Carbon Dioxide Sequestered Concrete: A Review Paper

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Abstract: Carbon dioxide, CO_2 accounts for most of the emission from all the types of greenhouse gasses in the world. The ability of CO_2 to remain longer than other greenhouse gases and the convenience of producing CO_2 has resulted in its high projection in a yearly manner. The prime factor for the emission of CO_2 are from the actions of human beings. One such human act is the concrete industry. Total emissions from the concrete industry could therefore contribute as much as 8% of global CO_2 emissions. Sequestered CO_2 in concrete can provide an impact on reducing the carbon footprint and is also able to improve the compressive strength of concrete. During this process, the sequestered carbon dioxide chemically reacts with cement to produce a mineral, trapping carbon dioxide gas in the concrete. Hence, sequestering carbon dioxide gas in concrete does not only on a bigger scale reduces carbon footprint, but it also reduces the impact the construction industry has on the environment. This paper presents a detailed review on the chemical reaction that takes place during the sequestration of carbon dioxide and the research published on the effects of carbon dioxide sequestered concrete on its properties. The impact this process has on the concrete industry and the environment is discussed in this paper.

Keywords: Sequestration, Carbon Dioxide, concrete strength, carbon footprint.

1. Introduction

Global warming is a primary problem faced by all nations in status quo. Despite the ongoing ridiculous debates on the existence of global warming, scientific research has continuously proven on the effects of global warming and how it will increase in the upcoming future, which is also reflected in Figure 1. Greenhouse gases is noticeably the primary cause for global warming. Of all the greenhouse gasses that are produced carbon dioxide is the gas that has the most impact on the world we live in. The ability of CO_2 to remain longer than other greenhouse gases and the convenience of producing CO_2 has resulted in its high projection in a yearly manner.

Cement production and carbon dioxide emissions is an issue that goes hand in hand as the latter is very much dependable on the use of cement and concrete as a whole. Studies found that about 5 to 8% of global CO_2 emissions is the result of the cement industry's contribution [1]. There are two parts of the production of cement that produces the outcome in emission of CO_2. The first part is the compound response when the primary constituents of concrete like clinker and carbonates (generally limestone, $CaCO_3$) are produced when they decay into oxides (CaO). Studies show that this process discharges contribute about 5 % of anthropogenic CO_2 outflows. The second source of emission occurs during the combustion of CO_2. This happens during the combustion of fossil fuels to generate significant energy required to heat the raw ingredients to well over 1000°C. Hence, it is crucial that a method of reducing CO_2 emission into the atmosphere is determined.

One such method of reducing CO_2 is the sequestration of CO_2 in concrete. This solution has the of reducing carbon footprint, as well as providing a loop for the carbon flow in order to achieve a more sustainable construction practice. CO_2 sequestration is performed by injecting CO_2 into ready mix concrete. Here, the CO_2 will be chemically converted into a mineral. This action does not only trap the CO_2 in the concrete, but it is also able to enhance the concrete's properties.

Hence, not only that CO_2 sequestration in concrete can result in a positive environmental impact, the possibility of sequestered concrete having higher strength as well as better quality might mean that it can be financially rewarding as well. Not only that the trapped CO_2 improves the concrete's attributes, but also contributes to the reduction of cement used in the making of the concrete itself. These two selling points makes this project environmentally appealing and leaves a good impact on the industry. This study is limited to the production of concrete only, leaving out the application on reinforced concrete due to the increased risk of corrosion of the reinforcing steel due to low alkalinity after carbonation.

