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Chapter

Accelerated Carbonation Curing as a Means of Reducing Carbon Dioxide Emissions

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Abstract

Globally, carbon dioxide concentration has immensely increased post the industrial revolution. With more greenhouse gases generated from human activities, more radiation is being absorbed by the Earth’s atmosphere, causing an increase in global temperature. The phenomenon is referred to as the greenhouse gas effect. Alone, the cement industry contributes to approximately 5–8% of the global greenhouse gas emissions. Scientists and environmentalists have proposed different scenarios to alleviate such emissions. Among these, accelerated carbonation curing has been advocated as a promising mechanism to permanently sequester carbon dioxide. It has been applied to numerous construction applications, including concrete masonry blocks, concrete paving blocks, ceramic bricks, concrete pipes, and cement-bonded particleboards. Experimental results have shown that not only does it significantly reduce the carbon emissions, it also improves the mechanical and durability properties of carbonated products. The process enhances material performance, offers environmental benefits, and provides an excellent means to recycle carbon dioxide.

Keywords: carbonation curing, construction applications, mechanical properties, durability performance, environmental benefits

1. Introduction

Greenhouse gases are responsible for maintaining ecological balance and warmth on the planet. Of the total greenhouse gases, carbon dioxide is the main component comprising about 76% [1, 2]. With more CO₂ generated from industries, urbanization, and human activities, more radiation will be absorbed by the Earth’s atmosphere, causing an increase in global temperature. The phenomenon is referred to as the greenhouse gas effect. In the 1990s, the rise in the planet’s average temperature was 0.74°C. By the end of the 21st century, it is projected to increase by up to 6.4°C [3], instigating cataclysmic changes, as melting of polar ice, increase in sea levels, variations in rainfall and relative humidity (RH), and disappearance of fauna, among others [4].

Of the emitted carbon dioxide gas, the cement industry is responsible for about 5–8% [5]. Such emission is associated with the calcination of limestone (CaCO₃) to produce lime (CaO) and CO₂ and the burning of fossil fuels for clinkerizing and grinding. Indeed, it is estimated that the production of one ton of cement releases an equal weight of CO₂ gas [6]. Cement is the main constituent of concrete, the world’s most
consumed man-made material with approximately one cubic meter being produced per capita [7]. With the rise in the human population, there is an ever-increasing demand for infrastructure and superstructures. Accordingly, more cement and concrete will be needed. As a result, cement production is becoming an increasing global pressing issue from an ecological, social, and environmental standpoint. To alleviate the emission of CO$_2$ associated with producing cement and concrete, scientists and environmentalists have proposed different schemes, including the replacement of cement with supplementary cementitious materials (SCMs), increase in energy efficiency, use of alternate fuels, and carbon sequestration [8].

The first scheme proposes modifications to the mixture proportions by replacing cement with SCMs, which are typically industrial waste materials. Cement kiln dust, a by-product of cement manufacturing, has been utilized in producing sustainable composites for construction applications with economic and environmental benefits [9–11]. Other industrial by-products, including fly ash, slag, rice husk ash, limestone filler, and silica fume, have also been used as partial cement replacement in the production of sustainable concrete [12–17]. The properties of so-produced concrete are equivalent, if not superior, to those of conventional cement-based counterparts. Furthermore, efforts have been made to fully replace cement in mortar and concrete. The resulting product has been denoted as alkali-activated or geopolymer mortar/concrete. Numerous studies have investigated the fresh and hardened properties of this novel material and have provided valuable input on its contribution to sustainable construction [18–43]. Nevertheless, the availability and innate compositional variability of the industrial by-products pose a challenge to the adoption and progression of this CO$_2$ mitigating strategy.

Cement-related carbon emissions could also be reduced by increasing energy efficiency or utilizing alternative fuels during cement production. The use of blended cements, high-activation grinding, and high-efficiency separators, driers, calciners, and clinker cools have been reported to significantly reduce the CO$_2$ emissions and energy requirements by the cement industry [44–47]. Yet, the suggested modifications in this scheme may not always be practical or economically feasible. Conversely, some studies aimed to alleviate the carbon emissions associated with the generated thermal energy by replacing fossil fuels with alternative fuels, including scrap tires, biomass residues, waste oils, plastics, slaughterhouse residues, spent pot lining, and sewage sludge [48–53]. The scenario is considered environment-friendly, as it conserves natural resources and recycles industrial wastes [54]. However, the different characteristics of these alternative fuels compared to fossil fuels have led to uneven heat distribution, unstable precalciner operation, and dusty kilns, among other complications [55].

While CO$_2$ emissions could be substantially reduced using the first three methods, they may not always be practical, feasible, or reliable. On the other hand, carbon sequestration or storage has been shown to be a more viable scheme due to its applicability to stationary point sources over the short term. Geological and ocean storage have been mainly practiced for the past few decades [56]. Nevertheless, mineral sequestration has shown great potential, specifically through the accelerated carbonation of hardened cement and concrete.

Carbonation is a curing mechanism applied to fresh concrete, i.e. within the first 24 hours after casting. It entails an exothermic chemical reaction between CO$_2$ and calcium-carrying compounds in cement. Its advantages are three-fold: 1) rapid strength gain, 2) enhanced durability performance, and 3) permanent sequestration of carbon dioxide gas [57, 58]. This chapter summarizes the research and experimental findings of collective studies that have utilized accelerated carbonation in construction applications, including concrete masonry blocks, concrete paving blocks, concrete pipes, reinforced concrete beams, cement-bonded particleboards,
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DOI: http://dx.doi.org/10.5772/intechopen.93929

and ceramic bricks. Other topics are also covered, comprising the fundamentals, processes, characterization techniques, and environmental benefits of carbonation of concrete. This work aims to shed light on the technical and environmental gains of accelerated carbonation and its applicability to different construction applications as a means of reducing cement-related carbon dioxide emissions.

2. Fundamentals of carbonation

2.1 Reaction kinetics

Carbonation is a physicochemical reaction between cement and carbon dioxide gas in aqueous conditions. More specifically, it is the calcium silicates and their hydration products that undergo carbonation. At early age, calcium silicates, in the form of alite (3CaO$\cdot$SiO$_2$ or $C_3S$) and belite (2CaO$\cdot$SiO$_2$, or $C_2S$), react with CO$_2$ in the presence of water to produce calcium silicate hydrate ($xCaO$$\cdot$SiO$_2$$\cdot$yH$_2$O, or C-S-H) and calcium carbonate (CaCO$_3$). The reaction is primarily dependent on the rate of CO$_2$ diffusion, which, in turn, is controlled by the concentration of CO$_2$ and its pressure during carbonation [59]. The exothermic reactions are shown in Eq. (1) and (2) [60, 61].

\[
3(3CaO\cdot SiO_2) + (3 - x) CO_2 + yH_2O \rightarrow xCaO\cdot SiO_2\cdot yH_2O + (3 - x)CaCO_3 \quad (1)
\]

\[
2(2CaO\cdot SiO_2) + (2 - x) CO_2 + yH_2O \rightarrow xCaO\cdot SiO_2\cdot yH_2O + (2 - x)CaCO_3 \quad (2)
\]

Carbonation is an accelerated hydration reaction; yet, it is different than typical hydration of cement with water, as calcium carbonate formed instead of calcium hydroxide (Ca(OH)$_2$) [60, 61]. In Eq. (1) and (2), the values of $x$ and $y$ depend on the extent of reaction, whereby the theoretical maximum degree of reactivity is 50% of the cement mass [62]. In the event of extensive carbonation exposure, CO$_2$ may decalcify the newly-formed C-S-H to produce silica gel (SiO$_2$) and calcium carbonate, as per Eq. (3) [63]. However, this reaction is not likely to occur in the short-term accelerated carbonation curing regimes employed in the studies addressed herein.

\[
xCaO\cdot ySiO_2\cdot zH_2O + xCO_2 \rightarrow xCaCO_3 + y(SiO_2\cdot tH_2O) + (z - yt)H_2O \quad (3)
\]

Moreover, the carbonation reaction does not consume all $C_3S$ and $C_2S$ particles, allowing for their subsequent hydration in a post-carbonation moist curing environment [64]. Accordingly, the end-result cementitious matrix is an intermix of $C_3S$, $C_2S$, CaCO$_3$, C-S-H, and Ca(OH)$_2$ [65–70].

