institutions. As more companies enter the emerging CO_2 utilization market, competition and risks are increasing.

To effectively manage accelerated carbonation curing at a commercial scale and prevent excessive carbonation, the implementation of a meticulous yet practical assessment system is crucial. This system should encompass a range of quantitative parameters such as CO_2 absorption, carbonation depth, and carbonation duration. Developing such an evaluation system necessitates extensive research on early-stage carbonation curing of cement-based materials under varying carbonation conditions. Furthermore, the lack of

Table 5
Benefits and drawbacks of common CO_2 use systems for producing low-carbon concrete. Summarized by earlier research [3,14,51,65,69,152].

Company	Product	Advantages	Disadvantages
CarbonCure	Concrete	**1)** Without of corrosion; **2)** Can not impact the properties of concrete; **3)** CO_2 reduction of roughly 25 lb/Y3	Only 10 wt% of CO_2 can be sequestered
Solidia	Cement and Concrete	Permanently store 300 kg of CO_2 per ton during the manufacturing of concrete	Applicable in the precast system only
Carbicrete	Carbonated blocks	**1)** Reducing 20,000 tons of CO_2 emission; **2)** Reducing 33,000 tons of landfill waste;	Curing is only possible in a regulated environment
Novacem	Cement	**1)** Savings per ton of 50–100 kg CO_2	High pressure is necessary for curing.
Heidelberg	Cement	**1)** Recyclable; **2)** Creating composite cement with clinker concentration as low as roughly 70 %	**1)** Low market share growth **2)** Curing required high pressure

systematic assessment of early-stage carbonation curing on cement-based composites containing pre-carbonated ingredients represents a significant research gap, hindering the utilization of such materials in the concrete industry. Addressing this gap is essential for advancing the effective use of pre-carbonated ingredients in concrete production.

7. Remaining challenges and conclusions

The utilization of CO_2 in cement concrete production has gained significant momentum over the past decade, offering substantial environmental benefits. We have discussed and reviewed relevant publications from the period of 2014–2024, leading to the identification of key findings and remaining challenges as follows:

1) Addressing climate change requires expedited action, with accelerated carbonation proving significantly more advantageous than natural weathering processes. Various technologies, including direct aqueous carbonation, carbonation mixing, and carbonation curing, demonstrate substantial promise in this context. A holistic approach that combines different carbonation methods with concrete recycling within a circular economy framework could establish a significant carbon sink. Consequently, comprehensive life cycle analyses and economic assessments of these technologies are crucial.
2) The complex interplay of factors such as pre-hydration durations and early-stage carbonation curing times on cement-based materials necessitates in-depth investigation. It is essential to construct a database detailing the effects of these diverse factors on material performance during early-stage carbonation curing. Developing statistical models, and utilizing machine learning and numerical simulations, can enhance the prediction of concrete carbonation depth and recommend protective measures.
3) To facilitate the widespread adoption of innovative materials incorporating sequestered CO_2, further fundamental research is essential. This research should thoroughly investigate the carbonation mechanisms, characteristics of novel construction materials, concrete mix formulations, mechanical properties, and durability aspects.
4) C-S-H, a primary component of cementitious materials, has significant potential for CO_2 capture through carbonation. While some studies have investigated the carbonation behaviors of C-S-H in relation to concrete durability, a comprehensive examination of C-S-H carbonation kinetics and the alterations that occur during the process is still needed.
5) Carbonation of RCA exploits the residual CH within the adhered old paste, resulting in the formation of $CaCO_3$. This formation enhances the solid volume and reduces porosity, thereby improving the mechanical properties, durability, and resistance to external factors in concrete that incorporate carbonated RCAs.
6) Implementing a robust assessment system is essential for managing accelerated carbonation curing on a commercial scale. This system should encompass quantifiable parameters to effectively monitor and control the process. Additionally, it must address the current lack of systematic evaluation of early-stage carbonation curing in cement-based composites that incorporate pre-carbonated materials, which poses a significant challenge to their widespread adoption in the concrete industry.
7) Optimization of CO_2 utilization processes is necessary to maximize efficiency and effectiveness. This includes refining the carbonation techniques to ensure optimal CO_2 absorption and minimizing any adverse effects on the concrete properties. Research should focus on the ideal conditions for carbonation, such as temperature, pressure, and duration, to enhance the overall performance of the concrete.
8) The successful implementation of CO_2 utilization technologies in concrete production requires substantial economic and policy support. Governments and industry stakeholders need to provide incentives, subsidies, and regulatory frameworks that encourage the adoption of these sustainable practices. This includes funding for research and development, as well as creating awareness about the benefits of low-carbon concrete among builders and consumers.

Overall, the utilization of CO_2 in cement concrete production presents a promising avenue for mitigating climate change and promoting sustainability in the construction industry. Despite significant advancements, several challenges remain, including the need for extensive research, optimized processes, robust assessment systems, and strong economic and policy support. Addressing these challenges will pave the way for the widespread adoption of low-carbon concrete, contributing to a more sustainable future.

CRediT authorship contribution statement

Dong Lu: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Fulin Qu:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Chao Zhang:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Yipu Guo:** Writing – review & editing, Data curation. **Zhiyu Luo:** Writing – review & editing. **Lei Xu:** Writing – review & editing. **Wengui Li:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors appreciate the support from the Australian Research Council (ARC), Australia (FT220100177; LP230100288; DP220101051; IH180100010; DP220100036) .

Data availability

Data will be made available on request.