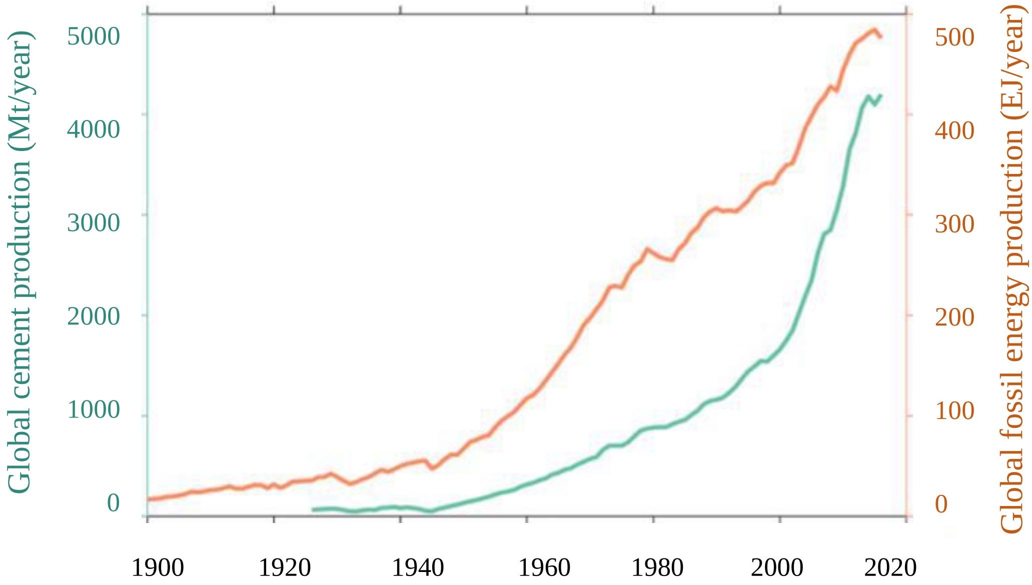

Fig. 1 – Projection of global cement and fossil energy production [1]

2. Application of carbonation on cementitious materials

In recent days, the application of carbonation in cementitious materials has been vast. Eun-Jin Moon and Young Cheol Choi (2019) the effects of CO_2 curing on the properties of four materials that are inorganic: argon oxygen decarburization (AOD) slag, research cement (RC), ground granulated blast-furnace slag (GGBFS), and circulating fluidized-bed combustion (CFBC) ash as shown in Table 1. The carbonation effect on the CO_2 uptake, bonding structure of the carbonated products, reaction products, compressive strength, and porosity were taken into account [2].

Table 1 - Carbon dioxide uptake of AOD slag, RC, GGBFS and CFBC [2]

	Δm_1 (mg)	$m_{dry,105°C}$ (mg)	CO_2 uptake (wt%)	Δm_2 (mg)
AOD slag	0.140	10.5	1.34	0.036
RC	0.364	9.7	3.75	0.063
GGBFS	0.129	10.4	1.24	0.095
CFBC	0.921	10.4	8.86	0.210

The four materials were mixed together with CO_2 through injection, each on its own in a temperature and humidity chamber. The amount of CO_2 was regulated and kept constant for all four materials. The CO_2 used was from a large-scale greenhouse gas sources such as thermal power plants. The purpose of the study was to develop a construction material with improved properties, and high carbon capture. It was found that all four materials had CO_2 uptake which decreased after 148 hours during carbonation curing process. CFBC had the highest CO_2 uptake, followed by RC, AOD slag, and GGBFS respectively. It was found that the correlation of a higher CaO content will cause a higher CO_2 uptake. This could be due to the reaction between the Ca and CO_2. In the interest of strength improvement after carbonation curing which is shown in Figure 2, AOD slag showed the highest strength improvement. The other three materials also showed positive strength improvement. This confirms that curing by means of carbonation has the potential to produce a higher strength material as compared to the conventional method of casting [2].

The difference in the strength improvement could be due to the differences in the reaction mechanism of carbonation between all the inorganic materials. At the beginning of the hydration process, calcium based inorganic materials and cement paste made it difficult for the penetration of CO_2. The main function of the inorganic materials and cement precipitate is to act as a filler to fill the internal pores, and hence does not affect the strength. However, after the carbonation process, the mechanical strength has increased positively, alongside it the applicability of the precipitate as a construction material also has increased.