2.2 Characterization of the reaction products

Carbonation of calcium silicates ($C_3S$ and $C_2S$) is a form of mineral carbon sequestration that converts carbon dioxide gas into thermodynamically stable calcium carbonate. The calcium carbonate has been detected in three polymorph phases, namely aragonite, vaterite, and calcite [61]. Microstructure analysis showed that the first two polymorphs formed due to carbonation of C-S-H, while the third
one was a product of carbonating calcium silicates [71, 72]. Yet, among the three, calcite has been predominantly identified as the main reaction product of accelerated carbonation. In fact, thermogravimetric analysis (TGA) and X-ray diffraction (XRD) have shown that poorly crystalline aragonite and vaterite transformed into the more stable crystalline calcite polymorph during subsequent hydration [66, 73]. This phenomenon is shown in the XRD spectra of Figure 1.

While calcium carbonate has been highlighted as the main carbonation reaction product, C-S-H gel has been identified on fewer occasions. Using XRD, C-S-H was qualitatively detected as a slight increase in the baseline between 25 and 35°2θ [66, 73]. This C-S-H was similar in its amorphous morphology to that formed during typical C₃S hydration but different in that it was characterized by a lower
CaO-to-SiO$_2$ ratio [71, 74, 75]. Actually, it was believed that a high degree of carbonation reaction (carbon uptake exceeding 18%, by cement mass) led to intermixing amorphous C-S-H with dominant CaCO$_3$ to form a calcium silicate hydrocarbonate product, rendering it difficult to be distinctively identifiable [66, 71]. Conversely, lower reactivity (carbon uptake below 10%, by cement mass) integrated small CaCO$_3$ crystals into a C-S-H-dominant nanostructure [65].

The morphology of these reaction products has also been studied. Calcium carbonate, in its three polymorphs, was reported in different shapes. Cubic, crystal shapes were identified, as depicted in Figure 2, when ordinary Portland cement (OPC) concrete was exposed to simultaneous carbonation and chloride ion ingress [76]. Successive preconditioning and carbonation curing of OPC paste and concrete presented amorphous C-S-H gel, calcium hydroxide hexagons, and amorphous calcium carbonate, as shown in Figure 3a [65]. A similar morphology is illustrated in Figure 3b, whereby OPC concrete made with drinking water treatment sludge was carbonated for 20 hours after 4 hours of preconditioning [77]. Further, an amorphous microstructure with a matrix comprising C-S-H and CaCO$_3$ was reported when OPC concrete was carbonated for 4 hours after 18 hours of preconditioning (Figure 4a). Similar findings have been reported in other studies [68, 78, 79]. Conversely, the morphology of Portland limestone cement (PLC) concrete exposed to a similar carbonation scheme encompassed ball-like forms covered with sharp crystals, as presented in Figure 4b [80]. Compared to carbonated OPC concrete, the microstructure of counterparts made with PLC was more porous with higher degree of crystallinity. It was believed that the presence of fine limestone in PLC may have served as nucleation sites for calcium carbonate crystal growth [80].

3. Carbonation process

With the advanced understanding of accelerated carbonation, more research has adopted carbonation curing for precast concrete products. The process promises to
alleviate anthropogenic emissions through a mineral carbon sequestration technique. However, the environmental impact of carbonation is related to the degree of reaction, which is a function of the availability of water and pore precipitation sites. As such, different curing regimes have been adopted to optimize the amount of water for the highest reaction efficiency. These curing regimes were somewhat different in the adopted duration, temperature, and relative humidity. Yet, they had commonly implemented a three-phase curing process, namely preconditioning, carbonation curing, and post-carbonation hydration.
3.1 Preconditioning

Past studies have reported that free water was necessary to facilitate the dissolution of CO$_2$, however excess water obstructed its penetration through the available porous path [66]. As such, preconditioning was introduced to optimize the amount of water prior to exposing the designated samples to carbon dioxide gas. The adoption of such a process led to a superior carbonation degree and enhanced long-term hydration [81].

For dry mixes, preconditioning took place immediately after casting and before the initial setting of the mix [65, 70, 73, 80, 82]. Conversely, wet mixes were only
preconditioned after the initial setting [67, 83]. In general, the conditions comprised a duration, temperature, and relative humidity in the ranges of 2–24 hours, 20–25°C, and 40–60%, respectively [66, 67, 70, 73, 80, 82–86]. The effect of preconditioning at 25°C and 50% relative humidity on the water content during 14-day preconditioning is illustrated in Figure 5. To simulate industrial practice and limit the total curing time window to 24 hours, a maximum preconditioning duration of 18 hours was recommended [82]. At the end of the preconditioning phase, the cementitious matrix would include anhydrous and hydrated calcium silicate compounds.

3.2 Carbonation curing

Carbonation curing encompasses the time period in which concrete is exposed to carbon dioxide gas. Typically, CO₂ is released into a closed chamber and left for a certain duration and under specific conditions for the reaction to take place. A static carbonation system has been typically adopted by most researchers, as shown in Figure 6a [66, 70, 80, 82, 85, 87–93]. This carbonation scheme utilized a closed system, whereby the water that evaporated due to the exothermic reaction was included in the estimation of the degree of carbonation. Nevertheless, the reaction was hindered through the precipitation of calcium carbonate particles in the available porous space, leading to a decrease in porosity and retarded diffusivity. To overcome this challenge, a pseudo-dynamic carbonation setup was devised (Figure 6b) [73, 94]. This system removed surface free water in a controlled environment and enhanced carbon dioxide penetration by creating a route of capillaries through the sample. It is worth noting that both systems employed a vacuum prior to injecting 99%-pure CO₂ and the pressure was set to 1 bar. Several other researchers used a flue gas to enhance the environmental impact of carbonation, however, the degree of reaction was lesser [67, 95, 96]. Higher pressures of up to 5 bars were also employed [70, 84, 85, 97–99]. Although some promising results were reported when carbonation was utilized at higher pressure, the applicability and feasibility of adopting pressurized carbonation by the industry are yet to be evaluated.

Figure 5.
Water loss during preconditioning of lightweight concrete [82]. Reproduced with permission from the publisher.
3.3 Post-carbonation hydration

The third phase of the carbonation process is the post-carbonation hydration. This step is critical to restore the water lost during preconditioning and the exothermic carbonation reaction and to promote subsequent hydration of unreacted hydraulic cement phases. Early research has reported up to 45% increase in the compressive strength when samples were placed in water for 3 days after...
carbonation [64]. Other work incorporated spraying 4-hour carbonated concrete samples every other day until the age of 7 days [82]. The compressive strength increased by 20% compared to carbonated samples left to cure in open air. It is believed that such improvement in mechanical properties is primarily owed to the enhanced pore structure [84].