References

[1] O. Cavalett, M.D.B. Watanabe, M. Voldsund, S. Roussanaly, F. Cherubini, Paving the way for sustainable decarbonization of the European cement industry, Nat. Sustain. 7 (5) (2024) 568–580.
[2] L. Fu, Z. Ren, W. Si, Q. Ma, W. Huang, K. Liao, Z. Huang, Y. Wang, J. Li, P. Xu, Research progress on CO_2 capture and utilization technology, J. CO2 Util. 66 (2022).
[3] M. Hanifa, R. Agarwal, U. Sharma, P.C. Thapliyal, L.P. Singh, A review on CO_2 capture and sequestration in the construction industry: emerging approaches and commercialised technologies, J. CO2 Util. 67 (2023).
[4] P. Ji, H. Lin, S. Li, X. Kong, X. Wang, J. Zhang, B. Zhu, X. Lin, Technical system and prospects for precise methane extraction in the entire life cycle of coal mining under the goal of “carbon peak and carbon neutrality”, Geoenergy Sci. Eng. 238 (2024).
[5] H. Xiao, Z. Xu, J. Ren, Y. Zhou, R. Lin, S. Bao, L. Zhang, S. Lu, C.K.M. Lee, J. Liu, Navigating Chinese cities to achieve sustainable development goals by 2030, Innovation 3 (5) (2022) 100288.
[6] X. Li, W. Xie, T. Yang, C. Lin, C.Y. Jim, Carbon emission evaluation of prefabricated concrete composite plates during the building materialization stage, Build. Environ. 232 (2023).
[7] X.-J. Li, W.-J. Xie, C.Y. Jim, F. Feng, Holistic LCA evaluation of the carbon footprint of prefabricated concrete stairs, J. Clean. Prod. 329 (2021).
[8] M. Liu, Y. Cai, Q. Liu, X.T. Jin, C. Xue, S.X. Zhang, P. Feng, Y.H. Luo, Porous calcium-silicate-hydrate as a low-cost nano-platform for ultra-high $CO(_2)$ capture and storage, Small Methods (2023) e2301337.
[9] D.A. Salas, A.J. Boero, A.D. Ramirez, Life cycle assessment of bioenergy with carbon capture and storage: a review, Renew. Sustain. Energy Rev. 199 (2024).
[10] X.-J. Li, Y.-d. Zheng, Using LCA to research carbon footprint for precast concrete piles during the building construction stage: a China study, J. Clean. Prod. 245 (2020).
[11] P.J.M. Monteiro, S.A. Miller, A. Horvath, Towards sustainable concrete, Nat. Mater. 16 (7) (2017) 698–699.
[12] M. Mahoutian, Y. Shao, Production of cement-free construction blocks from industry wastes, J. Clean. Prod. 137 (2016) 1339–1346.
[13] B. Zhang, Durability of low-carbon geopolymer concrete: a critical review, Sust. Mater. Tech (2024) 40.
[14] L. Li, M. Wu, An overview of utilizing CO_2 for accelerated carbonation treatment in the concrete industry, J. CO2 Util. 60 (2022).
[15] F. Althoey, Y. Farnam, The effect of using supplementary cementitious materials on damage development due to the formation of a chemical phase change in cementitious materials exposed to sodium chloride, Construct. Build. Mater. 210 (2019) 685–695.
[16] B. Lothenbach, K. Scrivener, R.D. Hooton, Supplementary cementitious materials, Cement Concr. Res. 41 (12) (2011) 1244–1256.
[17] W. Wang, C. Lu, Y. Li, G. Yuan, Q. Li, Effects of stress and high temperature on the carbonation resistance of fly ash concrete, Construct. Build. Mater. 138 (2017) 486–495.
[18] A.S.M.A. Awal, I.A. Shehu, M. Ismail, Effect of cooling regime on the residual performance of high-volume palm oil fuel ash concrete exposed to high temperatures, Construct. Build. Mater. 98 (2015) 875–883.
[19] S. Bhanja, B. Sengupta, Influence of silica fume on the tensile strength of concrete, Cement Concr. Res. 35 (4) (2005) 743–747.
[20] O. Burciaga-Díaz, J.I. Escalante-García, Comparative performance of alkali activated slag/metakaolin cement pastes exposed to high temperatures, Cement Concr. Compos. 84 (2017) 157–166.
[21] B. Li, T.-C. Ling, J.-G. Yu, J. Wu, W. Chen, Cement pastes modified with recycled glass and supplementary cementitious materials: properties at the ambient and high temperatures, J. Clean. Prod. 241 (2019).
[22] T. Xie, M.S. Mohamad Ali, M. Elchalakani, P. Visintin, Modelling fresh and hardened properties of self-compacting concrete containing supplementary cementitious materials using reactive moduli, Construct. Build. Mater. 272 (2021).
[23] Y. Huo, S. Hu, D. Lu, X. Han, H. Sun, X. Ma, T. Liu, C. Zhang, Z. Chen, J. Huang, Y. Yang, Understanding the roles of Li_2CO_3 in a sulphoaluminate cement system at negative temperatures, Case Stud. Constr. Mater. 19 (2023).
[24] Y. Huo, J. Huang, D. Lu, X. Han, H. Sun, T. Liu, J. Wang, F. Wang, P. Tan, M. Wang, J. Zhou, Y. Yang, Durability of alkali-activated slag concrete incorporating silica fume and rice husk ash, J. Build. Eng. 78 (2023).
[25] Y. Huo, J. Huang, N. Xu, D. Lu, X. Han, H. Sun, S. Hu, T. Liu, J. Wang, J. Zhou, Y. Yang, Comparison of stearic acid and oleic acid for shrinkage-mitigating of alkali-activated slag composites, J. Sustain. Cement Base Mater. (2023) 1–14.
[26] J. Lu, Z. Cai, Y. Gao, Y. Yin, Z. Ma, C. Liang, Effects of pretreatment methods on the properties of recycled aggregates and prepared concrete under CO_2-curing, Case Stud. Constr. Mater. 18 (2023).
[27] C. Pan, Y. Song, Y. Zhao, T. Meng, Y. Zhang, R. Chen, X. Zhou, S. Ruan, Performance buildup of reactive magnesia cement (RMC) formulation via using CO_2-strengthened recycled concrete aggregates (RCA), J. Build. Eng. 65 (2023).
[28] W. Xing, V.W.Y. Tam, K.N. Le, A. Butera, J.L. Hao, J. Wang, Effects of mix design and functional unit on life cycle assessment of recycled aggregate concrete: evidence from CO_2 concrete, Construct. Build. Mater. 348 (2022).
[29] Y. Tian, X. Yan, D. Lu, T. Yang, Z. Wang, W. Li, Internal transport and corrosion behaviors of sulfate corrosion media carried by recycled aggregate in concrete, Construct. Build. Mater. 260 (2020) 120480.
[30] L.R. Steiner, A.M. Bernardin, F. Pelisser, Effectiveness of ceramic tile polishing residues as supplementary cementitious materials for cement mortars, Sust. Mater. Tech 4 (2015) 30–35.
[31] N. Makul, Modern sustainable cement and concrete composites: review of current status, challenges and guidelines, Sust. Mater. Tech (2020) 25.
[32] T.M. Oyinkanola, D.K. Panesar, Natural carbonation of uncracked and cracked concrete: sensitivity of regional geographical variations on the CO_2 uptake-to-emissions ratio compared to global estimates, Construct. Build. Mater. 409 (2023).
[33] E. Ozturk, C. Ince, S. Derogar, R. Ball, Factors affecting the CO_2 emissions, cost efficiency and eco-strength efficiency of concrete containing rice husk ash: a database study, Construct. Build. Mater. 326 (2022).
[34] G. Zhang, J. Liu, J. Qian, X. Zhang, Z. Liu, Review of research progress and stability studies of amine-based biphasic absorbents for CO_2 capture, J. Ind. Eng. Chem. 134 (2024) 28–50.
[35] X. Liu, P. Feng, Y. Cai, X. Yu, C. Yu, Q. Ran, Carbonation behavior of calcium silicate hydrate (C-S-H): its potential for CO_2 capture, Chem. Eng. J. 431 (2022).
[36] Y. Pu, L. Li, Q. Wang, X. Shi, C. Luan, G. Zhang, L. Fu, A. El-Fatah Abomohra, Accelerated carbonation technology for enhanced treatment of recycled concrete aggregates: a state-of-the-art review, Construct. Build. Mater. 282 (2021).
[37] F. Qu, W. Xia, C. Sun, H. Hou, B. Huang, G. Wang, S. Hu, Modeling carbonation depth of recycled aggregate concrete containing chlorinated salts, Construct. Build. Mater. 430 (2024).
[38] C. Schiefer, J. Plank, CO_2 emission of polycarboxylate superplasticizers (PCEs) used in concrete, J. Clean. Prod. 427 (2023).
[39] Y. Tao, M. Brander, A comparative prospective life cycle assessment of coal-fired power plants in the US with MEA/MOF-based carbon capture, J. Clean. Prod. 456 (2024).
[40] Z. Wu, Z. Zhu, X. Zhang, L. Zhou, K. Zhang, P. Wu, New insights into carbon capture and re-direction technologies for wastewater resource recovery: a critical review, J. Water Proc. Eng. 59 (2024).
[41] B. Li, Z. Jiang, N. Jin, Y. Tian, X. Jin, Carbonation process simulation for cement-based materials based on microstructure by a cement hydration model, Construct. Build. Mater. 259 (2020).
[42] H. Patel, A. Mohanty, M. Misra, Post-combustion CO_2 capture using biomass based activated porous carbon: latest advances in synthesis protocol and economics, Renew. Sustain. Energy Rev. 199 (2024).
[43] D. Lu, X. Jiang, Z. Leng, Y. Huo, D. Wang, J. Zhong, Electrically conductive asphalt concrete for smart and sustainable pavement construction: a review,