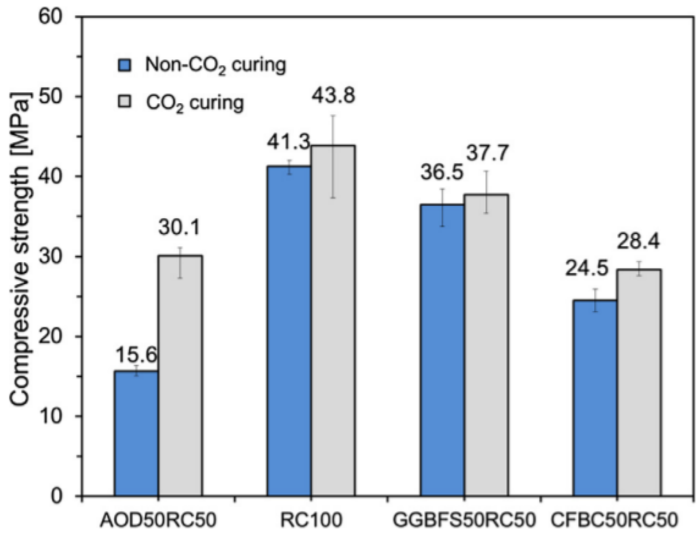

Fig. 2 – Compressive strength of all four CO_2 sequestered materials at 14th day [2]

3. Chemistry of CO_2 sequestered concrete

CO_2 gas sprayed from the gas cylinder into the fresh concrete changes its state to aqueous. The reaction with water will allow the hydration of the gas to form H_2CO_3. H_2CO_3 then ionizes to form H^+, HCO_3^- and CO_3^{2-}. The pH of the mix is lowered. The calcium silicate present is then coated with a layer of calcium-silicate-hydrate gel which dissolves to release Ca^{2+} and SiO_4^- ions. Nano sized $CaCO_3$ are formed.

The condition of concrete during exposure to the CO_2 dosage is that the concrete mixture has to be of fresh concrete and not of mature concrete microstructure. This is due to the different effects that CO_2 has on different conditions of concrete. Figure 3 shows the eight phases of early carbonation of concrete, which results in the production of Calcium Carbonate, $CaCO_3$. Further weathering of the concrete exposes the concrete to external influences like water and carbon dioxide, as can be seen in Figure 4. The reaction of carbon dioxide with a mature concrete microstructure can be associated with durability issues such as shrinkage, reduced pore solution pH and carbonation induced corrosion while carbonation reaction integrated into concrete production applies CO_2 to fresh concrete to react with hydrating cement, rather than the hydration phases present in mature concrete, and does not have the same effects [3].

The reaction that takes place is concrete carbonation. Studies have shown on the negative impacts of carbonation on the development of concrete in the long term, but the reaction that takes place here is early carbonation. Weathering carbonation has negative effects on the concrete, but early age carbonation does not. Hence, the impact is dissimilar. Early age carbonation occurs alongside the hydration of cement when fresh concrete mix is exposed to CO_2 [4]. It accelerates the early age strength gain of the concrete and also enhances the durability properties of the cement-based materials which includes the resistance to sulphate attack, chloride permeation, and freeze−thaw damage [5-7].

The main problem with CO_2 sequestered concrete is the long-term hydration property of the concrete. Here, it is suggested that the pre-hydration period of the cement before carbonation should be left until the late deceleration stage of the concrete hydration. Studies to determine the optimum pre-hydration age for the sequestration of CO_2 to occur through carbonation by Zhang D, Victor C. Li, and Brian R. Ellis (2018) suggested that when the pre-hydration is extended, the amount of CO_2 taken by the cement has decreased, hence extending the hydration of the concrete to 28 days [8].

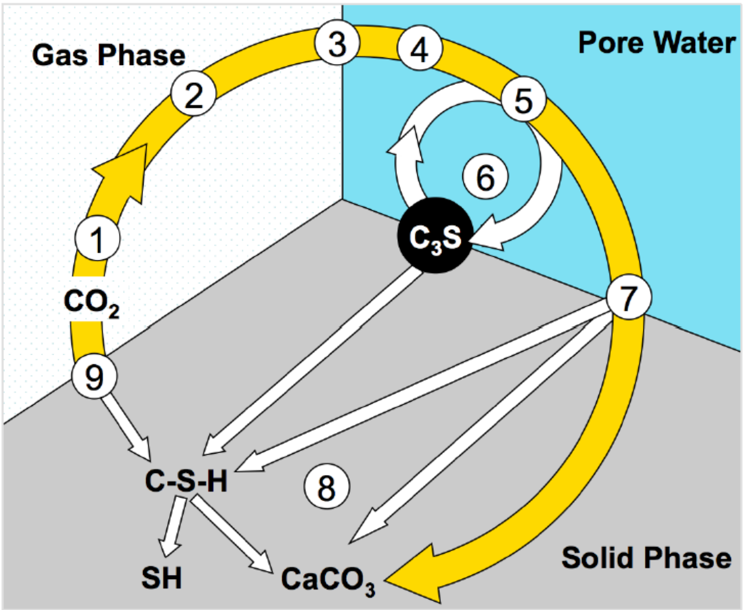

Fig. 3 – Early age carbonation of concrete [3]