4. Carbonation degree and characterization techniques

Experimental research findings have provided evidence of the feasibility of utilizing carbonation curing for precast concrete products. Yet, the construction industry has not widely adopted it. To promote its utilization and adoption, most past studies aimed to augment the environmental benefit by maximizing the degree of carbonation reaction, which was typically characterized by the carbon uptake. One way to measure the carbon uptake was by examining the mass gained during the carbonation period, assuming homogeneous carbonation across the sample. Because the system was treated as a closed one, the water lost during the exothermic carbonation reaction was collected and added to the final sample mass. Based on Eq. (4), the carbon uptake is the difference in mass between before and after carbonation with the addition of the mass of water lost as a function of the mass of cement. This method has been implemented in several past studies [60, 66, 70, 73, 74, 80, 82, 89, 100–102].

\[
\text{Carbon uptake (\%)} = \frac{\text{Final mass} - \text{Initial mass} + \text{water lost}}{\text{Mass of cement}} \times 100\% \quad (4)
\]

Thermal analysis is another means of measuring the absolute carbon uptake. In this technique, a thermogravimetric analyzer (TGA) was utilized to monitor the mass loss of a powder sample of carbonated concrete with heat [103]. Alternatively, concrete chunks were decomposed in an electrical muffle furnace by raising the temperature from 25°C to approx. 1000°C. Within this range, multiple hydration and carbonation products were decomposed. The temperature ranges 105–200°C, 200–420°C, 420–550°C, 550–720°C, and 720–950°C were associated with the decomposition of low-temperature C-S-H and ettringite, well-formed C-S-H and C-A-H, calcium hydroxide, poorly crystalline calcium carbonate (vaterite and aragonite), and well crystalline calcite, respectively [66, 71, 73, 80, 81, 104, 105]. However, these ranges slightly differed depending on the type of binder used and the mixture proportions in general, and may even result in an overlap between carbonates and hydrates. To overcome this problem, Fourier transform infrared spectroscopy (FTIR) was employed alongside TGA, as shown in Figure 7 [106]. It is a vibrational spectroscopic analytical technique that could detect calcium carbonate from the C-O characteristic peak at a wavelength of 1415 cm\(^{-1}\) [106]. Other analytical tools have also been utilized together with TGA to identify carbonation products, including nuclear magnetic resonance (\(^{29}\)Si NMR) and XRD [65].

Carbon uptake was also determined by employing coulometric titration in a solution of hydrochloric acid [107]. The technique involved submerging a carbonated concrete powder in the acid solution and measuring the released carbon using the coulometer. The carbon uptake was then obtained using stoichiometric proportions. It is worth noting that thermal analysis and coulometric titration decompose all the carbonates present in the concrete. In an attempt to improve the sustainability of cement, some manufacturers have been replacing
cement with certain amounts of limestone powder. Such limestone should be deducted from the overall measured carbon content to obtain the absolute carbon uptake [80, 108].
5. Carbonation in construction applications

Carbonation curing has been investigated for precast concrete products as a sustainable alternative curing regime to the more typically used steam and moist curing techniques. This section summarizes the collective studies that have examined the effect of accelerated carbonation on the performance of concrete masonry blocks, concrete paving blocks, concrete pipes, reinforced concrete beams, cement-bonded particleboards, and ceramic materials.

5.1 Concrete masonry blocks

Accelerated carbonation has been examined as a sustainable curing technique to replace steam curing for concrete blocks. Past studies have examined the mechanical and durability properties of concrete masonry units made with OPC and cured following 0- to 18-hour initial air curing and 2- to 4-hour static carbonation [82, 86, 87, 101, 109, 110]. The carbon uptake reached up to 24%, by cement mass, representing a 48% degree of reaction. The compressive strength within 1 day and at 28 days was comparable to that of steam- and moist-cured counterparts, with values reaching up to 10 and 39 MPa, respectively. It is worth noting that the highest carbon uptake and strength results were noted for samples that were preconditioned for 18 hours in open air prior to carbonation [82, 86, 109, 110]. Additionally, carbonation improved the resistance to chloride penetration by 1.4 and 6.2 times compared to the two conventionally-cured concrete, respectively, and enhanced resistance to sulfate attack by at least 1.5 times [101]. Also, carbonation-cured concrete (18a + 4c and 18a + 4c + sp) had 2 to 3 times better freeze-thaw resistance than concrete cured using steam (2a + 4 s) or moist curing (0a), as shown in Figure 8 [87].

When OPC was replaced by PLC, similar trends related to mechanical properties were noted, but the strength was ultimately lower due to a more porous and crystalline microstructure, as noted in Figure 4 [66, 80]. Furthermore, concrete blocks

![Figure 8](image.png)

*Figure 8. Freeze-thaw resistance of carbonated and hydrated concrete [87]. Reproduced with permission from the publisher.*
were made with partial replacement of fine aggregates with drinking water treatment sludge and subjected to carbonation [77, 111]. The 1- and 28-day compressive strengths of carbonation-cured concrete blocks were up to 273 and 42% higher than those that of normally-cured counterparts, respectively. Splitting tensile strength of the former was also higher than the latter but by no more than 45%. The durability of the concrete blocks was improved, evidenced by the reduction in water capillary absorption and better resistance to sulfate attack. It is believed that this enhancement in durability performance was owed to the pore-filling capacity of newly-formed calcium carbonate [77, 111]. The only detrimental effect of carbonation curing was the increased leaching of aluminum and copper ions, especially for the first 3 days. Nevertheless, the total 60-day leaching concentrations were within the acceptable range, indicating that carbonated concrete blocks made with drinking water treatment sludge were environment-friendly construction materials [111].

5.2 Concrete paving blocks

Paving blocks are precast non-reinforced concrete products used in construction applications, including pedestrian and vehicle pavements. With no steel reinforcement and the ability to mass-produce in a precast concrete plant, it is an ideal construction product that could sequester CO$_2$ through accelerated carbonation curing. In one study, Wang, Yeung [102] examined the use of CO$_2$ curing to create high performance, low-carbon paving blocks made with contaminated sediment and binary cement. Concrete samples were left to cure in a waterproof membrane until test age, after which they were placed in a drying chamber for 4 hours and cured with CO$_2$ gas for 24 hours at 0.1 bar above atmospheric pressure. Results of Figure 9 show that the compressive strength of carbonation-cured concrete blocks was at least 2 times higher than that of air-cured counterparts. Evidently, carbonation curing accelerated the transformation of anhydrous phases into carbonates, while also promoting the formation of more hydrates during subsequent hydration.

Accelerated carbonation has also been employed to cure concrete paver blocks using pure CO$_2$ and flue gas [112–114]. After preconditioning, concrete samples were exposed to 2 to 4-hour carbonation and then, placed in a mist room to promote subsequent hydration up to 28 days. The CO$_2$ uptake was reported to be 3.29

Figure 9. Compressive strength of concrete paving blocks with various curing methods [102]. Reproduced with permission from the publisher.
and 10.38%, by cement mass, for samples that were carbonated in 20 and 99% CO₂, respectively. Such lower uptake in the former was due to the lower CO₂ concentration, leading to less CaCO₃ formation and lower compressive strength than the latter. This also resulted in higher water absorption and inferior resistance to efflorescence [112, 113]. In addition, Shao and Lin [114] reported up to 60 times more freeze–thaw resistance when concrete paver blocks were carbonated rather than hydrated.

