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Review Article

A State-of-the-Art Review of Building a Greener Future: Direction of Carbon Dioxide Curing and Eco-Friendly Concrete

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Abstract - *Growing awareness of global warming and the significant impact of Carbon Dioxide (CO_2) emissions on this issue among the building industry. A key component of the building sector, cement manufacture accounts for around 7% of total CO_2 emissions. The International Energy Agency (IEA) estimates that yearly global CO_2 emissions are around 33.5 billion tons, which emphasizes how urgently research and invention are needed to help solve this problem. Over the past few years, one of the most exciting technologies in sustainable building has been made available by Carbon Cure (CC). This environmentally sustainable method provides concrete properties and eco-friendly building codes by decreasing the cement carbon footprint. Numerous materials and experimental techniques are utilized to investigate the mechanical properties and chemical reactions of CO_2-cured concrete to ensure its longevity and structural integrity. CC technology in traditional construction may contribute to a sustainable future by reducing emissions and ensuring a materials economy. State-of-the-art modern CO_2 curing techniques, the evolution of production, and the introduction of environmentally friendly concrete alongside the potential to deliver the transformation of the building sector into a more sustainable industry are provided in this review.*

Keywords - *CO_2 curing, Carbon Cure technology, Eco-friendly concrete, Sustainable construction, Cement emissions, Carbon sequestration, Green building materials, Climate change mitigation, Mineralization process, Cement sustainability.*

1. Introduction

Portland cement is widely used in concrete manufacturing, and the building sector has long been identified as a major contributor to global Carbon Dioxide (CO_2) emissions. The Conventional concrete production has significant environmental effects, mostly related to CO_2 emissions during cement clinker processing and energy-intensive curing [1]. As an advancement, both eco-friendly concrete technologies [2, 3] and CO_2 curing can be stepping stones to the challenges of cutting carbon footprints and improving concrete [2, 3]. Converging their capacity to reduce environmental challenges and enhance material properties, this review provides a holistic outlook on the progress of CO_2 curing technologies and green cement technologies. Carbonation curing, sometimes referred to as CO_2 curing, is an accelerated reaction between CO_2 and cementitious materials used to increase mechanical strength, lower porosity, and improve durability [4, 5]. This method provides increased long-term performance of the building materials and CO_2 sequestration in concrete. Early carbonation curing has been shown to change the microstructure of cement pastes, thereby improving their strength and durability [6, 7]. Moreover, recycled aggregates have been successfully treated by carbonation curing, thereby enabling more environmentally friendly building methods [8, 9]. Recent studies have examined the efficiency of carbonation curing, which varies with the temperature, pressure, and CO_2 content. It has been demonstrated that by optimizing these parameters, concrete blocks and precast parts have significantly improved mechanical properties and durability [10, 11]. Furthermore, new CO_2-based admixtures and additional cementitious materials [12, 13]. In addition to conventional cementitious materials, advances in carbonation curing cover alternative binders, including waste-derived cementitious systems, calcium silicate-based composites, and steel slag-cement mixes [14, 15]. These creative materials improve CO_2 absorption and support the building sector's circular economy ideas and resource efficiency. Recent research has shown that mineral carbonation improves cementitious materials' thermal resistance and durability under demanding environmental conditions [16, 17]. Carbonation curing has significant benefits, but its general acceptance is still hindered. Scalability, economic viability, and long-term performance at various exposure levels require additional investigation [18, 19]. In addition, the standardization of impositions and regulations for the carbonation hallowing process is essential for its regular and reliable application in the construction industry [20]. This study seeks to critically review recent developments in CO_2 curing and sustainable concrete technologies. The high levels of Portland Cement (PC), on which concrete production depends, are well known as one of the major causes of global Carbon Dioxide (CO_2) emissions. Cement production alone causes 7–8% of CO_2 emissions worldwide, largely because of energy-intensive clinker manufacturing and traditional curing methods [1]. Despite its strength, conventional concrete is increasingly under fire owing to its environmental impact. This trend has placed an urgent demand for sustainable and innovative concrete technologies that meet global carbon reduction targets and deliver equivalent or improved performance.

1.1. Objectives of the Study

This review attempts to address this knowledge deficiency by critically investigating the latest developments in carbonation curing and green concrete technologies. Based on a systematic literature review, two extensive experiments, and industrial cases, this work aims to

- Review of Trends and Applications of CO_2 Curing and Green Binder Technologies
- Assess their combined values to obtain maximum environmental and structural advantages.
- Suggest directions for future research on scalable, standardized, and high-performance methods to achieve this.

Ultimately, this work hopes to see CO_2 curing as a game-changer in sustainable construction: it is a process that does not sacrifice integrity but creates the base material for climate-smart-built systems.

2. Literature Review

Carbonation, which produces calcium carbonates when atmospheric Carbon Dioxide (CO_2) combines with calcium hydroxide, is a well-researched process in concrete. This process is often linked to a decrease in the alkalinity of the concrete, which may cause the reinforcing components to corrode. Nonetheless, it is important to remember that concrete has been shown to benefit greatly from extended exposure to CO_2 during curing.

This prolonged exposure may positively affect several factors, including durability, mechanical qualities, and microscopic structural modifications. In particular, it has been discovered that carbonation increases the resistance to chemical assaults, reduces permeability, and improves compressive strength.

Additionally, it promotes stronger cement particle bonding. Through an enhanced comprehension of carbonation and its benefits, scientists and engineers may more effectively adjust concrete compositions and curing methods to obtain optimal outcomes. However, a great deal of research is still required to completely understand and realize the potential advantages of carbonation in the building sector.