Construct. Build. Mater. 406 (2023) 133433.
[44] S.Y.W. Chai, L.H. Ngu, B.S. How, M.Y. Chin, K. Abdouka, M.J.B.A. Adini, A.M. Kassim, Review of CO_2 capture in construction-related industry and their utilization, Int. J. Greenh. Gas Control 119 (2022).
[45] Y. Chang, S. Gao, Q. Ma, Y. Wei, G. Li, Techno-economic analysis of carbon capture and utilization technologies and implications for China, Renew. Sustain. Energy Rev. 199 (2024).
[46] M.-Y. Xuan, R.-S. Lin, Y. Han, G.-y. Zhang, C. Guo, X.-Y. Wang, Produce low-CO_2 silica fume hybrid high-strength concrete using dry ice (solid CO_2) as a CO_2-utilized admixture, J. Clean. Prod. 458 (2024).
[47] F. Wang, J.D. Harindintwali, Z. Yuan, M. Wang, F. Wang, S. Li, Z. Yin, L. Huang, Y. Fu, L. Li, S.X. Chang, L. Zhang, J. Rinklebe, Z. Yuan, Q. Zhu, L. Xiang, D.C.W. Tsang, L. Xu, X. Jiang, J. Liu, N. Wei, M. Kastner, Y. Zou, Y.S. Ok, J. Shen, D. Peng, W. Zhang, D. Barcelo, Y. Zhou, Z. Bai, B. Li, B. Zhang, K. Wei, H. Cao, Z. Tan, L.B. Zhao, X. He, J. Zheng, N. Bolan, X. Liu, C. Huang, S. Dietmann, M. Luo, N. Sun, J. Gong, Y. Gong, F. Brahushi, T. Zhang, C. Xiao, X. Li, W. Chen, N. Jiao, J. Lehmann, Y.G. Zhu, H. Jin, A. Schaffer, J.M. Tiedje, J.M. Chen, Technologies and perspectives for achieving carbon neutrality, Innovation 2 (4) (2021) 100180.
[48] S.I. Eyitayo, C.J. Okere, A. Hussain, T. Gamadi, M.C. Watson, Synergistic sustainability: future potential of integrating produced water and $CO(_2)$ for enhanced carbon capture, utilization, and storage (CCUS), J. Environ. Manag. 351 (2024) 119713.
[49] M. Liu, S. Hong, Y. Wang, J. Zhang, D. Hou, B. Dong, Compositions and microstructures of hardened cement paste with carbonation curing and further water curing, Construct. Build. Mater. 267 (2021).
[50] X. Liu, P. Feng, C.R. Agudo, H. Sun, X. Yu, J. Avaro, J. Huang, D. Hou, Q. Ran, J. Hong, J. Liu, C. Miao, H. Cölfen, High energy absorption nacre-like calcium silicate hydrate (C-S-H) composite toward elastic cementitious materials, Adv. Funct. Mater. 34 (7) (2023).
[51] Supriya, R. Chaudhury, U. Sharma, P.C. Thapliyal, L.P. Singh, Low-CO_2 emission strategies to achieve net zero target in cement sector, J. Clean. Prod. 417 (2023).
[52] M. Ehsani, M. Ostovari, S. Mansouri, H. Naseri, H. Jahanbakhsh, F. Moghadas Nejad, Machine learning for predicting concrete carbonation depth: a comparative analysis and a novel feature selection, Construct. Build. Mater. 417 (2024).
[53] M.I. Haque, R.I. Khan, W. Ashraf, H. Pendse, Production of sustainable, low-permeable and self-sensing cementitious composites using biochar, Sust. Mater. Tech (2021) 28.
[54] T.P. da Costa, P. Quinteiro, L. Arroja, A.C. Dias, Environmental performance of different end-of-life alternatives of wood fly ash by a consequential perspective, Sust. Mater. Tech 32 (2022).
[55] F. Winnefeld, A. Leemann, A. German, B. Lothenbach, CO_2 storage in cement and concrete by mineral carbonation, Curr. Opin. Green Sustainable Chem. 38 (2022).
[56] X. Zhang, S. Liu, K. Wu, Z. Yuan, Experimental investigation into the self-carbonation mechanism of magnesium oxide carbon sequestration foamed concrete, Cement Concr. Compos. 148 (2024).
[57] R. Sharma, J. Pei, J.G. Jang, Microstructural evolution of belite-rich cement mortar subjected to water, carbonation, and hybrid curing regime, Cement Concr. Compos. 139 (2023).
[58] R. Alizadeh, L. Raki, J.M. Makar, J.J. Beaudoin, I. Moudrakovski, Hydration of tricalcium silicate in the presence of synthetic calcium–silicate–hydrate, J. Mater. Chem. 19 (42) (2009).
[59] E. Berodier, K. Scrivener, G. Scherer, Understanding the filler effect on the nucleation and growth of C-S-H, J. Am. Ceram. Soc. 97 (12) (2014) 3764–3773.
[60] E. John, J.D. Epping, D. Stephan, The influence of the chemical and physical properties of C-S-H seeds on their potential to accelerate cement hydration, Construct. Build. Mater. 228 (2019).
[61] H. Manzano, J.S. Dolado, A. Guerrero, A. Ayuela, Mechanical properties of crystalline calcium-silicate-hydrates: comparison with cementitious C-S-H gels, Phys. Status Solidi 204 (6) (2007) 1775–1780.
[62] C. Zhong, X. Chen, W. Mao, S. Xin, J. Chen, J. Zhou, Carbonation resistance of recycled fine aggregate concrete reinforced by calcium sulfate whiskers, J. Build. Eng. 92 (2024) 109476.
