

Carbonated Durability of Premixed Concrete with Carbon Dioxide as an Admixture

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Abstract

The cement manufacturing industry emits a large amount of CO₂ during the production process, exacerbating environmental problems such as greenhouse effect. To solve this problem, researchers in the engineering field have developed a large number of new technologies and products to reduce carbon emissions when using Portland cement concrete. Among them, injecting CO₂ into fresh concrete is a direct approach to the topic. However, further research is needed on its carbon sequestration efficiency and whether it will have adverse effects on the durability of concrete structures. This article summarizes the current research status of pre mixed concrete using CO₂ as an admixture, analyzes its carbon sequestration efficiency, and based on a concrete carbonation durability life prediction model, analyzes the impact of CO₂ injection on carbonation durability life during concrete mixing.

Keywords

Carbon Dioxide; Durability; Premixed Concrete.

1. Introduction

The global warming caused by the massive emission of carbon dioxide (CO₂) is the biggest environmental problem facing all humanity today. Industrial production is the main source of carbon dioxide emissions, especially the cement manufacturing industry, which requires a large amount of raw materials to be consumed in the cement production process! Coal and electricity, as well as other resources, emit a large amount of CO₂. The global cement industry emits approximately 1.35 billion tons of CO₂ annually, accounting for 5% to 7% of CO₂ anthropogenic sources [1]. Approximately 0.8-1 tons of CO₂ are emitted for every 1 ton of ordinary Portland cement produced [2]. The huge energy consumption and CO₂ emissions of the cement industry have put it at the center of the global warming debate. Based on data released by the International Energy Agency, the global CO₂ emissions reached 37.4 billion tons in 2023. Greenhouse gases such as CO₂ have caused a series of serious environmental problems such as global warming and glacier melting. How to reduce CO₂ emissions and reduce the impact of greenhouse effects has become a challenge that the world needs to face and solve together. The goal of "carbon neutrality" is of utmost importance for the construction industry to reduce carbon emissions.

Carbon sequestration technology is a significant CO₂ reduction technology, which is based on the carbonization reaction between alkali metal ions (such as Ca²⁺/Mg²⁺) in natural minerals or solid waste and CO₂, converting CO₂ in the atmosphere into stable inorganic carbonates, thereby achieving CO₂ sequestration. As a major carbon emitter in the construction industry, the hydration products of concrete (Ca (OH) 2, C-S-H, etc.) can react with CO₂, thus possessing the potential for carbon sequestration. At different stages of the entire life cycle (mixing, curing, service, and secondary utilization), concrete can achieve permanent CO₂ storage through carbonation reactions [3, 4]. Among them, the carbonation during the mixing, curing, and

secondary utilization stages is active carbonation [5], which refers to the injection of CO₂ into fresh concrete or carbonation curing of concrete, recycled aggregates, and recycled powder. The carbonation during the service stage is passive carbonation, which refers to the spontaneous carbonation of concrete with CO₂ in the atmosphere without human intervention. The development of passive carbonation to a certain extent will affect the durability of concrete structures.

2. Carbon Fixation Mechanism During the Concrete Mixing Stage

Although hardened concrete can store CO₂ through carbonation reactions, its carbonation rate is very low. Injecting CO₂ during the concrete mixing stage can significantly improve the carbonation rate of concrete [6]. The mechanism is to inject CO₂ into fresh concrete in the form of gas or dry ice. During the mixing process, CO₂ reacts with the pore solution and anhydrous calcium silicate (CaOSiO₂) to produce calcium carbonate (CaCO₃) and hydrated calcium silicate (C-S-H) [7] (Equations 1 and 2). The generated CaCO₃ can provide additional nucleation sites for concrete, thereby accelerating its carbonation [8]. This technology can overcome the problem of slow diffusion of CO₂ into concrete.