Table 1. Compare studies of the microscopic study

Study	Key Findings	Reference
Chen & Gao (2019)	Mercury Intrusion Porosimetry (MIP) test showed that carbonation reduces large capillary pores, while water curing reduces small capillary pores. Proper pre-curing and controlled carbonation are crucial to prevent C-S-H gel decalcification.	[15]
Meng et al. (2019)	Scanning Electron Microscopy (SEM) revealed that CO_2 curing at 600°C improved the microstructure of cement. XRD and DTG analyses confirmed $Ca(OH)_2$ consumption, forming $CaCO_3$, which altered mechanical and physical properties.	[17]
Sharma & Goyal (2020)	Carbonation densifies concrete as $CaCO_3$ develops in surface voids. TGA analysis indicated 14.1% CO_2 absorption, demonstrating increased density and carbon sequestration.	[18]
Wang et al. (2016)	Carbonation curing improved high-performance cement-bonded particleboard from polluted wood, reducing its carbon footprint. Magnesia-containing cement had additional benefits. The study highlighted the microscopic role of carbonation and its effect on particleboard properties.	[28]

2.1. Recycled Concrete Aggregates (RCA)

The benefits of Carbonation Curing (CC) of recycled aggregates have been highlighted in several studies. These benefits include densification of mortar, decreased porosity and water absorption, improved mechanical qualities, and decreased permeability. Below is an overview of their main conclusions:

Zhan et al. (2014) found that the properties of Recycled Aggregate (RA) are altered by carbonation curing. Carbonation causes the mortar stuck to the Recycled Concrete Aggregate (RCA) to become denser, and aggregates with smaller particle sizes more readily carbonate. The pore volume of concrete decreases during carbonation, which lowers the porosity and water absorption of the material after curing. Curing proceeds quickly over the first two hours and then slows [29].

According to Zhan et al. (2016), the apparent density of concrete increases and the permeability decreases during carbonation curing. Following CO_2 curing, the apparent density increased from 2995 to 2222 kilograms per cubic meter. The amount of recycled material used determines the degree of carbonation. Carbonation curing aids in compensating for the strength loss caused by the recycled aggregate's lower grade. The research found that excessively damp or dry weather is detrimental to carbonation curing, and that concrete blocks must be pre-treated to lower their moisture content. Additionally, it was shown that, in comparison to steam curing, a 2-hour carbonation curing technique yields results of comparable quality [30].

Pan et al. (2017) examined the characteristics of recycled concrete aggregate (RCA) made from demolished concrete and how pre-soaking and carbonation curing might improve it. For carbonation curing, the parameters used were 5% CO_2 concentration, 70% humidity, and 0.04-0.05 mol/kg of Ca(OH)2. After curing, the RCA's water absorption dropped from 4.35% to 1.65%, and its powder content decreased from 14.2% to 9.1%. The water-demand ratio dropped from 1.17 to 1.10, and the crushing value decreased from 18% to 13%. The RCA's compressive strength rose between 0.95 and 1.04 percent [31].

Xuan and Poon et al. (2019) examined How Recycled Coarse Aggregate (RCA) sucked up CO_2 and how it affected the material characteristics. They discovered that during the first phase (less than five hours), the rate at which CO_2 is sequestered is greater and decreases thereafter. Carbon absorption depends on the RCA's properties and carbonation conditions. The mechanical, physical, and microstructural characteristics of RCA were altered by accelerated carbonation. There is a decrease in water absorption and an increase of 10% in the fines content. Additionally, the RCA's permeability drops [32].

The cumulative findings of these studies highlight the benefits of carbonation curing for recycled aggregates, with particular attention paid to densification, decreased porosity and water absorption, enhanced mechanical quality, and decreased permeability. For carbonation curing to be successful, concrete must be properly treated under the right circumstances.

2.2. Research Gaps, Status and Future Trends

Carbonation Curing (CC) is a promising alternative to steam curing for reinforced structures. Despite initial concerns regarding pH reduction and corrosion risks, CC mitigates these issues through hydration. The use of waste materials such as ferrochrome ash and rice husk ash allows for a comprehensive analysis of their properties. CC is an eco-friendly substitute for steam curing because it sequesters CO_2 in concrete, making it a permanent fixture within the structure. The combination of CC with industrial by-products, such as red mud and Ground Granulated Blast Furnace Slag (GGBFS), results in significant compressive strength gains. CC compensates for the strength loss of the recycled coarse aggregate. CC is cost-effective and can accommodate reinforced bars because the concrete core retains its alkaline properties after curing. Overall, CC presents a sustainable, environmentally conscious approach to concrete curing and has immense potential for widespread adoption in the construction industry with continued research and development. Although there are numerous studies on CO_2 emissions from cement production, as well as the waste number of isolated, green-concrete solutions investigated, there is still a lack of comprehensive understanding of how carbonation curing CO_2-based additives and alternative binders can be combined in a synergetic way to improve sustainability and structural behavior. Moreover, most investigations refine laboratory-scale results with scant consideration of the realizability in the industry and long-term durability under practical service.

3. Mechanical Properties

Numerous investigations have delved into the intriguing field of Carbonation Curing (CC) in concrete, highlighting its extraordinary impact on the material characteristics and functionality. An extensive summary of these observations is provided in the table below:

Table 2. The comprehensive overview of the mechanical benefits of carbonation curing in concrete

Reference	Research Focus	Key Findings
Rostami et al. [1]	The microstructure of the OPC paste was subjected to early CC.	CC after hydration resulted in higher compressive strength than hydration alone.
Xuan et al. [2]	Effect of curing duration on strength development	Strength increased after 6 hours of CC; 24-hour CC had reduced or insignificant strength improvement.
Jang and Lee et al. [3]	Mechanical strength of carbon belite-rich OPC mortar	CC increased mechanical strength compared to standard curing.
Monkman et al. [4]	Effect of CO_2 addition on concrete strength	CO_2 significantly enhanced compressive strength and durability.
Liu et al. [5]	Strength development at different ages	CC improved strength at 3, 7, and 28 days, benefiting steel slag cement hydration.
He et al. [6]	CC for three hours, followed by hydration	Increased compressive strength due to CC and hydration synergy.
Zhan et al. [7]	Impact of pressure during CC	A 2-hour CC improved compressive strength and fire resistance in RA concrete.

Wang et al. [8]	Influence of pressure during CC	Pressure (0.5–2.5 MPa) improved strength; moist curing enhanced strength development.
Shi et al. [9]	Chemical interactions in cementitious materials	CO_2 reacted with silicate phases to form stable carbonates, increasing strength.
Ahmad et al. [10]	Effect of ACC duration and pressure	60 psi for 10 hours significantly increased strength and CO_2 uptake.
Xuan et al. [11]	CO_2 absorption rate impact	Quick gas flow and normal humidity improved the strength and maturity index.
Zhang and Shao et al. [12]	Short- and long-term strength in ACC concrete	CC reduced capillary pore capacity and enhanced freeze-thaw resistance.
Sharma and Goyal et al. [13]	Use of cement kiln dust in ACC concrete	Improved compressive strength with rehydration.
Chen and Gao et al. [14]	Impact of pre-curing period	Significant early strength improvement in cement mortars with CC.
He et al. [15]	Flexural strength via CC	Rapid flexural strength development, an alternative to autoclave curing.
Meng et al. [16]	CC benefits on concrete blocks	Higher compressive strength and lower water sorptivity in CC blocks.
Sharma and Goyal et al. [17]	Reinforcement of mechanical strength with ACC	Reaffirmed the strength increase in ACC concrete.
Ahmad et al. [18]	Carbonation depth in self-compacting concrete	Silica fume and limestone powder increased strength and reduced steel corrosion risk.
Chen and Gao et al. [19]	Aggregate-cement paste bonding	6-hour CC enhanced bonding and compressive strength of pervious concrete.
Qin and Gao et al. [20]	Strength loss compensation in waste AAC	CO_2 curing mitigated strength loss at a 10–20% replacement rate.