[63] J. Zhu, D. Ma, S. Liu, X. Guan, S.P. Shah, The influence of nano-SiO_2 on the carbonation properties of low calcium CO2 sequestration binder and its mechanism, Construct. Build. Mater. 416 (2024).
[64] T. Sato, F. Diallo, Seeding effect of nano-$CaCO_3$ on the hydration of tricalcium silicate, Transport. Res. Rec.: J. Transport. Res. Board 2141 (1) (2010) 61–67.
[65] E. Gartner, H. Hirao, A review of alternative approaches to the reduction of CO_2 emissions associated with the manufacture of the binder phase in concrete, Cement Concr. Res. 78 (2015) 126–142.
[66] Y. Gao, Y. Jiang, Y. Tao, P. Shen, C.S. Poon, Accelerated carbonation of recycled concrete aggregate in semi-wet environments: a promising technique for CO_2 utilization, Cement Concr. Res. 180 (2024).
[67] Z. Liu, P. Van den Heede, C. Zhang, X. Shi, L. Wang, J. Li, Y. Yao, B. Lothenbach, N. De Belie, Carbonation of blast furnace slag concrete at different CO_2 concentrations: carbonation rate, phase assemblage, microstructure and thermodynamic modelling, Cement Concr. Res. 169 (2023).
[68] F. Kaddah, H. Ranaivomanana, O. Amiri, E. Rozière, Accelerated carbonation of recycled concrete aggregates: investigation on the microstructure and transport properties at cement paste and mortar scales, J. CO2 Util. 57 (2022).
[69] M. Lei, Z. Liu, F. Wang, Review of lightweight cellular concrete: towards low-carbon, high-performance and sustainable development, Construct. Build. Mater. 429 (2024).
[70] C.S. Poon, P. Shen, Y. Jiang, Z. Ma, D. Xuan, Total recycling of concrete waste using accelerated carbonation: a review, Cement Concr. Res. 173 (2023).
[71] C. Liang, B. Li, M.-Z. Guo, S. Hou, S. Wang, Y. Gao, X. Wang, Effects of early-age carbonation curing on the properties of cement-based materials: a review, J. Build. Eng. 84 (2024).
[72] Y. Pu, L. Li, X. Shi, Q. Wang, A. Abomohra, Recent advances in accelerated carbonation for improving cement-based materials and CO_2 mitigation from a life cycle perspective, Construct. Build. Mater. 388 (2023).
[73] J. Bawab, H. El-Hassan, A. El-Dieb, J. Khatib, Accelerated carbonation curing of concrete incorporating calcium carbide residue, J. Build. Eng. 88 (2024).
[74] X. Shang, Y. Chen, Y. Qi, J. Chang, J. Yang, N. Qu, Comparative life cycle environmental assessment of recycled aggregates concrete blocks using accelerated carbonation curing and traditional methods, Construct. Build. Mater. 404 (2023).
[75] M. El-Hallak, H. El-Hassan, A. El-Dieb, A. Alzamly, Synergic effect of metal-organic frameworks and process parameters on the properties of concrete subjected to accelerated carbonation, Construct. Build. Mater. 414 (2024).
[76] Y. Tang, J. Xiao, H. Zhang, D. Wang, M. Zhang, J. Zhang, Effect of accelerated carbonation of fully recycled aggregates on fracture behaviour of concrete, Cement Concr. Compos. 148 (2024).
[77] X. Wang, M.-Z. Guo, T.-C. Ling, Review on CO_2 curing of non-hydraulic calcium silicates cements: mechanism, carbonation and performance, Cement Concr. Compos. 133 (2022).
[78] N. Li, C. Unluer, Enhancement of the wet carbonation of artificial recycled concrete aggregates in seawater, Cement Concr. Res. 175 (2024).
[79] Q. Xue, L. Zhang, K. Mei, X. Li, P. Newell, Y. Wang, X. Cheng, W. Zheng, CO_2-induced evolution of chemical, structural and mechanical properties of reinforced concrete: a review, Construct. Build. Mater. 353 (2022).
[80] B. Dong, G. Fang, Y. Liu, P. Dong, J. Zhang, F. Xing, S. Hong, Monitoring reinforcement corrosion and corrosion-induced cracking by X-ray microcomputed tomography method, Cement Concr. Res. 100 (2017) 311–321.
[81] Q. Xue, L. Zhang, K. Mei, L. Wang, Y. Wang, X. Li, X. Cheng, H. Liu, Evolution of structural and mechanical properties of concrete exposed to high concentration CO_2, Construct. Build. Mater. 343 (2022).
[82] L. Zhang, Q. Xue, K. Mei, X. Li, Y. Wang, X. Cheng, X. Fu, Bonding strength evolution of the steel-concrete interface exposed to high concentration CO_2 up to 1000 kPa partial pressure, Construct. Build. Mater. 417 (2024).
[83] H. Wu, C. Liang, J. Xiao, Z. Ma, Properties and CO_2-curing enhancement of cement-based materials containing various sources of waste hardened cement paste powder, J. Build. Eng. 44 (2021).
[84] D. Xuan, B. Zhan, C.S. Poon, Development of a new generation of eco-friendly concrete blocks by accelerated mineral carbonation, J. Clean. Prod. 133 (2016) 1235–1241.