5.3 Concrete pipes

Past research has shown that carbonation curing is best applied to fresh concrete directly after casting to promote the chemical reaction between calcium silicates and CO₂ gas. Wet mixes are problematic when demolding within the first few minutes, while dry mixes are ideal for such applications. Concrete pipes are among the different types of concrete products that utilize dry mixes with zero slump. Accordingly, carbonation curing of concrete pipes has been investigated [114]. Samples were cast with a water-cement ratio (w/c) of 0.26 with cement, coarse aggregate, and fine aggregate contents of 426, 853, and 853 kg/m³. Directly after casting, they were demolded and placed in a carbonation chamber for 2 hours at a pressure of 1.5 bar and CO₂ purity of 99%. The average carbon uptake was found to be 11.3%, by cement mass. Compared to the hydrated control samples, the carbonated counterparts had a similar 28-day compressive strength of 16 MPa. As concrete pipes may be reinforced with steel, the pH of the carbonated concrete was measured. It was interesting to note that the pH remained above 12, indicating the ability to employ carbonation curing for concrete pipes even in the presence of steel reinforcement.

Other work investigated the feasibility of curing concrete pipes in combined steam and carbonation regime in an attempt to reduce the energy footprint of steam curing, while also sequestering CO₂ [70]. Based on the early-age strength results, concrete pipe samples cured in a combination of the two curing regimes, i.e. steam and carbonation, provided equivalent and superior results to those that were steam and carbonation-cured, respectively, and had a CO₂ uptake of approx. 9%, by cement mass. Compared to samples exposed to steam, those that underwent combined curing showed higher resistance to chloride penetration, sulfate attack, and acid attack, possibly due to the consumption of hydroxyl ions and the formation of calcium carbonate.

5.4 Reinforced concrete beams

Despite its adverse effect on reinforced concrete, carbonation of precast reinforced concrete products may be beneficial if performed at an early age. An early-age carbonation curing process was developed for precast reinforced concrete [90, 115]. The detailed curing regime encompassed i) 5-hour in-mold curing at 25°C and 60% RH, ii) 5–6-hour off-mold preconditioning at 25°C and 50 ± 5% RH, iii) 12-hour carbonation curing at a pressure of 5 bars, and iv) 27-day subsequent hydration at 25°C and 95% RH. Carbon sequestration potential was characterized by the CO₂ uptake. It increased from 8 to 15% as the pressure increased from 1 to 5 bar, respectively. This was also associated with an increase in carbonation depth from 8 to 17 mm. Although carbonation decreased the pH of the surface at early age to 9.2, it could recover to 12.3 after 27-day subsequent hydration, evident by the phenolphthalein color profile of Figure 10. Evidently, the pH of the area surrounding the steel reinforcement was not affected by carbonation. This indicated that the suggested carbonation curing process posed no risk of corrosion to the
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DOI: http://dx.doi.org/10.5772/intechopen.93929

steel reinforcement and could be adopted for precast reinforced concrete products. Furthermore, carbonation-cured samples exhibited higher compressive strength, surface resistivity, resistance to chloride penetration, and resistance to weathering carbonation than hydration-cured counterparts. Apparently, carbonation curing reduced the pore size and volume due to calcium carbonate formation and precipitation within the cementitious matrix.

5.5 Cement-bonded particleboards

Cement-bonded particleboards are construction products that incorporate cement and fine wood chip fractions. As cement is the main binder in such products, past studies have investigated the use of carbonation curing as a replacement to typical hydration to expedite the production process, while also providing a sink for carbon sequestration. Early studies showed that 2-hour carbonation resulted in a carbon uptake of up to 24%, by cement mass, and compressive strength of 10.5 MPa, which was three times that of the hydrated reference [113, 116]. Nevertheless, prolonging carbonation to 24 hours enhanced the reaction efficiency to obtain an uptake of up to 28% [117]. The resulting flexural strength, freeze-thaw resistance, and wet-dry durability were higher than conventionally-cured counterparts.

Another study employed a wetting-drying-carbonation curing scheme for cellulose fiber-reinforced cement boards [69]. Experimental results showed that accelerated carbonation curing was beneficial to the performance of cement boards. Compared to conventional water curing, it provided superior flexural strength and toughness and reduced capillary porosity and microcracking in the autoclave. Similar findings were reported when cement-bonded particleboards were subjected to supercritical CO₂ curing [118, 119].

In addition to the utilization of carbonation curing to sequester carbon dioxide in cement-bonded particleboards, it has been employed to promote the recyclability of waste materials [120–123]. The mechanical, durability and physical properties of carbonated cement-bonded particleboards were comparable, if not superior, to those of air-cured and hydrated counterparts. Such performance enhancement is owed to the ability of carbonation curing to improve the intactness at the cement-fiber interface, limit the interfacial microcracks, and occupy the capillary space with newly-formed calcium carbonate.

Figure 10. Depth of carbonation in a reinforced concrete beam: (a) after carbonation curing; (b) after carbonation curing and 28-day subsequent hydration [92]. Reproduced with permission from the publisher.
5.6 Ceramic bricks

The applicability of accelerated carbonation curing has been explored in numerous construction applications. The common factor among these applications is the carbonation of calcium or magnesium silicates to produce carbonates. Ceramic materials are rich in such silicates and may be carbonated upon exposure to CO$_2$. As such, accelerated carbonation was applied to ceramic bricks from Andalusian factories in Spain [124]. The curing process entailed 24- to 720-hour exposure to CO$_2$ at a pressure of 10 bars. The authors noted that longer exposure led to higher carbon uptake, with values reaching up to 10%, by ceramic weight. These results highlight the possibility of employing carbonation curing to ceramic waste materials as a means of permanently sequestering carbon dioxide. Yet, more research is needed to validate the findings and evaluate the feasibility of adopting such a technique by the industry.

6. Environmental benefit

Concrete construction applications serve as a potential carbon dioxide sink for CO$_2$ sequestration. Rather than disposing of CO$_2$ in geological sites, it can be recycled into concrete with the added benefit of early-age strength and improved durability performance. Concrete products that are typically cured using the steam curing regime can be carbonated to relieve the dependency on high pressure and temperature steam. For instance, a concrete block can sequester nearly 0.5 kg of CO$_2$, at an uptake of 24%, by cement mass. At a global annual production of 1800 billion concrete blocks and bricks [125], it will be possible to sequester 900 million tons of CO$_2$, which is equivalent to carbon sequestration in approx. 900 geological sites. In comparison, a single concrete paver block could sequester 15.3 g of CO$_2$, characterized by an update of 10.4%, by cement mass. With 51.4 billion concrete paver blocks (assuming 20% cement content, a thickness of 80 mm, and a density of 2200 kg/m$^3$) produced annually [126], these products could sequester up to 1.07 million tons of CO$_2$.