3.1. Curing Concrete Using Carbon Dioxide

CO_2 Curing's Principles and Chemical Mechanisms is an intriguing method for improving the mechanical qualities and durability of cement-based materials, and concurrently, Carbon Dioxide (CO_2) curing in concrete results in lower carbon emissions. The basic idea of CO_2 curing is the reaction between the calcium-containing components of cement and carbon dioxide, which generates stable Calcium Carbonate ($CaCO_3$) [21].

This method increases the early age strength of concrete and helps with carbon sequestration, thereby lowering the general environmental impact of cement manufacturing. Studies have indicated that by encouraging the development of calcite, which improves the microstructure and densifies the matrix of concrete [22], CO_2 curing accelerates the hydration reactions. Furthermore, changing the pore structure lowers permeability and increases resilience to hostile environmental conditions [23].

3.1.1. Originality / Value

This work is an original synthesis of the developments of CO_2 curing (early age carbonation, CO_2-reactive admixtures, and waste-derived binders), with a particular emphasis on their holistic influence on carbon sequestration, microstructural refinement, and mechanical performance under the same scenario. In contrast to previous summarizations, we incorporate insights from the latest experimental research and industrial trials, providing an overall view of the question and shedding light on the main technical and regulatory barriers at the origin of the industrial upscaling delay. Carbonation curing (also called CO_2 curing) is the fast carbonation reaction of CO_2 with cementitious materials, which gives rise to higher compressive strength, lower porosity, and better durability [4–6]. Apart from the environmental benefits, early carbonation alters the structure of the cement paste, which can enhance the performance and use life of concrete in aggressive environments [7, 8]. The successful use of recycled aggregate treatment [9] and precast elements has recently been reported, with the enhancement of performance depending on temperature, pressure, and CO_2 concentration [10–12]. Furthermore, CO_2-based additives and alternative cementitious materials such as calcium silicate systems, steel slag binders, and industrial by-products have opened up routes that can potentially lead to a more circular and resource-efficient construction industry [13–15]. These new materials enhance the CO_2 uptake capability of concrete and fit into the global trend of circular economy in construction waste. Some studies have also demonstrated the potential of mineral carbonation to improve heat and high-temperature resistance [16, 17]. Nevertheless, standardized devices with cost, scalability, and long-term performance under different environmental exposures remain challenging [18, 19]. The absence of standard industrial procedures for carbonation curing also hampers the general acceptance of this method [20].

Benefits Of CO_2 Curing on Concrete Properties

CO_2 curing has significant advantages over traditional curing methods, particularly in terms of mechanical performance, durability, and sustainability. Concrete is better in compressive strength cured with CO_2 since the enhanced packing density of carbonated reaction products [24]. CO_2 curing has been demonstrated to increase the mechanical strength when used in oil shale ash concrete; strength gains match the CO_2 pressure and curing duration [22]. Moreover, CO_2 curing improves the carbonation resistance of concrete, thereby guaranteeing long-term durability in various environmental settings [23]. Precast concrete applications find the technology appealing because it accelerates early strength gain, thereby saving the time needed for concrete to attain load-bearing capacity [25]. Furthermore, CO_2 curing buildings allow partial replacement of cement with other materials, such as fly ash and slag, thereby reducing cement consumption [26].

Challenges and Limitations in Implementing CO_2 Curing

Difficulties and constraints: The general acceptance of CO_2 treatment presents various difficulties, even if its potential advantages are great. The demand for specialized curing chambers that maintain regulated CO_2 concentrations and pressures limits one of the main aspects and may raise the initial setup costs [27]. In addition, optimization of different material compositions is highly desirable because of the influence of the porosity and chemical properties of the concrete mix on CO_2 curing [25]. The long-term durability of CO_2-cured concrete, particularly in hostile environments where carbonation-induced shrinkage and cracking may undermine structural integrity [28]. Furthermore, as current uses are mostly limited to precast concrete manufacturing plants [26], the scalability of CO_2 curing for large-scale infrastructure projects still presents a challenge. Future developments in CO_2 capture technology and the incorporation of CO_2 curing in on-site building processes should assist in overcoming these constraints, thereby making the technique more viable for general use in sustainable buildings [27].

3.2. Materials of Concrete: Eco-Friendly

Eco-concrete material development is necessary for sustainable buildings because it reduces environmental effects and conserves resources while enhancing the performance of concrete structures. Supplementary materials, such as supplementary cementitious materials (SCMs), recycled aggregates, alternative binders, and waste-based materials, greatly augment sustainable concrete production.

3.2.1. Use of Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs), such as fly ash, silica fume, Ground Granulated Blast Furnace Slag (GGBFS), and metakaolin, are often considered for the partial replacement of Portland cement to improve concrete durability and reduce its carbon footprint. SCM enhances the mechanical properties, ensures durability and resistance against chemical attacks, and simultaneously reduces the consumption of natural resources and CO_2 emissions. The addition of SCMs improves the strength and durability of basalt fibre high-performance concrete even in severe environments, such as dune sand [29]. Moreover, SCMs enhance the workability and setting time; thus, they are preferable for a range of construction applications.

3.2.2. Use of Recycled Aggregates

A recent approach to finding a solution to waste disposal problems and energy savings by natural aggregates is the development of Recycled Aggregate Concrete (RAC). Demolished concrete structures generate recycled coarse and fine aggregates, which can be reused for new concrete formulations, reducing waste sent to landfills and lowering the ecological footprint associated with concrete manufacturing. Research suggests that concrete containing 100% recycled aggregates retains mechanical properties similar to standard concrete and adds to sustainability [30]. Furthermore, recycled aggregates' adherence and bonding properties can be improved during recycling and processing, ensuring their compatibility with cementitious materials.