[85] C. Shi, Z. Wu, Z. Cao, T.C. Ling, J. Zheng, Performance of mortar prepared with recycled concrete aggregate enhanced by CO_2 and pozzolan slurry, Cement Concr. Compos. 86 (2018) 130–138.
[86] Y. Li, T. Fu, R. Wang, Y. Li, An assessment of microcracks in the interfacial transition zone of recycled concrete aggregates cured by CO_2, Construct. Build. Mater. 236 (2020).
[87] Z. Tu, M.-z. Guo, C.S. Poon, C. Shi, Effects of limestone powder on $CaCO_3$ precipitation in CO_2 cured cement pastes, Cement Concr. Compos. 72 (2016) 9–16.
[88] W. Tang, B. Zhan, C. Wu, S.-c. Kou, Experimental investigation and mathematical modelling of the carbon dioxide sequestration of cement pastes during pressurized CO_2 curing, Construct. Build. Mater. 302 (2021).
[89] L. Li, C.S. Poon, J. Xiao, D. Xuan, Effect of carbonated recycled coarse aggregate on the dynamic compressive behavior of recycled aggregate concrete, Construct. Build. Mater. 151 (2017) 52–62.
[90] X. Fang, B. Zhan, C.S. Poon, Enhancing the accelerated carbonation of recycled concrete aggregates by using reclaimed wastewater from concrete batching plants, Construct. Build. Mater. 239 (2020).
[91] H. Gao, H. Liao, M. Wang, F. Cheng, Reinforcing the physicochemical properties of concrete through synergism of CO_2 curing and $Ca(OH)_2$ solution drenching, Construct. Build. Mater. 280 (2021).
[92] Y. Pu, L. Li, Q. Wang, X. Shi, L. Fu, G. Zhang, C. Luan, A.E.-F. Abomohra, Accelerated carbonation treatment of recycled concrete aggregates using flue gas: a comparative study towards performance improvement, J. CO2 Util. 43 (2021).
[93] Y. Wu, H. Mehdizadeh, K.H. Mo, T.-C. Ling, High-temperature CO_2 for accelerating the carbonation of recycled concrete fines, J. Build. Eng. 52 (2022).
[94] Y. Zhang, H. Chen, Q. Wang, Accelerated carbonation of regenerated cementitious materials from waste concrete for CO_2 sequestration, J. Build. Eng. 55 (2022).
[95] Y. Zhang, H. Qi, C. Li, J. Zhou, Enhancing safety, sustainability, and economics in mining through innovative pillar design: a state-of-the-art review, J.Saf. Sustain. 1 (1) (2024) 53–73.
[96] S. Kim, J. Seo, S. Park, H.K. Lee, Effect of accelerated carbonation curing on thermal evolution of hydrates in calcium sulfoaluminate cement, Construct. Build. Mater. 416 (2024).
[97] M.-Y. Xuan, S.-h. Lee, H.-q. Hu, X.-Y. Wang, Adding dry ice into ultra-high-performance concrete to enhance engineering performances and lower CO_2 emissions, Construct. Build. Mater. 392 (2023).
[98] D. Zhang, $CO(_2)$ utilization for concrete production: commercial deployment and pathways to net-zero emissions, Sci. Total Environ. 931 (2024) 172753.
[99] A. Gasós, M. Meijssen, M. Mazzotti, Indirect mineral carbonation of recycled concrete aggregate: enhancing calcium extraction using a packed bed reactor, J. Clean. Prod. 449 (2024).
[100] F.W. Jativa, L.E. Dalton, M. Pourghaz, Gas CO_2 foaming and intermixing in portland cement paste to sequester CO_2, Cement 16 (2024) 100099.
[101] X. Li, T.-C. Ling, Instant CO_2 curing for dry-mix pressed cement pastes: consideration of CO2 concentrations coupled with further water curing, J. CO2 Util. 38 (2020) 348–354.
[102] Y. Li, W. Liu, T. Mi, X. Ding, L. Tang, F. Xing, Durability study of seawater and sea-sand concrete under the combined effects of carbonation and chloride redistribution, J. Build. Eng. 89 (2024).
[103] Q. Guan, Y. Ma, M. Jin, H. Zeng, C. Gao, J. Tang, J. Liu, F. Han, W. Li, J. Liu, Carbonation curing of belite-rich cement: the role of fly ash and strengthening mechanism, Cement Concr. Compos. 149 (2024).
[104] H.M. Hamada, A. Al-Attar, F. Abed, S. Beddu, A.M. Humada, A. Majdi, S.T. Yousif, B.S. Thomas, Enhancing sustainability in concrete construction: a comprehensive review of plastic waste as an aggregate material, Sust. Mater. Tech (2024) 40.
[105] Z. Luo, F. Ren, J. Dang, H. Du, Sustainable utilization of low-value lithium-ion battery wastes in cement and concrete, Sust. Mater. Tech (2024) 40.
[106] M.U. Hossain, C.S. Poon, I.M.C. Lo, J.C.P. Cheng, Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach, Int. J. Life Cycle Assess. 21 (1) (2015) 70–84.
