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Enhancement of Properties of Concrete Using Carbon Dioxide: An Initiative to Curb Carbon Footprints

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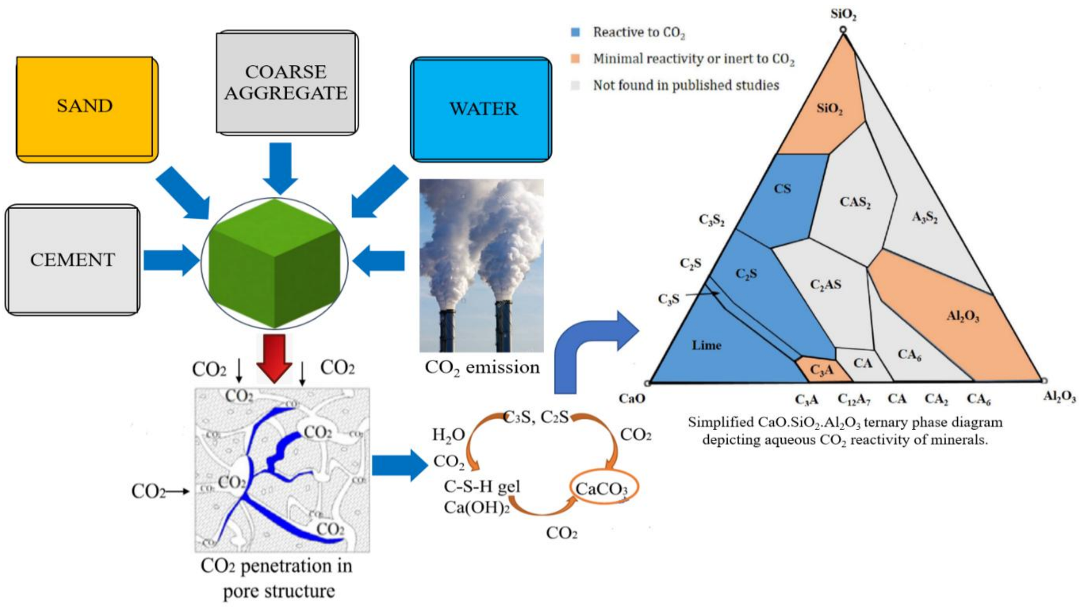

Graphical Abstract:

***Abstract**: In the present era, the word "Global Warming" needs no further introduction as 72% of the emitted greenhouse gases arecarbon dioxide of which 7%is produced when calcium carbonate is calcinated during the manufacturing of cement. This process is perilous to the environment. According to the International Energy Agency (IEA), every year approximately 33.5 billion tonnes of CO_2 is emitted which contributes to global warming. Therefore, it has become an arduous challenge to the construction industry to emphasize this matter for further research. By adopting Carbon Cure technology as the curing at the initial stage will help in eradicating the impact. So far 22,400 tonnes of CO_2 have been utilized and gainfully used utilizing CC technology. In this mechanism CO_2 collected, purified, and infused into the concrete. This process helps the concrete in attaining high early strength in comparison to the conventional curing. The injected CO_2 gets transformed into a mineral and gets permanently embedded into the concrete. This method of curing could replace steam curing in the field of cost. It is also eco-friendly as entrapped CO_2 doesn't leave the concrete even after pulverization as it chemically rearranged into a mineral.This paper focuses on mechanism, outcome, feasibility, applications,Andthe future scope of this technology. Materials used are Ordinary Portland Cement (OPC), Fly ash(FA), Ground Granulated Blast Furnace Slag (GGBFS), Red Mud (RA), and Superplasticizer.*
The concrete is tested for mechanical, flexural, and split tensile strength. Microscopic tests include X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM)Thermogravimetric Analysis (TGA), Mercury Intrusion Porosimetry (MIP) to examine the chemical reactions and products formed. The durability test includes a carbonation test to evaluate the depth of carbonation to state its durability parameter. Lastly, to determine its feasibility and scope in the future to practice in the construction industry.
***Keywords**: CO_2, Carbon Curing, Carbonation, Concrete.*

I. Introduction

At present utilization of industrial wastes and by-products has got a significant role in the construction sector. This helps in reducing pollution in the atmosphere and promotes green concrete. According to the International Energy Agency (2019), approximately 33.5 Gig tons of CO_2 gas is emitted due to anthropogenic activities of which 5% is contributed by the cement industry. CO_2 is a major greenhouse gas having 400 ppm.