3.2.3. Development of Alternative Binders

Aligning this with the current era of climate change exemplifies the employment of alternative binders, such as alkali-activated materials and geopolymers, as sustainable replacements for ordinary Portland cement. These resources, obtained from industrial by-products (fly ash, slag, and rice husk ash), are energy-saving and have lower emissions of CO_2. Alternative binders have been found to enhance the durability, mechanical performance, and resistance to aggressive environments [31], and additional research has been conducted to explore various alternative binder types. Notably, alkali-activated binders have demonstrated excellent features for minimizing the carbon footprint of concrete without losing their strength and durability.

Table 3. Summary of CO_2 curing in concrete

References	Details
[21, 22]	CO_2 reacts with calcium compounds in cement to form stable $CaCO_3$, improving early-age strength.
[22, 23]	Accelerates hydration reactions, modifying the pore structure and increasing matrix density.
[24, 25]	CO_2 curing increases compressive strength by enhancing packing density and reaction products.
[23, 26]	Enhances durability by improving resistance to carbonation and reducing permeability.
[25]	Reduces curing time, making it ideal for precast concrete applications.
[26, 27]	Allows partial replacement of cement with supplementary materials, reducing the CO_2 footprint.

[27, 28]	Requires controlled curing chambers, increasing setup costs.
[25, 26]	Effectiveness depends on concrete porosity and chemical mix composition.
[26, 27]	Mainly used in precast concrete; large-scale implementation is still limited.
[28]	Potential carbonation-induced shrinkage and cracking in harsh environments.

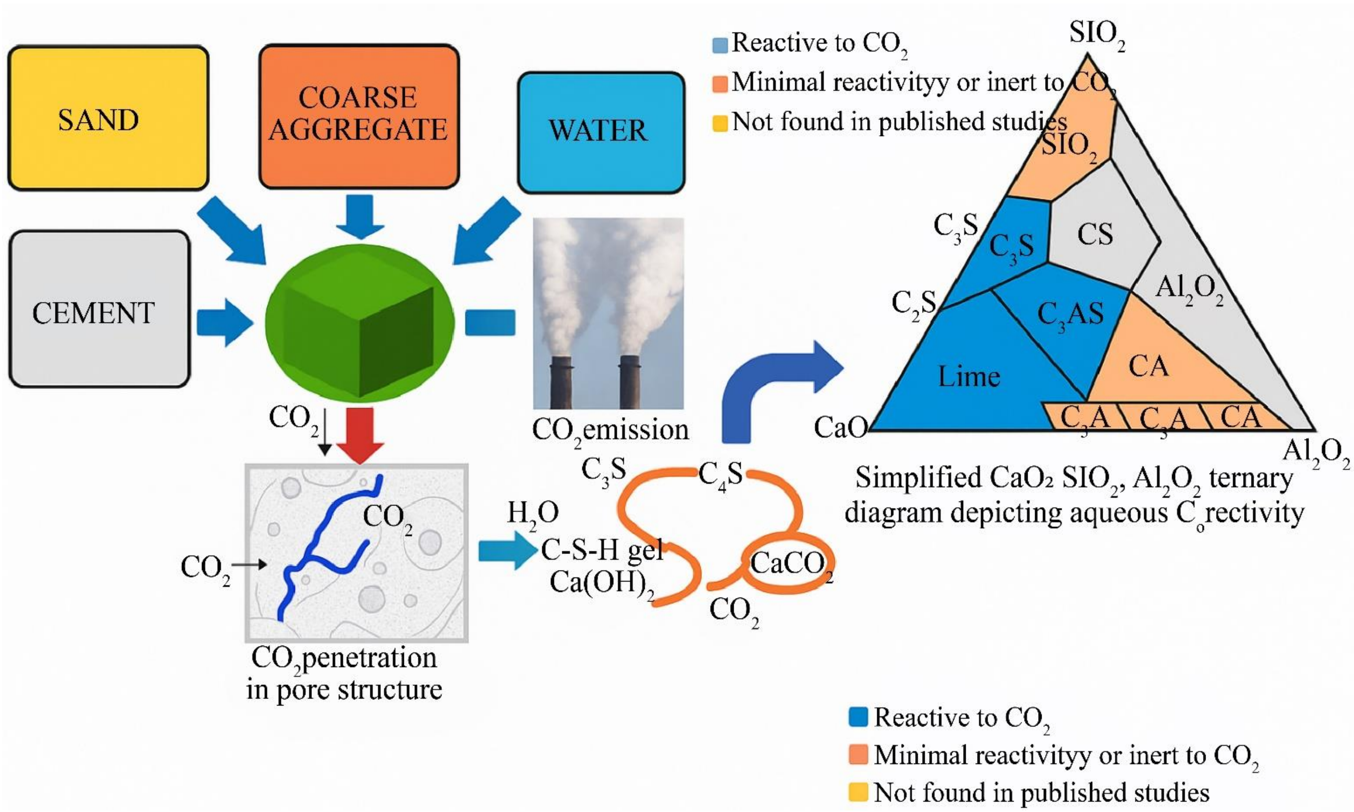

Fig. 1 Carbon dioxide curing and eco-friendly concrete

3.2.4. Pharmaceutical Mixtures with Extraction of Wastes

The inclusion of industrial and agricultural waste materials into concrete mixtures can be considered an application of a circular economy, in which waste is transformed into valuable construction materials. Such alternative additions involve waste glass, rice husks, and shell-based materials (such as insect shells) because waste and plastic waste cover the gaps in concrete's mechanical, durability, and sustainability characteristics [32]. Studies carried out by XT and its related corporations have suggested new ways of utilizing unwanted raw materials in high-quality building materials to solve the reliance on traditional raw materials and natural substances. In addition, the pozzolanic nature of ground waste glass improves the strength and durability of concrete.

3.3. Advances in Technology for 3D Concrete Printing (3DCP)

In recent years, 3D Concrete Printing (3DCP) has seen significant advancements in automation, materials science, and construction methodologies. In 3D printing, the most notable new technologies are robotic printing systems, advanced nozzle designs, and monitoring systems. Deliver real-time feedback. Digital fabrication techniques have provided architects with tools to sculpt extremely complex virtual architectural shapes and render them in material form with remarkable accuracy and effectiveness [33]. Moreover, new extrusion mechanisms and layer-by-layer deposition strategies have improved the mechanical integrity of printed structures by reducing the number of cold joints and maximizing interlayer bonding [34].