[107] C.M.V.B. Almeida, D. Borges, S.H. Bonilla, B.F. Giannetti, Identifying improvements in water management of bus-washing stations in Brazil, Resour. Conserv. Recycl. 54 (11) (2010) 821–831.
[108] X. Qian, J. Wang, Y. Fang, L. Wang, Carbon dioxide as an admixture for better performance of OPC-based concrete, J. CO2 Util. 25 (2018) 31–38.
[109] S. Monkman, M. MacDonald, Carbon dioxide upcycling into industrially produced concrete blocks, Construct. Build. Mater. 124 (2016) 127–132.
[110] D. Zhang, Z. Ghouleh, Y. Shao, Review on carbonation curing of cement-based materials, J. CO2 Util. 21 (2017) 119–131.
[111] S. Monkman, M. MacDonald, R.D. Hooton, P. Sandberg, Properties and durability of concrete produced using CO_2 as an accelerating admixture, Cement Concr. Compos. 74 (2016) 218–224.
[112] J. Herrera-González, G. Ortiz-Rabell, J. Xilotl-Domínguez, O. Ojeda-Farias, I. Flores-Vivian, F. Vázquez-Leal, G. Fajardo-San-Miguel, Use of waste material from the chemical industry for the production of low-strength concrete hollow blocks, Sust. Mater. Tech 40 (2024).
[113] T. Chen, L. Zhao, X. Gao, L. Li, L. Qin, Modification of carbonation-cured cement mortar using biochar and its environmental evaluation, Cement Concr. Compos. 134 (2022).
[114] S. Siddique, A. Naqi, J.G. Jang, Influence of water to cement ratio on CO_2 uptake capacity of belite-rich cement upon exposure to carbonation curing, Cement Concr. Compos. 111 (2020).
[115] B. Tang, M. Fan, Z. Yang, Y. Sun, L. Yuan, A comparison study of aggregate carbonation and concrete carbonation for the enhancement of recycled aggregate pervious concrete, Construct. Build. Mater. 371 (2023).
[116] L. Li, N. Ziyabek, Y. Jiang, J. Xiao, C.S. Poon, Effect of carbonation duration on properties of recycled aggregate concrete, Case Stud. Constr. Mater. 19 (2023).
[117] E.M. Golafshani, A. Behnood, T. Kim, T. Ngo, A. Kashani, Metaheuristic optimization based- ensemble learners for the carbonation assessment of recycled aggregate concrete, Appl. Soft Comput. 159 (2024).
[118] S. Zhang, Q. Yuan, J. Ni, K. Zheng, Y. Xu, J. Zhang, $CO(_2)$ utilization and sequestration in ready-mix concrete-A review, Sci. Total Environ. 907 (2024) 168025.
[119] Y. Tang, J. Qiu, CO_2-sequestering ability of lightweight concrete based on reactive magnesia cement and high-dosage biochar aggregate, J. Clean. Prod. 451 (2024).
[120] Y. Yang, Y. Lai, L. Xu, W. Wang, J. Fang, Q. Yuan, K. Wu, Z. Yang, Effect of ZnO on the clinkerization and carbonation behavior of γ-C_2S, Sust. Mater. Tech 40 (2024).
[121] M. Feng, M. Li, H. Qu, D. Tian, M. Lu, T. Gui, G. Li, Degradation mechanism and evaluation of the carbonation resistance of concrete after high-temperature exposure, Structures 58 (2023).
[122] C. Rodriguez-Navarro, T. Ilić, E. Ruiz-Agudo, K. Elert, Carbonation mechanisms and kinetics of lime-based binders: an overview, Cement Concr. Res. 173 (2023).
[123] S. Monkman, M. MacDonald, On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete, J. Clean. Prod. 167 (2017) 365–375.
[124] J. Di Filippo, J. Karpman, J.R. DeShazo, The impacts of policies to reduce CO_2 emissions within the concrete supply chain, Cement Concr. Compos. 101 (2019) 67–82.
[125] K.M. Anwar Hossain, High strength blended cement concrete incorporating volcanic ash: performance at high temperatures, Cement Concr. Compos. 28 (6) (2006) 535–545.
[126] D. Lu, Z. Sheng, B. Yan, Z. Jiang, D. Wang, J. Zhong, Rheological behavior of fresh cement composites with graphene oxide-coated silica fume, J. Mater. Civ. Eng. 35 (10) (2023).
[127] Z. Mkahal, W. Maherzi, Y. Mamindy-Pajany, B. Bouzar, N.-E. Abriak, Development of a low-carbon binder based on raw, ground, and carbonated waste paper fly ash, Sust. Mater. Tech 36 (2023).
[128] G. Faneca, I. Segura, J.M. Torrents, A. Aguado, Development of conductive cementitious materials using recycled carbon fibres, Cement Concr. Compos. 92 (2018) 135–144.
[129] M. Mazloom, A.A. Ramezanianpour, J.J. Brooks, Effect of silica fume on mechanical properties of high-strength concrete, Cement Concr. Compos. 26 (4) (2004) 347–357.