Injecting CO₂ during the mixing stage not only directly offsets some of the carbon emissions of concrete, but also improves its mechanical and durability properties. However, it can have some adverse effects on its workability, such as shortened initial setting time and significant loss of slump. CO₂ has a significant impact on the hydration behavior of cement, as well as the pore structure and macroscopic properties of concrete. Through reasonable design, this technology can effectively regulate the setting time, hydration behavior, and pore structure of concrete. The carbon sequestration efficiency of concrete is usually evaluated based on the carbon sequestration amount, which is the mass ratio of stored CO₂ to cementitious materials [9]. During the mixing stage, there are unhydrated and partially hydrated cement particles in the concrete. At this point, the injected CO₂ gas dissolves into water and can react with pore solutions and hydration products, indicating that fresh concrete has the potential to absorb CO₂ [10]. Compared to hardened concrete, injecting CO₂ gas during the mixing stage can not only improve the carbon sequestration efficiency of concrete, but also enhance its compressive and flexural strength. The reason is that CO₂ promotes the hydration of cement, increases the volume of hydration products, and makes the microstructure more dense [8]. A case study shows that injecting carbon dioxide to reduce carbon footprint by 4.6% is feasible, which can reduce cement load [11]. Due to the injection of only a very small amount of carbon dioxide during the mixing process, it has been reported that the alkalinity and durability of concrete will not be affected like in the case of weathering and carbonation [10]. Although it can improve performance, the carbon sequestration ability of the pre carbonization method is very limited considering the relatively small amount of CO₂ used and the short injection time.

It should be noted that carbonation can cause a decrease in the pH value of the concrete pore solution. When the pH value is less than 8.3, the passivation film on the surface of the steel bar will dissolve and induce corrosion of the steel bar. Due to the short duration and low carbon fixation efficiency of the concrete mixing stage, the mass of CO₂ solidified is generally only 0.3% to 1.4% of the mass of the cementitious material. Therefore, carbonization in this stage often does not exacerbate the risk of steel corrosion [8].

There are still some defects that need to be solved urgently when CO₂ is added as an admixture to concrete. Firstly, if CO₂ is added in the form of dry ice, the dry ice is prone to volatilization during the cement hydration process, and the resulting gas can easily form connected pores inside the concrete. These connected pores will reduce the mechanical and durability performance of concrete. As the amount of dry ice increases, the degree of decrease in concrete strength also increases. Adding in the form of gas will reduce carbon sequestration efficiency, increase stirring time, and energy consumption. Secondly, this process involves energy consumption and new carbon emissions, and further evaluation is needed to determine whether it can reduce carbon footprint. Monkman et al. [12, 13] questioned the carbon sequestration effect during the mixing stage, stating that carbon emissions are generated during CO₂ capture, compression, and transportation processes. Producing 1 ton of liquid CO₂ will produce 102.5kg of gaseous CO₂. During the process of transporting CO₂ from the capture source to the mixing plant (a truck with a loading capacity of 25 tons), the CO₂ emissions per mile are 0.063kg/t. In addition, the operation of CO₂ treatment equipment also consumes energy, compressing 1 ton of CO₂ consumes 200 kWh of electricity. The energy and equipment required to implement this technology will still generate carbon emissions. Each production of 1 cubic meter of fixed carbon concrete consumes 0.018 kWh of electricity, which is equivalent to emitting 9.23 g of CO₂. Therefore, whether net zero CO₂ emissions can be truly achieved is a key issue faced by carbon sequestration technology at this stage.

3. The Impact of Passive Carbonization on Durability

Although S Monkman pointed out in his paper [10] that the quality of CO₂ mixed during the mixing process is relatively low and does not affect the durability and alkalinity of concrete. However, concrete carbonation is a long-term process and passive carbonation may occur during its service life. Due to the increase in the initial mass ratio of CO₂ in concrete by pre mixed CO₂, its durability against carbonation is inevitably weakened, and the degree of its impact is a matter of concern. Passive carbonation reduces the alkalinity of concrete. When the pH value is below 10, the passivation film on the surface of the steel bar will be damaged, accelerating the corrosion of the steel bar. Corrosion of steel bars can cause volume expansion, leading to cracking or peeling of the concrete protective layer, accelerating further carbonation of the concrete. Affects the physical properties of concrete. The continuous carbonation process will ultimately cause shrinkage of concrete, generate tensile stress, and may lead to micro cracks, reducing the flexural and compressive strength of concrete. Carbonization can also cause deformation on the surface of concrete, such as cracking and bulging. In addition, carbonation of concrete can lead to the loss of calcium ions in the concrete, accelerate the aging of cement paste, and thus affect the structural safety and service life of buildings.