Apart from the new rheological tools for measuring and monitoring printed concrete's flow ability and setting properties, researchers have also recently studied adaptive mix design and real-time rheology control. Automating mixing and material delivery systems simplifies printing by removing human elements and maximizing efficiency. Moreover, innovations in hybrid printing technologies, which combine the 3D printing process with auxiliary reinforcement materials such as steel fibers and mesh reinforcement, have greatly enhanced the load-bearing performance of 3D-printed structures [36]. One of the most important advantages of 3DCP is the reduction in material waste, which leads to sustainability. Traditional construction methods are notorious for large amounts of material waste, such as formwork, overconcreting while pouring, and their labour-intensive nature. On the contrary, because 3DCP is characterized by high precision in the deposition of materials, it prevents a large amount of waste material [37]. Because a given technique does not use a board, up to 60% of the waste can be saved in the structure, making this technique an environmentally friendly amendment method [38]. Moreover, other environment-friendly material solutions, such as geopolymer -based concrete and recycled aggregates, have been utilized during printing to minimize the carbon footprint. Geopolymers, formed from clay and industrial by-products (fly ash and slag), are alternatives to Portland cement and can achieve nearly 80% [39] savings equivalent to carbonic acid emissions. In addition, projects with local materials cut transport and carbon emissions. 3D printing has enormous promise for sustainable construction as demonstrated by its numerous practical applications. A significant example is the production of geopolymer concrete houses via 3D printing in the Netherlands. Such structures can provide higher durability, lower carbon emissions, and lower production costs than traditional housing using concrete [40].

Another case study of 3DCP applied to bridge construction demonstrated optimized material formulations used in combination with reinforced printing techniques, yielding environmentally and structurally sound bridges. Structural engineering research has proven that such structures can not only carry heavy loads but are also 40% more material-efficient than conventionally cast bridges The Circular Economy is another emerging discourse in the field of 3DConP, and promoting the use of recycled aggregates and bio-based binders for 3D printing is a way to advocate the 3DCP potential of actually aiding circular economy principles in practice, as demonstrated through large-scale 3D-printed pavilions developed by researchers in Singapore [35]. 3DCP has the potential to incorporate new material solutions for sustainable and efficient construction at the same time, as exemplified by these projects.

3.4. Concrete and Carbon Sequestration

Concrete carbonation, or carbon sequestration in concrete, is the capture and storage of Carbon Dioxide (CO_2) in cement-based materials. This strategy is highlighted as an efficient way to improve the concrete properties and decrease the carbon footprint of the construction industry. The cement industry is among the largest sources of CO_2 emissions, accounting for approximately 8% of the global emissions. Carbon sequestration techniques enable the industry to substantially reduce its environmental footprint as well as the physical and durability specifications of concrete.

3.4.1. CO_2 Capture and Storage Methods in Concrete

There are several methods for capturing and storing it in concrete. Methods for reducing the carbon footprint of concrete. There are two different approaches for incorporating CO_2 into the concrete matrix, either during production or after the product has been cured. The most common methods involve CO_2 mineralization during curing, accelerated carbonation curing, Supplementary Cementitious Materials (SCM), and CO_2 sequestration in concrete production waste.

3.4.2. CO_2 Mineralization during Curing

CO_2 mineralization during curing is one of concrete's most researched approaches for carbon sequestration. This involves the solitary injection of CO_2 into new concrete and its reaction with Calcium Hydroxide ($Ca(OH)_2$) that is present in cement paste, thus forming Calcium Carbonate ($CaCO_3$). The formation of stable carbonates safeguards CO_2 forever, reinforcing and making the material more resilient. This process, otherwise known as carbonation curing, helps decrease the permeability of concrete, which results in increased resistance to environmental degradation [41].

3.4.3. CO_2 Curing: Superior Carbonation

CO_2 is naturally incorporated into cement hydration products over time in a process known as carbonation, and enhanced carbonation curing accelerates this process. In addition, CO_2 curing has been shown to significantly enhance the compressive strength and density of concrete blocks [22]. Absorbing CO_2 in a controlled environment allows greater sequestration and better mechanical performance. Also, CO_2 curing can be combined with precast concrete production, lending further viability to the industrial application of this solution.

3.4.4. Sustainable Applications of Supplementary Cementitious Materials (SCMs)

SCMs, such as fly ash, silica fume, oil shale ash, and Ground Granulated Blast-Furnace Slag (GGBFS), are key components for improving the carbon sequestration capability of concrete. When blended with cement, these materials provide additional sites for CO_2 to react and form stable carbonates. [23] reported his work on the utilization of oil shale ash in concrete and concluded that oil shale ash with superior mechanical properties could be used in concrete, leading to improved sequestration potential. SCMs not only aid in carbon capture but also substitute traditional Portland cement, thus reducing emissions.

3.4.5. CO_2 Sequestration in Waste from Concrete Production

It generates a large amount of waste, such as Recycled Concrete Aggregates (RCA), Cement Kiln Dust (CKD), and other by-products. CO_2 can also be used to treat these materials to increase their sequestration while modifying their structural properties. This area of research was developed by studying the effect of carbon dioxide curing on RCA. It concluded that carbonation treatment improved the RCA's mechanical performance, thus preparing it for reuse in new concrete mixtures [24]. The principles of a circular economy, in which waste is minimized and resource use is maximized, are enabled by this approach.

3.4.6. Assessment of Carbon Sequestration Potential

Factors influencing the carbon sequestration potential of concrete include CO_2 uptake capacity, long-term carbonation effects, and Life Cycle Assessment (LCA) studies.

3.4.7. CO_2 Uptake Capacity

The amount of CO_2 that concrete can absorb depends on its composition, porosity, and curing conditions. Based on [42], adding $CaCO_3$ suspension in situ increases sequestration potentials at a particular time of production. Incorporating larger volumes of raw materials that contain $Ca(OH)_2$ in larger quantities can also increase CO_2 uptake and enhance the stability of the material in the long run.

3.4.8. Long-Term Carbonation Effects

As CO_2 reacts with the hydrated cement components, further sequestration occurs over time. According to [50], carbonation durability and CO_2 curing significantly prolong the lifetimes of concrete structures. Carbonation lowers the concrete matrix pH and reduces the risk of steel-reinforcement corrosion; thus, it can be particularly advantageous for reinforced concrete.