[130] P. Nath, P.K. Sarker, Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition, Construct. Build. Mater. 66 (2014) 163–171.

[131] S. Luo, M.-Z. Guo, T.-C. Ling, Mechanical and microstructural performances of fly ash blended cement pastes with mixing CO_2 during fresh stage, Construct. Build. Mater. 358 (2022).

[132] D. Lu, F. Qu, Y. Su, K. Cui, Nano-engineered the interfacial transition zone between recycled fine aggregates and paste with graphene oxide for sustainable cement composites, Cement Concr. Compos. 154 (2024) 105762.

[133] K.L. Scrivener, Backscattered electron imaging of cementitious microstructures: understanding and quantification, Cement Concr. Compos. 26 (8) (2004) 935–945.

[134] P. Suraneni, A. Hajibabaee, S. Ramanathan, Y. Wang, J. Weiss, New insights from reactivity testing of supplementary cementitious materials, Cement Concr. Compos. 103 (2019) 331–338.

[135] L. Chen, Z. Tian, Z. Zhu, R.K.L. Su, Effects of carbonation and sponge wetting solution on diffusion potential of carbonated concrete with supplementary cementitious materials, Construct. Build. Mater. 430 (2024).

[136] Q. Liu, S. Chen, X. He, Y. Su, J. Zeng, Y. Zhu, Y. Pan, B. Zhang, H. Xu, Y. Wu, Surface modification of fly ash by waste engine oil under mechanical activation enhanced the sustainable service life of asphalt, J. Clean. Prod. 404 (2023).

[137] M.A.S. Anjos, A. Camões, P. Campos, G.A. Azeredo, R.L.S. Ferreira, Effect of high volume fly ash and metakaolin with and without hydrated lime on the properties of self-compacting concrete, J. Build. Eng. 27 (2020).

[138] O. Karahan, Transport properties of high volume fly ash or slag concrete exposed to high temperature, Construct. Build. Mater. 152 (2017) 898–906.

[139] F. Qu, W. Li, Z. Tao, A. Castel, K. Wang, High temperature resistance of fly ash/GGBFS-based geopolymer mortar with load-induced damage, Mater. Struct. 53 (4) (2020).

[140] F. Qu, W. Li, K. Wang, S. Zhang, D. Sheng, Performance deterioration of fly ash/slag-based geopolymer composites subjected to coupled cyclic preloading and sulfuric acid attack, J. Clean. Prod. 321 (2021).

[141] H. He, E. Shuang, D. Lu, Y. Hu, C. Yan, H. Shan, C. He, Deciphering size-induced influence of carbon dots on mechanical performance of cement composites, Construct. Build. Mater. 425 (2024) 136030.

[142] M. Mutti, S. Joseph, R. Snellings, Ö. Cizer, Effect of slag pre-carbonation on its early-age reactivity in alkali activated binder, Construct. Build. Mater. 411 (2024).

[143] P. Hu, R. Tanchak, Q. Wang, Developing risk assessment framework for wildfire in the United States - a deep learning approach to safety and sustainability, J.Saf. Sustain. 1 (1) (2024) 26–41.

[144] L. Li, T. Chen, X. Gao, Synergistic effect of CO_2-mineralized steel slag and carbonation curing on cement paste, Cement Concr. Compos. 145 (2024).

[145] R. Manjunath, M.C. Narasimhan, K.M. Umesha, Studies on high performance alkali activated slag concrete mixes subjected to aggressive environments and sustained elevated temperatures, Construct. Build. Mater. 229 (2019).

[146] A. Radović, V. Carević, S. Marinković, J. Plavšić, K. Tešić, Prediction model for calculation of the limestone powder concrete carbonation depth, J. Build. Eng. 86 (2024).

[147] S. Rathnarajan, B.S. Dhanya, R.G. Pillai, R. Gettu, M. Santhanam, Carbonation model for concretes with fly ash, slag, and limestone calcined clay - using accelerated and five - year natural exposure data, Cement Concr. Compos. 126 (2022).

[148] D. Lu, F. Qu, P. Punetha, X. Zeng, Z. Luo, W. Li, Graphene oxide nano-engineered recycled aggregate concrete for sustainable construction: a critical review. Developments in the Built Environment 18, 2024.

[149] R. Infante Gomes, C. Brazão Farinha, R. Veiga, J. de Brito, P. Faria, D. Bastos, CO_2 sequestration by construction and demolition waste aggregates and effect on mortars and concrete performance - an overview, Renew. Sustain. Energy Rev. 152 (2021).

[150] D. Lu, D. Wang, Y. Wang, J. Zhong, Nano-engineering the interfacial transition zone between recycled concrete aggregates and fresh paste with graphene oxide, Construct. Build. Mater. 384 (2023).

[151] D. Lu, X. Jiang, Z. Leng, Sustainable microwave-heating healing asphalt concrete fabricated with waste microwave-sensitive fillers, J. Clean. Prod. 434 (2024).

[152] V.W.Y. Tam, A. Butera, K.N. Le, W. Li, Utilising CO_2 technologies for recycled aggregate concrete: a critical review, Construct. Build. Mater. 250 (2020).

[153] J. Jiang, Y. Tian, D. Lu, X. Lu, K. Ji, K. Jia, J. Zhang, Internal corrosion characteristics of endogenous sulfate introduced by recycled aggregates in recycled aggregates concrete: insights into the macro-mechanical and meso-mechanical properties, J. Clean. Prod. 426 (2023).

[154] D. Lu, C. Fu, X. Jiang, Z. Chen, F. Qu, Y. Huo, Z. Leng, J. Zhong, Sustainable microwave-heating healing asphalt concrete incorporating functional aggregates and waste ferrite, Transport. Res. Transport Environ. 129 (2024).

[155] D. Lu, L.P. Ma, J. Zhong, J. Tong, Z. Liu, W. Ren, H.M. Cheng, Growing nanocrystalline graphene on aggregates for conductive and strong smart cement composites, ACS Nano 17 (4) (2023) 3587–3597.

[156] X. Zhu, T. Wang, Z. Yi, Z. Zhu, Kinetics and structure analysis of CO_2 mineralization for recycled concrete aggregate (RCA), J. Clean. Prod. 448 (2024).

[157] D. Lu, X. Jiang, F. Qu, Y. Huo, Mitigating sulfate ions migration in concrete: a targeted approach to address recycled concrete aggregate's impact, J. Clean. Prod. 442 (2024).

[158] D. Lu, Y. Huo, Z. Jiang, J. Zhong, Carbon nanotube polymer nanocomposites coated aggregate enabled highly conductive concrete for structural health monitoring, Carbon 206 (2023) 340–350.

[159] S.H. Han, S.M. Kim, Y. Jun, T.H. Han, J.H. Kim, Carbon-captured sodium hydroxide solution for sustainable alkali-activated slag, Sust. Mater. Tech 40 (2024).