Concrete pipes are produced on the scale of 62 million tons per year [127]. At a carbon uptake of 20%, the concrete pipe industry can sequester up to 1.2 million tons of CO$_2$ per year. Further, precast concrete products in the form of railway ties can store a total of 0.1 million tons of CO$_2$ per year globally [128]. Conversely, the 9.5 billion m$^2$ of cement-bonded boards produced annually could sequester 10.8 million tons of CO$_2$, assuming 50% cement content, a thickness of 8 mm, a density of 1500 kg/m$^3$, and CO$_2$ uptake of 19%, by cement mass [129]. Although ceramic tiles are different than cementitious concrete, they have also presented a 10% carbon uptake, by total weight. With the global production of 13.6 billion m$^2$, and assuming a typical thickness of 1.5 cm, the ceramic tile industry would be capable of sequestering 20.4 million tons of CO$_2$ [130]. Yet, it should be noted that only one study has been conducted in this research area, signifying the need for further investigation. On a global scale, if all producers of the concrete products presented herein were to adopt carbonation curing, a total of 934 million tons of CO$_2$ could be sequestered. With an annual global cement production of 4.2 billion tons [131], accelerated carbonation curing could reduce the carbon emissions associated with the cement industry by 22.2%. This capacity could further increase if carbonation were adopted for curing various precast reinforced concrete products.

While the environmental benefit in terms of CO$_2$ sequestration has been addressed in various research studies, the curing-related water consumption in carbonation curing compared to steam and moist counterparts has not been
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DOI: http://dx.doi.org/10.5772/intechopen.93929

investigated yet. Based on the work of El-Hassan, Shao [82], the only water required in accelerated carbonation curing is that for spraying the sample after carbonation. This water promoted subsequent hydration by compensating for the water lost due to preconditioning and the carbonation reaction. As such, the total water consumed in this curing regime was about 0.085 m$^3$ per m$^3$ of concrete. In contrast, moist and steam curing are estimated to consume about 3 and 1 m$^3$ of water for the same volume of concrete, respectively [132]. Clearly, carbonation curing could be deemed more advantageous than moist and steam curing from a water preservation standpoint.

7. Conclusions

Accelerated carbonation is an innovative curing regime that promises to expedite strength gain, improve durability performance, and permanently sequester CO$_2$ gas in concrete products. Thus, it has the potential to enhance the sustainability of the construction industry.

Reaction kinetics, processes, and final products are comprehensively reviewed. The main chemical reactions occur between calcium silicates (C$_3$S and C$_2$S) in the cement and CO$_2$ gas to produce calcium silicate hydrate (C-S-H) gel and calcium carbonate (CaCO$_3$). Calcium carbonate was detected in its three polymorphic phases, aragonite, vaterite, and calcite, with the former two and latter being associated with the carbonation of C-S-H and calcium silicates, respectively. Their morphology was typical of amorphous, except for the case of carbonating PLC concrete, whereby sharp highly crystalline crystals formed. Conversely, C-S-H was not as easy to detect. In fact, it was intermixed with calcium carbonates to form an amorphous calcium silicate hydrocarbonate product.

The carbonation process was divided into three main stages, preconditioning, carbonation, and subsequent hydration. The utilization of preconditioning was found essential to optimize the water content and promote a higher degree of carbonation reaction. The optimum relative humidity employed in preconditioning was reported as 50–60%. As for carbonation curing, higher reactivity was noted when higher concentration and pressure of CO$_2$ were used, evidenced by the higher carbon uptake. Subsequent hydration was introduced afterward to enhance the late age mechanical and durability performance.

The applicability of accelerated carbonation to different construction applications has also been highlighted. Carbonated concrete masonry blocks showed comparable mechanical properties to those of steam- and moist-cured counterparts. Yet, the former’s resistance to freeze-thaw damage and sulfate attack was greater than that of the latter. Furthermore, carbonation was applied to concrete paving blocks. The compressive strength and freeze-thaw resistance of carbonated samples were superior to those of hydration- and air-cured equivalents. Similarly, the mechanical and durability performance of concrete pipes and beams subjected to carbonation curing were superior to conventionally-cured counterparts. Also, it was interesting to note that there was no risk of corrosion to the steel reinforcement, as the pH of the surrounding 28-day concrete was above 12. Moreover, the feasibility of employing carbonation as a curing regime for cement-bonded particleboards was assessed. Carbonation curing improved the overall interfacial structure between the cement and fiber and led to the filling of capillary space with newly-formed CaCO$_3$. As a result, enhanced physical, mechanical, and durability properties were reported for carbonated samples compared to conventionally-cured samples. Lastly, carbonation was applied to ceramic bricks as a means of permanently sequestering carbon dioxide.
In addition to its evident improvement in the performance of construction applications, carbonation curing provides a carbon sink to beneficially recycle CO₂. Yet, its full potential can only be attained if it is adopted on a global scale. The application of carbonation curing to all globally-produced concrete blocks, concrete paving blocks, concrete pipes, cement-bonded particleboards, and ceramic bricks can store up to 934 million tons of CO₂, leading to a 22.2% reduction in cement-related carbon emissions. Additionally, it has the potential to reduce the water consumed in moist and steam curing by 97 and 91%, respectively. Evidently, the carbonation curing process enhances material performance, offers environmental benefits, and provides an excellent means to recycle carbon dioxide emitted by the cement industry.

Acknowledgements

This work was financially supported by the United Arab Emirates under grant number 31 N398.

Conflict of interest

The authors declare no conflict of interest.

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DOI: http://dx.doi.org/10.5772/intechopen.93929

References

[1] Global greenhouse gas emissions data. https://www.epa.gov/ghgemissions/globalgreenhouse-gas-emissions-data [cited 2020].

[2] Climate change indicators: greenhouse gases. https://www.epa.gov/climateindicators/greenhouse-gases#ref3 [cited 2020].

[3] IPCC. Projections of Future Changes in Climate. Intergovernmental Panel on Climate Change, 2007.

[4] What is the greenhouse effect? http://www.livescience.com/37743-greenhouseeffect.html [cited 2020].

[5] Pacheco-Torgal F, Abdollahnejad Z, Camões AF, Jamshidi M, Ding Y. Durability of alkali-activated binders: A clear advantage over Portland cement or an unproven issue? Constr Build Mater. 2012;30:400-5.

[6] Chindaprasirt P, Charerat T, Sivivatnanon V. Workability and strength of coarse high calcium fly ash geopolymer. Cem Concr Compos. 2007;29(3):224-9.

[7] US Geological Survey. Minerals commodity summary - cement USA: USGS; 2016 [cited 2016 October 6].

[8] An update on CO2 capture from cement production. http://www.globalccsinstitute.com/insights/authors/dennisvanpuyvelde/2013/02/20/update-co2-capturecement-production [cited 2020].

[9] Saleh HM, El-Saied FA, Salaheldin TA, Hezo AA. Macro- and nanomaterials for improvement of mechanical and physical properties of cement kiln dust-based composite materials. J Clean Prod. 2018;204:532-41.

[10] Saleh HM, El-Saied FA, Salaheldin TA, Hezo AA. Influence of severe climatic variability on the structural, mechanical and chemical stability of cement kiln dust-slag-nanosilica composite used for radwaste solidification. Constr Build Mater. 2019;218:556-67.

[11] Saleh HM, Salman AA, Faheim AA, El-Sayed AM. Sustainable composite of improved lightweight concrete from cement kiln dust with grated poly(styrene). J Clean Prod. 2020;277:123491.

[12] Samad S, Shah A. Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review. International Journal of Sustainable Built Environment. 2017;6(2):663-74.

[13] Panesar DK, Zhang R. Performance comparison of cement replacing materials in concrete: Limestone fillers and supplementary cementing materials – A review. Constr Build Mater. 2020;251:118866.

[14] Kayali O, Sharfuddin Ahmed M. Assessment of high volume replacement fly ash concrete – Concept of performance index. Constr Build Mater. 2013;39:71-6.