3.4.9. Life Cycle Assessment (LCA) Studies

The results of LCA studies should guide how this overall contribution to the environment can be calculated (i.e., evaluation of embedded carbon) from CO_2 sequestration in concrete. These figures show how much CO_2 is added vs. how much CO_2 is produced in the making of cement. It is claimed that CO_2 sequestration can compensate for the total emissions caused by the entire process of producing concrete on a large scale, from raw material extraction to manufacturing, to the tune of 5–10% of total emissions [43], and the construction industry can digitize and adopt carbon sequestration techniques and contribute towards net-zero emissions goals.

4. Effect of Mechanical Properties and Durability of Concrete

While the environmental benefits of CO_2 sequestration in concrete are undoubtedly appealing, it is with regard to mechanical performance and durability that it truly has the most enduring consequences.

4.1. Higher Strength and Density

During carbonation, stable $CaCO_3$ is formed and occupies the pore spaces of concrete; as a result, a much stronger product is obtained. [41] reported a 20% increase in the compressive strength for CO_2 curing. This advancement allows carbonated concrete to be employed in load-bearing structures requiring high quality.

4.2. Enhanced Resistance to Chemical Attack

The conversion of $Ca(OH)_2$ to $CaCO_3$ ultimately lowers the porosity of concrete; hence, it can resist sulphate and chloride ions more effectively. [23] reported that exposure to carbonated concrete material showed a lower resistance against chemical corrosion, such as in marine and industrial environments.

4.3. Improved Resilience to Freeze-Thaw Cycles

Freeze-thaw cycling can damage concrete structures. Concrete treated with CO_2 performs well in such scenarios because the pore connectivity is minimized by carbonation, which inhibits the entrance of water.

As popularized in [24], sustainable engineering found carbonated RCA to be the most resistant to freeze-thaw damage, implying its increased utility over wide usage in colder climate regions.

4.3.1. Lowered Alkali-Silica Reaction (ASR)

One significant durability problem in concrete structures is expansion and cracking owing to Alkali-Silica Reaction (ASR). CO_2 sequestration reduces ASR by immobilizing reactive silica components. [50] reported that carbonated concrete exhibited a significantly decreased degree of damage due to ASR and hence provided an extended service life of structures. The process of sequestering CO_2 in concrete is a possible way to reduce potentially dangerous emissions and improve the strength and durability of cement-based materials.

This method is extensively used in the construction industry to reduce the environmental impact through the storage of carbon in concrete (Marvin, 2007). Carbon sequestration technologies and Lifecycle Assessment (LCA) studies will be extremely important to facilitate sustainable construction methods, which are still in their infancy and require further research and development. As the global demand for green building materials grows, CO_2 sequestering concrete will contribute to meeting the carbon-neutral infrastructure needs.

Table 4. Compare studies on the durability of concrete

Reference	Key Findings
[4]	CC improved resistance to freeze-thaw damage, scaling due to de-icing salts, and shrinkage. It also extended the setting periods, benefiting the curing process.
[16]	Carbonation in fiberboards led to carbonate precipitation, enhancing durability by improving freeze-thaw and wet-dry cycle resistance.
[18]	CC reduced carbonation depth and chloride permeability, preventing chloride infiltration and reinforcing steel corrosion.
[19]	Autoclaved Carbonated Concrete (ACC) exhibited higher dry shrinkage than moist-cured specimens, making it

	suitable for precast concrete applications.
[22]	Carbonation caused an initial pH drop, followed by gradual restoration, enhancing corrosion resistance and lowering chloride levels in OPC-FA concrete.
[5]	Formation of a $CaCO_3$ layer during carbonation prevented disintegration and improved performance. Controlled hydration rates were emphasized to avoid cracking.
[24]	CC was effective for structures with large surface areas and thin depths, but potential pH drops and corrosion risks in steel-reinforced parts need careful evaluation.
[25]	Using GGBFS as an aggregate in CC improved freeze-thaw resistance and increased carbon sequestration potential, enhancing durability.
[26]	CC could replace steam curing in concrete pipes, improving durability, sulfate resistance, pH balance, and reducing ion migration.

Table 5. Compare studies on carbon uptake

Reference	Key Findings
[27]	CO_2 uptake in pre-cured concrete was 22%–24%. Without pre-curing, carbonation for four days increased CO_2 absorption to 35%, making CC a viable alternative to steam curing.
[18]	Thermogravimetric Analysis (TGA) showed that concrete had a CO_2 absorption of 14.1%, highlighting its ability to sequester CO_2.
[11]	Higher CO_2 absorption through rapid gas flow and normal humidity improves strength and maturity index in carbonated concrete.
[14]	CO_2 sequestration in aerated concrete using red mud, Fly Ash (FA), and GGBFS showed maximum CO_2 absorption in red mud. GGBFS exhibited the highest compressive strength improvement.
[16]	Maximum CO_2 uptake was 23.2% for 18-hour carbonation and 28.5% for 24-hour carbonation, showing that preconditioning enhances CO_2 sequestration.
[21]	Cement replacement (10–50%) resulted in CO_2 uptake between 11.23% and 19.02%, indicating that alternative materials can aid carbon sequestration.

5. Case Studies and Applications

CO_2 sequestration in concrete has been successfully introduced in the marketplace, championed by sustainable construction, and studied in long-term environmental impact projects. Sustainable concrete remains adept at improving durability while employing low carbon emissions by means of CO_2 curing and green in-place materials. The evolution of carbon-sequestering concrete and its potential impact on the construction industry in the future can be drawn from real-life case studies.

Commercial Projects with CO_2: Curing Implementation, Commercial-scale and widely adopted, refer to CO_2 curing as a concrete carbon sequestration method. Technology has already been successfully applied in precast concrete manufacturing and large-scale infrastructure. For example, Carbon Cure Technology is a commercial technology that injects CO_2 into fresh concrete and permanently mineralizes CO_2 in $CaCO_3$. This process increases the concrete strength and decreases the amount of cement used, thereby reducing total emissions. Shi and Wu [5] showed that CO_2 curing increases the compressive strength of concrete blocks and their durability so that these blocks can be used in structural applications. One of the largest CO_2 curing commercial implementations was the NRMCA project, in which extremely large batches of CO_2-treated concrete were deployed in commercial buildings and roads. Zhang et al. For example, [7] studied the effects of CO_2 curing on precast elements for commercial infrastructure, where this method increased the strength by 20–25% while reducing the curing time significantly. In Canada, a commercial-scale project was implemented to assess the practicality of CO_2-injected concrete pavements. The findings confirm that the pavement showed a better resistance to freeze-thaw cycles and presented lower permeability, indicating that the new material is effective in improving long-term durability [6]. Another high-profile project is the Stanford University Energy System Innovations (SESI) initiative, which built CO_2-sequestering concrete referenced in its infrastructure and achieved over a 50% reduction in its embodied carbon footprint. According to Meng et al. [1], such implementations not only improve the mechanical properties of concrete but also have a tremendous impact on lowering global CO_2 emissions in the construction practice.