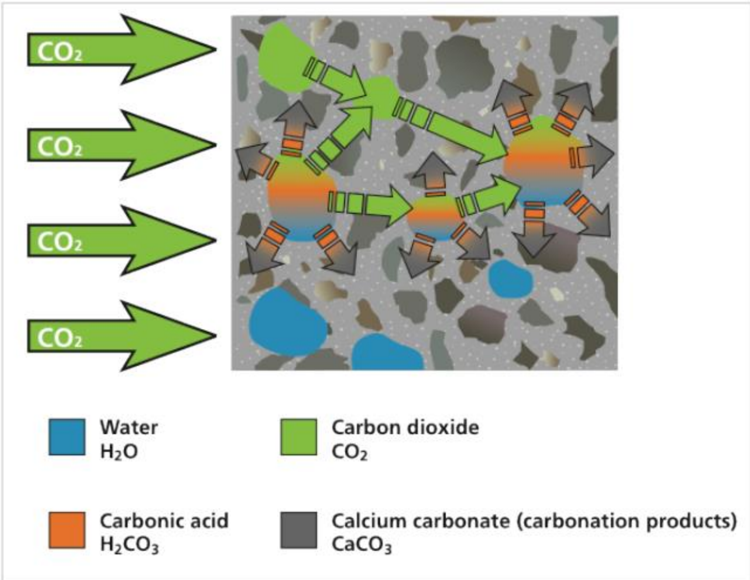

Fig. 4 – Weathering carbonation of concrete [3]

4. Properties of CO_2 sequestered concrete

Essentially, there are two methods where the sequestration of CO_2 takes place, one during the curing phase of the concrete, and the other during the mixing phase of the concrete. Both have the same benefits on the concrete but impacts at different levels or phases. CO_2 sequestration has also been used to improve the properties of concrete that was made of recycled aggregates [9,10,11]. As can be seen in Figures 5 and 6 for sequestrated concrete during curing of the concrete, the compressive strength was found to be lower after 28 days compared to controlled concrete, but then became similar over the period of 90 days. Hence, recycled aggregates concrete with CO_2 sequestration is able to achieve the similar strength requirements to a natural aggregate concrete.

CO_2 curing of concrete is usually done in an air tight vessel. A regulator is then used to control the pressure at which the CO_2 was injected. This process takes 24 hours, after which the concrete is placed for curing in a curing tank. Whereas the CO_2 sequestration during the mixing of concrete is when CO_2 gas is injected directly into an enclosed mixer to ensure the injected gas is contained effectively [12]. Therefore, carbonation occurs during early hydration of the cement.

For both methods, the properties of the concrete or the impact it has on the concrete is similar. The density of CO_2 sequestered concrete is higher than of controlled concrete for both methods. This is possibly because of the voids of the concrete being filled with the nanosized $CaCO_3$ produced in the process. The water needed for CO_2 sequestration during concrete mixing is also slightly higher in order to hold the mixture together, that is also another possible reason for the increase in density. Besides that, the water absorption was more positive for the cases with CO_2 present. This is because both methods projected a lesser water absorption with regards to the controlled concrete.

On the matter of strength improvement, specifically compressive strength, CO_2 sequestered concrete portrays positive results. The compressive strength of concrete is measured on the 7th, 14th and the 28th day respectively. CO_2 sequestered concrete with accelerated carbonation showed that the concrete samples achieved higher strength faster compared to controlled concrete on all 7 days. The compressive strength for both methods showed a relatively higher strength on the 28th day compared to normal concrete. It is possible that this is because of the nanosized $CaCO_3$ that have improved the cementitious matrix [13]. Carbonation on these criteria is known to improve surface hardness, strength and durability of products based on cement by the filling of the pores of the cement paste matrix.