[15] Hooton RD. Canadian use of ground granulated blast-furnace slag as a supplementary cementing material for enhanced performance of concrete. Canadian Journal of Civil Engineering. 2000;27(4):754-60.

[16] Khatib JM, Hibbert JJ. Selected engineering properties of concrete incorporating slag and metakaolin. Constr Build Mater. 2005;19(6):460-72.

[17] Juenger MCG, Siddique R. Recent advances in understanding the role of supplementary cementitious...
Cement Industry

materials in concrete. Cem Concr Res. 2015;78:71-80.

[18] Elahi MMA, Hossain MM, Karim MR, Zain MFM, Shearer C. A review on alkali-activated binders: Materials composition and fresh properties of concrete. Constr Build Mater. 2020;260:119788.

[19] Nawaz M, Heitor A, Sivakumar M. Geopolymers in construction - recent developments. Constr Build Mater. 2020;260:120472.

[20] Amran YHM, Alyousef R, Alabduljabbar H, El-Zeadani M. Clean production and properties of geopolymer concrete; A review. J Clean Prod. 2020;270:119679.

[21] El-Hassan H, Ismail N. Effect of process parameters on the performance of fly ash/GGBS blended geopolymer composites. J Sustain Cem Mater. 2018;7(2):122-40.

[22] Zhang P, Gao Z, Wang J, Guo J, Hu S, Ling Y. Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. J Clean Prod. 2020;270:122389.

[23] Adesanya E, Ohenoja K, Kinnunen P, Illikainen M. Alkali Activation of Ladle Slag from Steel-Making Process. Journal of Sustainable Metallurgy. 2016;3:300-10.

[24] El-Hassan H, Elkholy S. Performance Evaluation and Microstructure Characterization of Steel Fiber-Reinforced Alkali-Activated Slag Concrete Incoporating Fly Ash. J Mater Civ Eng. 2019;31(10):04019223.

[25] Al-Majidi MH, Lampropoulos A, Cundy A, Meikle S. Development of geopolymer mortar under ambient temperature for in situ applications. Constr Build Mater. 2016;120:198-211.

[26] Aydin S, Baradan B. Mechanical and microstructural properties of heat cured alkali-activated slag mortars. Mater Des. 2012;35:374-83.

[27] Bernal S, De Gutierrez R, Delvasto S, Rodriguez E. Performance of an alkali-activated slag concrete reinforced with steel fibers. Constr Build Mater. 2010;24(2):208-14.

[28] Bernal SA, Rodríguez ED, Mejía de Gutiérrez R, Provis JL, Delvasto S. Activation of Metakaolin/Slag Blends Using Alkaline Solutions Based on Chemically Modified Silica Fume and Rice Husk Ash. Waste Biomass Valorization. 2012;3(1):99-108.

[29] Ismail N, El-Hassan H. Development and Characterization of Fly Ash/Slag-Blended Geopolymer Mortar and Lightweight Concrete. J Mater Civ Eng. 2018;30(4).

[30] Choi S-J, Choi J-I, Song J-K, Lee BY. Rheological and mechanical properties of fiber-reinforced alkali-activated composite. Constr Build Mater. 2015;96(Supplement C):112-8.

[31] Gu YM, Fang YH, Gong YF, Yan YR, Zhu CH. Effect of curing temperature on setting time, strength development and microstructure of alkali activated slag cement. Materials Research Innovations. 2014;18(sup2):S2-829-S2-32.

[32] Gu Y-m, Fang Y-h, You D, Gong Y-f, Zhu C-h. Properties and microstructure of alkali-activated slag cement cured at below- and about-normal temperature. Constr Build Mater. 2015;79:1-8.

[33] Islam A, Alengaram UJ, Jumaat MZ, Bashar II. The development of compressive strength of ground granulated blast furnace slag-palm oil fuel ash-fly ash based geopolymer mortar. Mater Des. 2014;56:833-41.

[34] Islam A, Alengaram UJ, Jumaat MZ, Bashar II, Kabir SMA. Engineering properties and carbon footprint of
Accelerated Carbonation Curing as a Means of Reducing Carbon Dioxide Emissions
DOI: http://dx.doi.org/10.5772/intechopen.93929

ground granulated blast-furnace slag-palm oil fuel ash-based structural geopolymer concrete. Constr Build Mater. 2015;101, Part 1:503-21.

[35] El-Hassan H, Shehab E, Al-Sallamin A. Influence of Different Curing Regimes on the Performance and Microstructure of Alkali-Activated Slag Concrete. J Mater Civ Eng. 2018;30(9):04018230.

[36] Karim MR, Hossain MM, Manjur A Elahi M, Mohd Zain MF. Effects of source materials, fineness and curing methods on the strength development of alkali-activated binder. J Build Eng. 2020;29:101147.

[37] Lee NK, Lee HK. Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature. Constr Build Mater. 2013;47:1201-9.

[38] El-Hassan H, Ismail N, Al Hinaii S, Alshehhi A, Al Ashkar N. Effect of GGBS and curing temperature on microstructure characteristics of lightweight geopolymer concrete. MATEC Web Conf. 2017;120:03004.

[39] Li J, Liu S. Influence of Slag as Additive on Compressive Strength of Fly Ash-Based Geopolymer. J Mater Civ Eng. 2007;19(6).

[40] Ismail N, Mansour M, El-Hassan H. Development of a low-cost cement free polymer concrete using industrial by-products and dune sand. MATEC Web Conf. 2017;120:03005.

[41] Puertas F, Martínez-Ramírez S, Alonso S, Vazquez T. Alkali-activated fly ash/slag cement strength behaviour and hydration products. Cem Concr Res. 2000;30:1625-32.

[42] Provis JL. Alkali-activated materials. Cem Concr Res. 2018;114:40-8.

[43] Elkholly S, El-Hassan H, editors. Mechanical and micro-structure characterization of steel fiber-reinforced geopolymer concrete. Interdependence between Structural Engineering and Construction Management; 2019; Chicago, IL: ISEC Press.

[44] Nidheesh PV, Kumar MS. An overview of environmental sustainability in cement and steel production. J Clean Prod. 2019;231:856-71.

[45] Hasanbeigi A, Price L, Lin E. Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review. Renewable and Sustainable Energy Reviews. 2012;16(8):6220-38.

[46] Scrivener K, Martirena F, Bishnoi S, Maity S. Calcined clay limestone cements (LC3). Cem Concr Res. 2018;114:49-56.

[47] Scrivener KL, John VM, Gartner EM. Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. Cem Concr Res. 2018;114:2-26.

[48] Rahman A, Rasul MG, Khan M, Sharma S. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel. 2015;145:84-99.

[49] Kääntee U, Zevenhoven R, Backman R, Hupa M. Cement manufacturing using alternative fuels and the advantages of process modelling. Fuel Processing Technology. 2004;85(4):293-301.

[50] Ghenai C, Inayat A, Shanableh A, Al-Sarairah E, Janajreh I. Combustion and emissions analysis of Spent Pot lining (SPL) as alternative fuel in cement industry. Sci Total Environ. 2019;684:519-26.

[51] Schneider M, Romer M, Tschudin M, Bolio H. Sustainable...
cement production—present and future. Cem Concr Res. 2011;41(7):642-50.

[52] Madlool NA, Saidur R, Hossain MS, Rahim NA. A critical review on energy use and savings in the cement industries. Renewable and Sustainable Energy Reviews. 2011;15(4):2042-60.