[160] S. Gupta, Y.-A. Lin, H.-J. Lee, J. Buscheck, R. Wu, J.P. Lynch, N. Garg, K.J. Loh, In situ crack mapping of large-scale self-sensing concrete pavements using electrical resistance tomography, Cement Concr. Compos. 122 (2021).

[161] S.-C. Kou, B.-j. Zhan, C.-S. Poon, Use of a CO_2 curing step to improve the properties of concrete prepared with recycled aggregates, Cement Concr. Compos. 45 (2014) 22–28.

[162] C.-R. Wu, Y.-G. Zhu, X.-T. Zhang, S.-C. Kou, Improving the properties of recycled concrete aggregate with bio-deposition approach, Cement Concr. Compos. 94 (2018) 248–254.

[163] D. Lu, X. Jiang, Z. Leng, S. Zhang, D. Wang, J. Zhong, Dual responsive microwave heating-healing system in asphalt concrete incorporating coal gangue and functional aggregate, J. Clean. Prod. 422 (2023).

[164] B.J. Zhan, D.X. Xuan, C.S. Poon, Enhancement of recycled aggregate properties by accelerated CO_2 curing coupled with limewater soaking process, Cement Concr. Compos. 89 (2018) 230–237.

[165] H. Zhang, T. Ji, H. Liu, S. Su, Modifying recycled aggregate concrete by aggregate surface treatment using sulphoaluminate cement and basalt powder, Construct. Build. Mater. 192 (2018) 526–537.

[166] A. Albayati, Y. Wang, Y. Wang, J. Haynes, A sustainable pavement concrete using warm mix asphalt and hydrated lime treated recycled concrete aggregates, Sust. Mater. Tech 18 (2018).

[167] Y. Pu, L. Li, X. Shi, Q. Wang, A. Abomohra, Improving recycled concrete aggregates using flue gas based on multicyclic accelerated carbonation: performance and mechanism, Construct. Build. Mater. 361 (2022).

[168] V. Letelier, F. Hott, M. Bustamante, B. Wenzel, Effect of recycled coarse aggregate treated with recycled binder paste coating and accelerated carbonation on mechanical and physical properties of concrete, J. Build. Eng. 82 (2024).

[169] J.T. Kolawole, A.J. Babafemi, S.C. Paul, A. du Plessis, Performance of concrete containing Nigerian electric arc furnace steel slag aggregate towards sustainable production, Sust. Mater. Tech 25 (2020).

[170] Z. Lu, Q. Tan, J. Lin, D. Wang, Properties investigation of recycled aggregates and concrete modified by accelerated carbonation through increased temperature, Construct. Build. Mater. 341 (2022).

[171] S. Ahmad, R.A. Assaggaf, M. Maslehuddin, O.S.B. Al-Amoudi, S.K. Adekunle, S.I. Ali, Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing, Construct. Build. Mater. 136 (2017) 565–573.

[172] U. Chandru, A. Bahurudeen, R. Senthilkumar, Systematic comparison of different recycled fine aggregates from construction and demolition wastes in OPC concrete and PPC concrete, J. Build. Eng. 75 (2023).

[173] D. Chen, M. Chen, Y. Zhang, X. Yang, J. Zhang, Y. Zhao, Y. Wu, Development of an environmental foamed concrete incorporating recycled cement concrete powder with carbonation, Construct. Build. Mater. 422 (2024).

[174] S. Luo, Q. Lin, T. Lin, D. Wang, S. Wang, Effects of pressurized carbonation with presoaking in calcium hydroxide solution on the fracture behaviours of recycled coarse aggregate concrete, Construct. Build. Mater. 397 (2023).

[175] W. Ma, B. Lv, Y. Wang, L. Huang, L. Yan, B. Kasal, Freeze-thaw, chloride penetration and carbonation resistance of natural and recycled aggregate concrete containing rice husk ash as replacement of cement, J. Build. Eng. 86 (2024).

[176] A. Leemann, F. Winnefeld, B. Münch, J. Tiefenthaler, Accelerated carbonation of recycled concrete aggregates and its implications for the production of recycling concrete, J. Build. Eng. 79 (2023).

[177] X.Y.D. Soo, J.J.C. Lee, W.-Y. Wu, L. Tao, C. Wang, Q. Zhu, J. Bu, Advancements in CO_2 capture by absorption and adsorption: a comprehensive review, J. CO2 Util. 81 (2024).

[178] M.L. Nehdi, A. Marani, L. Zhang, Is net-zero feasible: systematic review of cement and concrete decarbonization technologies, Renew. Sustain. Energy Rev. 191 (2024).

[179] M.S. Imbabi, C. Carrigan, S. McKenna, Trends and developments in green cement and concrete technology, Int. J. Sustain. Built. Environ. 1 (2) (2012) 194–216.

[180] S. Griffiths, B.K. Sovacool, D.D. Furszyfer Del Rio, A.M. Foley, M.D. Bazilian, J. Kim, J.M. Uratani, Decarbonizing the cement and concrete industry: a systematic review of socio-technical systems, technological innovations, and policy options, Renew. Sustain. Energy Rev. 180 (2023).

[181] H.-J. Ho, Y. Izumi, A. Iizuka, A CO_2 removal technology based on mineral carbonation and the stability of product carbon storage in a cement matrix, Environ. Technol. Innovat. 34 (2024).

[182] J.B. Wietzel, M. Schmidt, Methane emission mapping and quantification in two medium-sized cities in Germany: Heidelberg and Schwetzingen, Atmos. Environ. X 20 (2023).

[183] C.S.L. Vaz, F.N. da Fonseca, D. Voss-Rech, M.A.Z. Mores, A. Coldebella, M.E. Cantao, Wild-type lytic bacteriophages against Salmonella Heidelberg: further characterization and effect of prophylactic therapy in broiler chickens, Res. Vet. Sci. 171 (2024) 105247.

[184] U. Dewald, M. Achternbosch, Why more sustainable cements failed so far? Disruptive innovations and their barriers in a basic industry, Environ. Innov. Soc. Transit. 19 (2016) 15–30.

[185] S.P. Deolalkar, Cement substitutes. Designing Green Cement Plants, 2016, pp. 379–384.