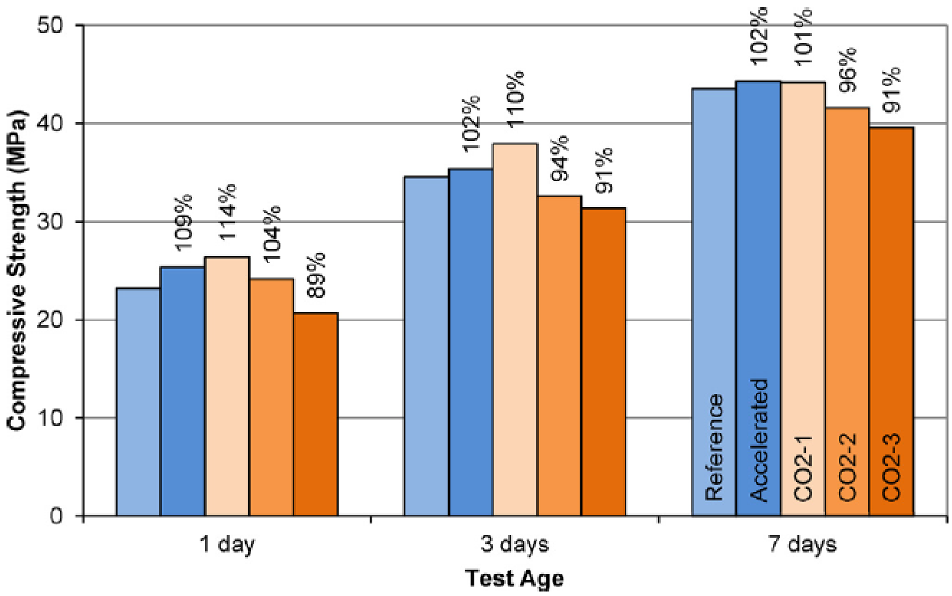

Fig. 5 – Early age compressive strength of concrete [13]

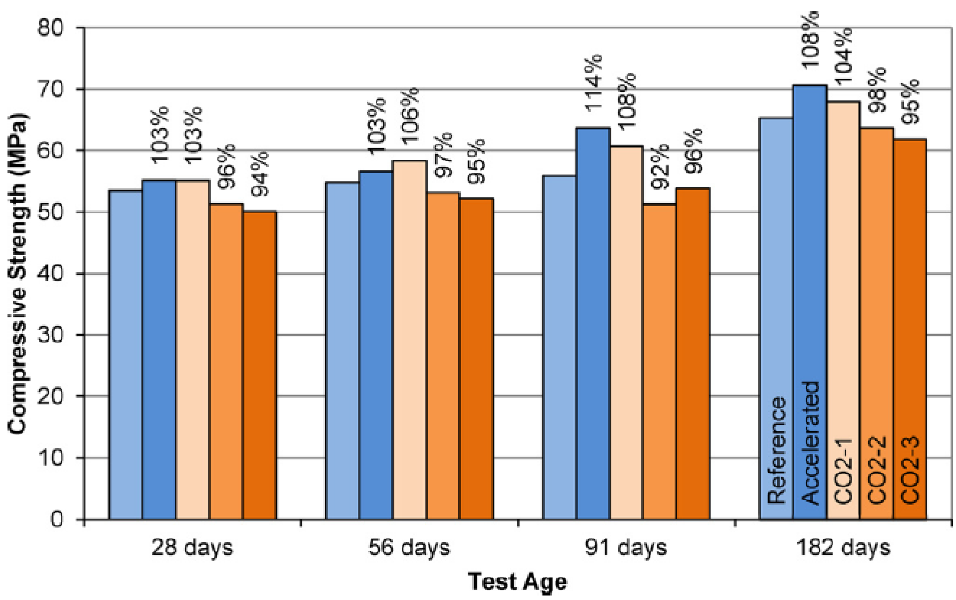

Fig. 6 – Later age compressive strength of concrete [13]

5. Environmental impact of CO_2 sequestered concrete

The environmental impact of this project lies in a spectrum of various benefits that affects environment. These includes the following factors. Firstly, the fact that recycled CO_2 is trapped in the concrete forever. It is well known that carbon dioxide is the leading and the primary greenhouse gas with the highest percentage amongst other greenhouse gases. Hence, this sequestration of concrete will definitely reduce the emission of CO_2 in the environment, specifically from the construction industry.