Green Concrete Application in Eco-Friendly Construction: Targeting eco-friendly construction concrete using Supplementary Cementitious Materials (SCMs) and alternative binders has increased relevance in green construction projects across the globe. The carbon footprint of concrete is significantly reduced by the addition of materials such as fly ash, Ground Granulated Blast-Furnace Slag (GGBFS), oil shale ash, and limestone powder. Ismail et al. reported that CO_2-cured concrete with oil shale ash has higher durability and a lower carbon footprint (up to 15% compared to ordinary concrete). Urban developments also use green concrete, such as One Central Park in Sydney, Australia, producing results. The first is SCM-based concrete for this high-rise building, resulting in its lower CO_2 emissions and thermal performance. The second is the Edge building in Amsterdam, a net-zero building that uses carbon-negative concrete with CO_2 sequestration technology, showing that sustainable materials can be deployed in volume without sacrificing structural integrity. The U.S. Department of Transportation (USDOT) has further encouraged the use of low-carbon concrete, including CO_2-cured precast elements and SCM-based concrete, in highways and bridges. As noted by Singh and Singh in their review of many of these unique projects, carbon-sequestered concrete can achieve up to 30% more sulphate resistance than the standard treatment, making it a suitable material of choice in some aggressive environments.

Evaluation of Sustainability and Environmental Impact: The use of CO_2 sequestering concrete in the construction industry depends on the long-term performance of the building materials. Studies have revealed that carbonated cement offers improved mechanical characteristics and long-term durability. The long-term effects of carbonation and curing concrete with CO_2 decrease porosity and improve the resistance of concrete against sulphate and chloride attack, increasing the longevity of concrete structures. In addition, Lifecycle Assessment (LCA) studies have been performed to evaluate the environmental impact of CO_2 sequestration in concrete. LCA analysis conducted to estimate the CO_2 emissions reduction potential showed that CO_2 curing during concrete production can mitigate up to 10–20% of cement industry emissions.

Furthermore, a recent study in TIME Magazine reported that carbon-negative concrete may transform the building industry by lowering the embodied carbon in buildings and renovations. Another long-term study on the performance of CO_2-treated RCAs highlighted that RCAs after carbonation curing displayed increased compressive strength and freeze-thaw stability compared to traditional recycled aggregate. This CO_2 sequestration would help alleviate carbon emissions and prolong concrete structures' integrity and lifespan.

CO_2 sequestration in concrete is no longer hypothetical, and the environmental and structural benefits of practical applications are widely recognized today. CO_2 curing enables applications in commercial projects. Eco-friendly materials have become prevalent in sustainable construction, and long-term studies have shown that carbon-sequestered concrete is durable and environmentally sustainable. With ongoing improvements, the widespread implementation of these methods will be instrumental in reducing the building industry's carbon footprint while preserving the strength of the contemporary infrastructure.

5.1. Carbon Sequestration in Concrete

Enzymatic CO_2 sequestration in concrete is a forward-thinking approach that can help reduce the carbon footprint of construction materials. However, multiple obstacles prevent its widespread implementation, including technical, economic, policy, and regulatory constraints. Seeming gaps in research are another opportunity for innovation; each future effort that advances the effectiveness of CO_2 curing and carbon-neutral concrete solutions can only extrapolate improvements in their efficiency. Tackling these challenges is essential for the scalability and long-term viability of sustainable concrete technology.

5.1.1. The Technical and Economic Barriers Associated with Adoption

Despite key advances in CO_2 curing and carbon sequestration, numerous technical and economic challenges still exist. The most notable technical challenge is that CO_2 curing is incompatible with conventional concrete production processes. Most existing concrete formulations are designed for conventional hydration curing, whereas successfully incorporating CO_2 curing would necessitate significant modifications. Implementing CO_2 sequestration technology in commercial-scale ready-mix concrete plants requires dedicated infrastructure and analytical systems, resulting in higher initial costs. Another notable challenge is the variable performance of CO_2-treated concrete across various cement compositions and aggregate types. Hence, this study sheds light on the indeterminate nature of the mechanical properties of concrete during CO_2 curing, leading to heterogeneous carbonation. The reaction kinetics and carbonation depth vary widely, making it difficult to standardize the processes, especially for large-scale construction projects.

The lack of clear regulations, incentives or economic aspects is two sides of the same coin. High initial investment in CO_2 curing infrastructure is a significant barrier for manufacturers. Setting up the necessary carbon capture, injection, and monitoring systems involves significant capital expenditure that most smaller producers cannot accommodate. The costs of CO_2 curing equipment and carbon storage facilities lead to 15–20% higher production costs compared to conventional concrete curing methods, making them less competitive. Moreover, industrial CO_2 emissions are currently very limited, so every supply chain and transportation of captured carbon comes with extra added costs. Moreover, as they lack a skilled workforce and training programs in CO_2 sequestration technologies, this also poses a barrier. Most construction professionals and concrete manufacturers have little exposure to CO_2 curing processes and their long-term impacts, so they do not always support them. Training programs and awareness campaigns may be necessary to fill this literacy gap and promote the shift towards low-carbon concrete alternatives, which is the transition "from the industry of the future to the future of industry".

5.1.2. Policy and Regulatory Considerations

The use of CO_2 sequestration in concrete depends significantly on government policies and regulatory frameworks. While some countries have initiated encouragement of carbon-neutral building activities, CO_2 curing and sequestration regulations have not yet been standardized worldwide. For example, recent studies focused on the durability and carbon sequestration efficiency of CO_2-treated concrete have not established standardized testing methods, making it difficult to obtain the requisite testing approval and certification for commercial applications. One of the main areas of struggle in regulations is well-defined guidelines on incentives for carbon credits, specifically for concrete manufacturers. North American and European governments implement carbon pricing systems and emission trading schemes. However, such policies usually fail to reward CO_2 sequestration in construction materials. CO_2 sequestration is highly incentivised in carbon credit markets, potentially making the technology commercially attractive for producers who implement it. Furthermore, CO_2-cured concrete is not a standard material covered by many countries' building codes and construction regulations. Most of the time, the market is composed of traditional concrete mixtures, and the approval of any alternative material towards regulatory entities is mostly lengthy and complex.