[53] Puertas F, Blanco-Varela MT. Use of alternative fuels in cement manufacture. Effect on clinker and cement characteristics and properties. Materiales de Construcción. 2004;54(274):51-64.

[54] Trezza MA, Scian AN. Burning wastes as an industrial resource: Their effect on Portland cement clinker. Cem Concr Res. 2000;30(1):137-44.

[55] Chinyama M. P. M. Alternative fuels in cement manufacturing. In: Manzanera M, editor. Alternative Fuel. Rijeka, Croatia: InTech; 2011.

[56] Gluyas J, Mathias S. Geological storage of carbon dioxide book. 1st Edition ed: Woodhead Publishing; 2014.

[57] Young JF, Berger RL, Breese J. Accelerated Curing Of Compacted Calcium Silicate Mortars On Exposure To CO2. Journal of the American Ceramic Society. 1974;57(9):394-297.

[58] Toennies HT, Shideler JJ. Plant Drying Carbonation of Concrete Block - NCMAPCA Cooperative Program. Journal of the American Concrete Institute. 1963;60(5):617-33.

[59] Shi C, Liu M, He P, Ou Z. Factors affecting kinetics of CO2 curing of concrete. J Sustain Cem Mater. 2012;1(1-2):24-33.

[60] Berger RL, Young, J. F., and Leung, K. Accelerated curing of cementitious systems by carbon dioxide - Hydraulic calcium silicates and aluminates - Part II. Cem Concr Res. 1972;2:647-52.

[61] Young JF, Berger, R. L., Breese, J. Accelerated Curing of Compacted Calcium Silicate Mortars on Exposure to CO2. Journal of the American Ceramic Society. 1974;57(9):394-7.

[62] Steinour H. Some Effects of Carbon Dioxide on Mortar and Concrete. American Concrete Institute Journal. 1956;30:905-7.

[63] Papadakis VG, Vayenas, C. G., and Fardis, M. N. Fundamental Modeling and Experimental Investigation of Concrete Carbonation. American Concrete Institute Materials Journal. 1991;88(4):363-73.

[64] Klemm WA, and Berger, R. L. Accelerated curing of cementitious systems by carbon dioxide - Part I - Portland Cement. Cem Concr Res. 1972;2:567-76.

[65] Rostami V, Shao Y, Boyd AJ, He Z. Microstructure of cement paste subject to early carbonation curing. Cem Concr Res. 2012;42(1):186-93.

[66] El-Hassan H, Shao Y, Ghouleh Z. Reaction Products in Carbonation-Cured Lightweight Concrete. J Mater Civ Eng. 2013;25(6):799-809.

[67] Jang JG, Lee HK. Microstructural densification and CO2 uptake promoted by the carbonation curing of belite-rich Portland cement. Cem Concr Res. 2016;82:50-7.

[68] Shah V, Scrivener K, Bhattacharjee B, Bishnoi S. Changes in microstructure characteristics of cement paste on carbonation. Cem Concr Res. 2018;109:184-97.

[69] Soroushian P, Won J-P, Hassan M. Durability characteristics of CO2-cured cellulose fiber reinforced cement
composites. Constr Build Mater. 2012;34:44-53.

[70] Rostami V, Shao, Y., and Boyd, A. J. Durability of concrete pipes subjected to combined steam and carbonation curing. Constr Build Mater. 2011;25:3345-55.

[71] Goto S, Suenaga, K., and Kado, T. Calcium silicate carbonation products. Journal of the American Ceramic Society. 1995;78(11):2867-72.

[72] Castellote M, and Fernandez, L. Chemical changes and phase analysis of OPC pastes carbonated at different CO2 concentrations. Mater Struct. 2009;42(4):515-25.

[73] El-Hassan H, Shao Y. Dynamic carbonation curing of fresh lightweight concrete. Mag Concr Res. 2014;66(14):708-18.

[74] Goodbrake CJ, Young, J. F., and Berger, R. L. Reaction of hydraulic calcium silicates with carbon dioxide and water. Journal of the American Ceramic Society. 1979;62(9-10):488-91.

[75] Berger RL. Stabilization of silicate structures by carbonation. Cem Concr Res. 1979;9(5):649-51.

[76] Ramezanianpour AA, Ghahari SA, Esmaeili M. Effect of combined carbonation and chloride ion ingress by an accelerated test method on microscopic and mechanical properties of concrete. Constr Build Mater. 2014;58:138-46.

[77] Liu Y, Zhuge Y, Chow CWK, Keegan A, Li D, Pham PN, et al. Properties and microstructure of concrete blocks incorporating drinking water treatment sludge exposed to early-age carbonation curing. J Clean Prod. 2020;261:121257.

[78] Groves GW, and Brough, A. Progressive Changes in the Structure of Hardened C3S Cement Pastes Due to Carbonation. Journal of the American Ceramic Society. 1991;74(11):2891-6.

[79] Mo L, Panesar DK. Effects of accelerated carbonation on the microstructure of Portland cement pastes containing reactive MgO. Cem Concr Res. 2012;42(6):769-77.

[80] El-Hassan H, Shao Y. Early carbonation curing of concrete masonry units with Portland limestone cement. Cem Concr Compos. 2015;62:168-77.

[81] Zhang D, Cai X, Jaworska B. Effect of pre-carbonation hydration on long-term hydration of carbonation-cured cement-based materials. Constr Build Mater. 2020;231:117122.

[82] El-Hassan H, Shao Y, Ghouleh Z. Effect of Initial Curing on Carbonation of Lightweight Concrete Masonry Units. ACI Mater J. 2013;110(4):441-50.

[83] Mo L, Zhang F, Deng M. Mechanical performance and microstructure of the calcium carbonate binders produced by carbonating steel slag paste under CO2 curing. Cem Concr Res. 2016;88:217-26.

[84] He P, Shi C, Tu Z, Poon CS, Zhang J. Effect of further water curing on compressive strength and microstructure of CO2-cured concrete. Cem Concr Compos. 2016;72:80-8.

[85] Zhang D, Cai X, Shao Y. Carbonation Curing of Precast Fly Ash Concrete. J Mater Civ Eng. 2016;28(11):04016127.

[86] Shi C, He F, Wu Y. Effect of pre-conditioning on CO2 curing of lightweight concrete blocks mixtures. Constr Build Mater. 2012;26(1):257-67.

[87] El-Hassan H. Static and Dynamic Carbonation of Lightweight Concrete Masonry Units. Montreal, QC: McGill University; 2012.
[88] Behfarnia K, Rostami M. An assessment on parameters affecting the carbonation of alkali-activated slag concrete. J Clean Prod. 2017;157:1-9.

[89] Monkman S, MacDonald M. Carbon dioxide upcycling into industrially produced concrete blocks. Constr Build Mater. 2016;124:127-32.

[90] Zhang D, Shao Y. Early age carbonation curing for precast reinforced concretes. Constr Build Mater. 2016;113:134-43.

[91] Matsushita F, Aono, Y., and Shibata, S. Carbonation degree of autoclaved aerated concrete. Cem Concr Res. 2000;30:1741-5.

[92] El-Hassan H, Shao Y. Carbonation Curing of Concrete Blocks to Mitigate Carbon Emission. The Conference on Carbon Capture, Utilization, and Storage, Annual CCUS 2015 Conference; Pittsburgh, PA, USA.2015.

[93] El-Hassan H, Shao Y. Carbon Storage through Concrete Block Carbonation. Journal of Clean Energy Technologies. 2014;2(3):287-91.