Sean Monkman and Mark MacDonald (2010) conducted studies on the estimation on the efficacy of the CO_2 used in concrete. It was shown that for 1000 blocks of sequestered concrete, from the 34,250g of CO_2 injected into the concrete, only 30,140g of the CO_2 was absorbed. It is shown in Table 2 that after the consideration of the reduction on the CO_2 lost during processing and transporting, it was deduced that the total CO_2 utilised per 1000 blocks is 26,139g, summing up to a 86.7% of the total CO_2 injected [12]. The fact that 80 to 90% of the carbon dioxide was absorbed by the concrete is the representation of the net removal of CO_2 from the atmosphere.

Table 2 - Net environmental impact summary [12]

Factor	Amount Per 1000 blocks
CO_2 dosed (g)	34,250
CO_2 absorbed (g)	30,140
CO_2e – gas processing (g)	3,522
CO_2e – gas transport (g)	479
Total CO_2 emissions (kg)	4001
Net CO_2 utilised (kg)	26,139
Net efficacy, %	86.7

Besides that, the sequestration of CO_2 into concrete mixing also allows concrete companies to reduce the consumption of binders used in concrete mixing since the injected CO_2 will produce nanosized $CaCO_3$ when it reacts with the fresh concrete mix. Hence, the amount of cement used can also be reduced since cement has become the primary binder in sequestered concrete.

A study has shown that the use of CO_2 sequestered concrete allows for a reduction of up to 5% of the cement in that concrete mix as shown in Table 3. Each 1% reduction in cement used in concrete represents a cement savings of 1,620 grams of cement per cubic yard of concrete. The reduction in cement usage represents a CO_2 emissions reduction of 1,260 grams of CO_2 per percent of cement reduced [14].

Table 3 - Carbon dioxide usage and savings from Carbon XPrize validation tests [14]

	Per Load	Per Cubic Yard
Concrete Shipped	494 Loads	3,957 Yards
Average Cement Usage	1,298 kgs	162 kgs
Average CO_2 Usage	1.284 kgs	0.160 kgs
Avoided Cement (1%)	13.0 kgs	1.62 kgs
Avoided Cement CO2 (1%)	10.1 kgs	1.26 kgs
Avoided Cement CO2 (4%)	40.4 kgs	5.04 kgs
Total CO2 reduction (4% avoided)	41.68 kgs	5.20 kgs

6. Conclusion

The aim of this paper is to give a review on the sequestration of CO_2 in concrete in order to improve the properties of the materials. One highlighted prospect is the use of fillers in concrete where after the fillers are injected with CO_2, the inorganic materials attributes are enhanced. The mechanical strength increased, adding more strength to the concrete parts they are filled into. Sequestration of CO_2 in concrete can be done in two methods, injection of CO_2 gas during the curing phase and the mixing phase of concrete. Both methods show positive progress but with different impacts. The injection of CO_2 during the mixing phase of concrete required more water as the initial amount of water was used in the reaction during sequestration and more was needed to hold the mixture together. Both methods are done in a sealed environment to avoid or minimize the amount of CO_2 emitted in the atmosphere. After the sequestration, the properties of the concrete also showed distinct difference when compared to controlled concrete. The density of CO_2 sequestered concrete is higher than of normal concrete due to the filling of pores of the concrete with the fine $CaCO_3$ produced during the sequestration. The absorption of water was lesser for CO_2 sequestered concrete for both during mixing and curing of concrete. Finally, for the compressive strength measured on the 7th, 14th and the 28th day, CO_2 sequestered concrete projected a higher compressive strength than controlled concrete, the time it takes to achieve a required strength is also faster. All in all, the sequestration of CO_2 in concrete provides a very positive environmental impact, an impact very much needed from the cement industry as it emits 8% of the CO_2 present in the atmosphere. Sequestration of CO_2 provides a closed loop for the cement industry. The very same CO_2 gas released to the atmosphere is then being injected into concrete in order to enhance its properties. It not only reduces carbon footprint, but the improvement in the strength of the concrete also allows the reduction of cement used in order to achieve intended strength and reduction of cement also means reduction of CO_2 emission to the atmosphere.

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