Stressed the need for policy reforms and new building standards to enable the acceptance of CO_2-sequestered concrete. She warned that contractors and developers would be slow to adopt new materials without clear regulations when there is uncertainty about how they need to comply with regulatory and approval processes. A further concern in policy is the integration of CO_2 curing into public infrastructure projects. Although some governments have tested carbon-negative concrete on roads, bridges, and buildings, broader deployment has lagged. The proposal that low-carbon materials be mandated in public projects can help drive demand and stimulate private sector investment in sustainable concrete technologies.

5.2. Discussion: Carbonation in Concrete

Carbonation is a natural and extensive process for concrete whereby CO_2 of the air penetrates the concrete pores and combines with $Ca(OH)_2$, which is one of the hydration products of cement, generating $CaCO_3$. This reaction decreases the pH of the concrete, changes its chemical properties and affects its mechanical resistance and durability. The basic carbonation reaction can be written as

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The environmental CO_2 concentration, relative humidity, concrete porosity, permeability, and composition affect carbonation. In the first, CO_2 dissolves in water to form carbonic acid (H_2CO_3) and reacts with hydrated cementitious compounds. The overall desaturation mechanistic pathway can be expressed as:

$$xCa0ySiO2yH_2O + (3-x)CO_2 + yH_2O + (3-x)CaCO_3$$

Alternatively,

$$(2Ca0ySiO2) + (2-x)CO_2 + yH_2 \rightarrow xCa0ySiO2yH_2O + (2-x)CaCO_3$$

5.3. Challenges and Hazards Associated with Carbonation

Although carbonation has certain benefits, particularly in reinforced concrete buildings, it also has several durability issues. The loss of alkalinity is the most important issue because the reaction with CO_2 lowers the pH of concrete from about 12-13 to below 9. This higher pH also removes the basic protective mechanism afforded by the embedded steel reinforcement. In the presence of chlorides or salts, it breaks down and becomes prone to rust formation during exposure to water and oxygen in the air. The corrosion of the reinforcement can decrease the lifetime of the concrete construction owing to the reduction in structural integrity, cracking, and spalling. The other factor involved in carbonation is the cross-section of concrete, which is associated with its porosity, permeability, and curing conditions. This more porous or under-cured concrete allows for a more profound penetration of CO_2, which increases the chances of premature corrosion of the reinforcement. Preventive measures are important because structures subjected to humidity and other climates are particularly sensitive to accelerated carbonation.

5.4. Mitigation Strategies for Risks of Carbonation

To mitigate the risks of carbonation, design and construction practices can be adopted to promote the long-term performance. One important strategy is to ensure sufficient cover of concrete over the steel reinforcement, prevent ingress of CO_2 and delay carbonation-induced corrosion. Supplementary cementitious materials, which include fly ash, slag, and silica fume, can be used, and these SCMs improve the porosity of concrete, which helps prevent carbonation in the long term. These materials enhance durability while still offering sufficient alkalinity to preserve reinforcement. Moreover, protective coatings or surface treatments (e.g., hydrophobic sealants or anti-carbonation coatings) can significantly reduce the rate of CO_2 diffusion into the concrete matrix. In addition, proper curing plays a key role in reducing carbonation risks. Therefore, one is tasked with outlining the significance of enhanced moisture curing, controlled environmental exposure, and optimized curing conditions to mitigate the risk of carbonation in concrete.

5.5. Carbonation-Based Curing

Although carbonation is a generally inevitable aging process of concrete, controlled carbonation curing at the early stage of concrete is gaining an increasing role as a green process to enhance concrete properties. Accelerated carbonation curing improves the strength and durability of concrete and achieves CO_2 capture, making it a suitable option for mitigating emissions from the cement industry. Nonetheless, such measures should be carefully controlled to retain carbonation in an optimum range and to avoid a potentially deleterious drop in pH, which may cause a loss of adhesion on reinforcements.

The emitted carbonate described above is responsible for the popularity of lotions and other surface treatments against dust in nature. It is balanced between the advantages of carbonation and long-term considerations of sustainability. Concrete carbonation: the good and bad. When controlled, it can increase the strength, densify the matrix, and sequester CO_2, all of which make it a promising route for sustainable construction. However, the durability of steel inside concrete in aggressive environments is a concern that requires careful mitigation to avoid corrosion-induced structural failure in the long run. In the future, we need to optimize the carbonation curing technique, design new materials, and adapt them to strength, durability, and environmental sustainability. With the implementation of these evaluations, the construction sector can capitalize on growth by using carbonation to generate more sustainable and resilient concrete structures.

6. Conclusion

Compared to traditional curing methods, liquefied CO_2 curing significantly improves the properties of concrete by promoting mineralization through carbonation. This process can turn the incorporated CO_2 into a stable, stone-like substance locked into the concrete matrix, even after being ground to a powder. A similar trend was observed at high carbonation exposure, yielding cement composites with superior compressive strengths and mechanical performance. The long curing time process is deemed advantageous. This carbonation approach mainly influences the hydration dynamics of essential cementitious phases like C_2S and C_3S, both of which undergo swift carbonation in the presence of sufficient moisture. The reaction consumes a significant portion of the Calcium-Silicate-Hydrate (C-S-H) gel, yielding mostly Silica (SiO_2) and Calcium Carbonate ($CaCO_3$), and continued reaction under humid conditions permits further hydration of the unreacted material. Carbonation lowers the concrete surface pH initially, but subsequent hydration restores alkalinity over time. In addition to strength, carbonation influences durability as it aids in resistance to salt scaling, freeze-thaw attacks, and chloride ingress.

Furthermore, carbonation densifies the microstructure of mortar, improving the compressive strength, water absorption, and apparent density when mortar is connected to recycled coarse aggregate. Performance studies indicate that carbonation is best for ~2 hr. Liquid CO_2 curing is a sustainable process. This increases the long-term durability of concrete and decreases the per-use curing pollution of carbon. As CO_2 curing technology advances, its rapid use in construction practices will be key to developing a more sustainable and resilient infrastructure.

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