The passive carbonation rate of concrete structures is mainly affected by the concentration of CO₂ in the environment, environmental temperature and humidity, as well as the material of the concrete. The most severe degree of carbonization occurs in indoor enclosed environments with high temperatures ranging from 50% to 70% relative humidity, followed by high temperature indoor ventilation environments, and the least severe is in low temperature indoor ventilation environments. The reason for this is that when the relative humidity exceeds 70%, a layer of water film will form on the surface of the concrete, making it difficult for CO₂ to diffuse into the concrete, resulting in a mild degree of carbonization; If the relative humidity is less than 50%, the carbonization reaction rate is slow; Under low temperature conditions, the diffusion coefficient and carbonation reaction rate of CO₂ in concrete are relatively slow, so the degree of carbonation is relatively light; Due to high temperature! Medium humidity environmental conditions are conducive to both CO₂ diffusion and the occurrence of carbonization reactions, so the degree of carbonization is the most severe.

Yu Bo[14] et al. comprehensively considered the effects of CO₂ diffusion rate and carbonation reaction rate on the carbonation depth of concrete, and quantitatively analyzed the effects of environmental factors such as temperature, relative humidity, and CO₂ concentration. A practical prediction model for the analysis of concrete carbonation depth was established by introducing environmental correction coefficients for temperature, relative humidity, and CO₂ concentration to modify the theoretical model [15,16], as shown in Equation 3:

$$X_c = k_j k_s k_e \sqrt{\frac{2D_{CO_2}^0 C_{CO_2}^0}{m_0} \sqrt{T}} \quad (3)$$

In the formula, X_c is the effective protective layer thickness (m), and k_j is the position influence coefficient [17]; k_s is the coefficient of influence of working stress [17]; k_e is the product of environmental correction coefficients, and for the environmental conditions considered in reference [14], the value range of k_e is 0.020 to 0.140, $D_{CO_2}^0$ is the diffusion coefficient of CO₂ in concrete under standard environmental conditions (m²/s); $C_{CO_2}^0$ is the molar concentration of CO₂ under standard environmental conditions (mol/m³); T is the carbonation time, and m_0 is the amount of CO₂ absorbed per unit volume of concrete during complete carbonation (mol/m³) [18]. For ordinary Portland cement concrete, the calculation formula for m_0 is shown in Equation 4:

$$m_0 = (1 - a)8.22B \quad (4)$$

In the formula, B is the amount of cementitious material per unit volume of concrete (kg/m³), and a is the amount of mixed material in ordinary Portland cement ($a=10\%$). After conversion, m_0 is equivalent to 32.6% of carbon sequestration. According to the practical prediction model for concrete carbonation analysis (Equation 3), the calculation formula for the service life of concrete structures under carbonation environment can be established:

$$T = \frac{m_0}{2D_{CO_2}^0 C_{CO_2}^0} \left(\frac{X_c}{k_j k_s k_e} \right)^2 \quad (5)$$

According to equation 5, the carbonation durability life of concrete structural components is linearly related to m_0 . The maximum carbon sequestration of CO₂ added to pre mixed concrete is 1.4%. Therefore, when passive carbonation is complete, the amount of CO₂ absorbed per unit volume of concrete m_0' should be deducted, that is:

$$m_0' = 32.6\% - 1.4\% = 31.2\% \quad (6)$$

By replacing m_0 in equation 5 with m_0' , the formula for calculating the service life of concrete structural components in a carbonated environment with a CO₂ fixed carbon content of 1.4% added to pre mixed concrete can be obtained:

$$T = \frac{m_0'}{2D_{CO_2}^0 C_{CO_2}^0} \left(\frac{X_c}{k_j k_s k_e} \right)^2 \quad (7)$$

Comparing equations 5 and 7, the carbonation durability life of pre mixed concrete structural components with a carbon sequestration rate of 1.4% is reduced by 4.3% compared to ordinary concrete structural components, and the impact is relatively small.

4. Conclusion

(1) Injecting CO₂ during the mixing stage can promote the carbonation of concrete, which helps to improve the CO₂ storage rate and efficiency. However, at the current technological level, the carbon fixation efficiency is too low, and the carbon fixation ability of the pre carbonization acidification method is very limited. During the simultaneous addition of CO₂, carbon emissions are generated during CO₂ capture, compression, and transportation processes. Therefore, further research is needed to determine whether carbon reduction can ultimately be achieved.

(2) The addition of CO₂ during pre mixed concrete can lead to an increase in the initial carbon content inside the concrete, but due to the low carbon fixation efficiency, the maximum is only 1.4%, so it will not significantly affect the carbonation durability life of concrete structural components (maximum reduction of 4.3%).

(3) If the technology can be improved to further enhance the carbon fixation efficiency of pre mixed concrete, the impact on the carbonation durability life of concrete structural components will also increase.

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