[94] El-Hassan H, Shao Y. Carbon Storage through Dynamic Carbonation of Fresh Lightweight Concrete. American Institute of Chemical Engineers (AIChE) 2016 Spring Meeting; Houston, TX, USA.2016.

[95] He Z, Wang S, Mahoutian M, Shao Y. Flue gas carbonation of cement-based building products. Journal of CO2 Utilization. 2020;37:309-19.

[96] Neves Junior A, Toledo Filho RD, de Moraes Rego Fairbain E, Dweck J. The effects of the early carbonation curing on the mechanical and porosity properties of high initial strength Portland cement pastes. Constr Build Mater. 2015;77:448-54.

[97] Xuan D, Zhan B, Poon CS. Development of a new generation of eco-friendly concrete blocks by accelerated mineral carbonation. J Clean Prod. 2016;133:1235-41.

[98] Ahmad S, Assaggaf RA, Maslehuddin M, Al-Amoudi OSB, Adekunle SK, Ali SI. Effects of carbonation pressure and duration on strength evolution of concrete subjected to accelerated carbonation curing. Constr Build Mater. 2017;136:565-73.

[99] Monkman S, Shao Y. Carbonation Curing of Slag-Cement Concrete for Binding CO2 and Improving Performance. J Mater Civ Eng. 2010;22(4):296-304.

[100] Monkman S, Shao Y. Assessing the carbonation behavior of cementitious materials. J Mater Civ Eng. 2006;November/December:768-76.

[101] Rostami V, Shao Y, Boyd AJ. Carbonation Curing versus Steam Curing for Precast Concrete Production. J Mater Civ Eng. 2012;24(9):1221-9.

[102] Wang L, Yeung TLK, Lau AYT, Tsang DCW, Poon C-S. Recycling contaminated sediment into eco-friendly paving blocks by a combination of binary cement and carbon dioxide curing. J Clean Prod. 2017;164:1279-88.

[103] Scrivener K, Snellings R, Lothenbach B. A Practical Guide to Microstructural Analysis of Cementitious Materials: CRC Press; 2015.

[104] Ramachandran VS, Beaudoin JJ. Handbook of Analytical Techniques in Concrete Science and Technology: William Andre Publishing/Noyes; 2001.

[105] Bukowski JM, and Berger, R. L. Reactivity and strength development of CO2 activated non-hydraulic calcium silicates. Cem Concr Res. 1979;9(1):57-68.
[106] Chang C, and Chen, J. The experimental investigation of concrete carbonation depth. Cem Concr Res. 2006;36:1760-7.

[107] Huffman EWD. Performance of a new automatic carbon dioxide coulometer. Microchemical Journal. 1977;22(4):567-73.

[108] El-Hassan H, Shao Y. Innovative CO2 Utilization By Carbonation Curing of Lightweight Concrete Made with Portland Limestone Cement. American Institute of Chemical Engineers (AIChE) 2016 Annual Meeting; San Francisco, CA, USA.2016.

[109] Shao Y, El-Hassan H, editors. CO2 Utilization in Concrete Block Production. American Institute of Chemical Engineers (AIChE) Annual Meeting 2012; 2012; Pittsburgh, PA, USA.

[110] Shao Y, El-Hassan H. CO2 Utilization in Concrete. Third International Conference on Sustainable Construction Materials and Technologies (SCMT3);, Kyoto, Japan 2013.

[111] Liu Y, Zhuge Y, Chow CWK, Keegan A, Pham PN, Li D, et al. Recycling drinking water treatment sludge into eco-concrete blocks with CO2 curing: Durability and leachability. Sci Total Environ. 2020;746:141182.

[112] Zhang S, Ghouleh Z, Shao Y. Effect of Carbonation Curing on Efflorescence Formation in Concrete Paver Blocks. J Mater Civ Eng. 2020;32(6):04020127.

[113] Shao Y, Monkman S, Wang S. Market Analysis of CO2 Sequestration in Concrete Building Products. Second International Conference on Sustainable Construction Materials and Technologies; Acona, Italy 2010.

[114] Shao Y, Lin X. Early-Age Carbonation Curing of Concrete Using Recovered CO2. Concrete International. 2011;33(9):50-6.

[115] Zhang D, Shao Y. Enhancing Chloride Corrosion Resistance of Precast Reinforced Concrete by Carbonation Curing. ACI Mater J. 2019;116(3):3-12.

[116] Shao Y, Wang S. Carbonation Curing of Cement Bonded Fiberboard Made by Slurry-Dewatering Process. ACI Symposium Publication. 2009;260:125-38.

[117] He Z, Jia Y, Wang S, Mahoutian M, Shao Y. Maximizing CO2 sequestration in cement-bonded fiberboards through carbonation curing. Constr Build Mater. 2019;213:51-60.

[118] Maail RS, Umemura K, Aizawa H, Kawai S. Curing and degradation processes of cement-bonded particleboard by supercritical CO2 treatment. Journal of Wood Science. 2011;57(4):302-7.

[119] Maail RS. Degradation Analysis on Manufacture of Cement-bonded Particleboard Using Supercritical CO2. 2017.

[120] Soroushian P, Aouadi F, Chowdhury H, Nossoni A, Sarwar G. Cement-bonded straw board subjected to accelerated processing. Cem Concr Compos. 2004;26(7):797-802.

[121] Wang L, Chen SS, Tsang DCW, Poon C-S, Dai J-G. CO2 curing and fibre reinforcement for green recycling of contaminated wood into high-performance cement-bonded particleboards. Journal of CO2 Utilization. 2017;18:107-16.

[122] Soroushian P, Hassan M. Evaluation of cement-bonded strawboard against alternative cement-based siding products. Constr Build Mater. 2012;34:77-82.

[123] Wang L, Chen SS, Tsang DCW, Poon C-S, Shih K. Recycling contaminated wood into eco-friendly particleboard using green cement and carbon dioxide curing. J Clean Prod. 2016;137:861-70.
[124] Martín D, Aparicio P, Galán E. Accelerated carbonation of ceramic materials. Application to bricks from Andalusian factories (Spain). Constr Build Mater. 2018;181:598-608.

[125] Transparency Market Research. Global Concrete Block and Brick Manufacturing Market Estimated to Surpass 2700 Billion Units by 2027. Albany, NY, USA: Transparency Market Research, 2018.

[126] Concrete Manufacturers Association. Concrete Block Paving. 5th Edition ed. Midrand, South Africa: Concrete Manufacturers Association; 2009. 30 p.

[127] Lucintel. Concrete Pipe Market Report: Trends, Forecast and Competitive Analysis. Dallas, TX, USA: 2020.

[128] Railway Tie Association. https://www.rta.org/faqs#:~:text=Currently%2C%20the%20industry%20has%20just%20over%2019%20million%20ties. Georgia, USA: Railway Tie Association; 2020 [cited 2020].

[129] Saunders A, Davidson E. Cement Boards. Global Cement. 2014:32-8.

[130] ACIMAC. World Production and Consumption of Ceramic Tiles. Italy: Association of Italian Manufacturers of Machinery and Equipment for Ceramics, 2018.

[131] Cement production worldwide from 1995 to 2019. https://www.statista.com/statistics/1087115/global-cement-production-volume/ [cited 2020].

[132] El-Dieb AS. Self-curing concrete: Water retention, hydration and moisture transport. Constr Build Mater. 2007;21(6):1282-7.