Approximately every 1000 Kgs of cement produces 927 Kgs of CO_2 which increases the concentrations of CO_2 in the atmosphere leading to an increase in temperature of the environment causing global warming.CC technology has recently got an imperative role in modifying the characteristic properties of concrete. It also helps in curbing the pollution generated by industries. In this mechanism CO_2 collected, purified, and infused into the concrete. This process helps the concrete in attaining high early strength in comparison to the conventional curing. The injected CO_2 gets transformed into a mineral and gets permanently embedded into the concrete. This method of curing could replace steam curing in the field of cost. It is also eco-friendly as entrapped CO_2 doesn't leave the concrete even after pulverization as it chemically rearranged into a mineral. In this experimental work, OPC is used along with other industrial byproducts like FA, GGBS, red mud. By research, it was established that 2-12 hours duration gives the best results in terms of early strength gain. On further hydration, it was observed an increased value in compressive strength as compared to conventional curing. Another mechanical test includes flexural and splits tensile. The chemical and microscopic tests include the measurement of the depth of carbonation, SEM,XRD, TGA, MIP whose results are to be evaluated and carefully examined to find out the compounds formed after the chemical reaction during CC. The results are carefully analyzed on determined its feasibility and scope in the future to entertain in the construction industry.

II. Literature Review

Carbonation is one of the detrimental aspects of concrete. Under this phenomenon, CO_2 present in the atmosphere penetrates the concrete leading to the formation of calcium carbonates. Due to which the alkalinity of concrete gets reduced thereby making the reinforcement prone to corrosion. But later it was established that prolong CO_2 curing has a good impact on concrete. Apart from mechanical characteristics it also modifies parameters like durability, microscopic structure.

2.1 Mechanical Properties

(Rostami et al., 2012) analyzed the microstructure of OPC paste exposed to early CC at different periods was examined. It was concluded that CC followed by hydration gives out the product having higher compressive strength values compared to the hydrated ones[1].

(Xuan et al., 2016)The first 6-hour of curing showed strength gain and turns futile when carried out for 24-hours[2].

(Jang & Lee, 2016)Carbon belite-rich OPC mortar showed improvement in mechanical strength in comparison to normal cured for the same duration [3].

(Monkman et al., 2016) Infusing CO_2 into concrete has shown a significant improvement in compressive strength [4].

(Liu et al., 2016) CC increases compressive strength, at different ages. At 3 days its compressive strength increased by 63.94%, whereas for 7 days it is 25.55%. the 28-days test showed an increment of 11.79%. The curing was carried out at 600^0C for 7 hours. The early, as well as the later hydration degree of steel slag cementitious materials, can also be increased by CC [5].

(He et al., 2016)CC of 3-hour duration followed by hydrationenhances the compressive strength [6].

(Zhan et al., 2016)ACC for 2-hours showed a sign of increment in compressive strength and curing degree. The increase in pressure ranging from 0.1-0.5 bar showed better results in terms of diffusion of CO_2, dissolution, and carbonation reactions. Also, it was favourable in terms of parameters like compressive strength and degree of curing. Further water curing showed again in compressive strength which is mutually corresponding to the early CO_2 curing degree obtained. Concrete made of RA when cured with CO_2 showed better fire-resistance over conventional methods [7].

(Wang et al., 2017) Pressure ranging from (0.5-2.5) is proved to be most effective and desirable for the process. Moist curing showed a significant impact on compressive strength [8].

(Shi et al., 2017) There is a vigorous chemical reaction of CO_2 with the main silicate's phases (C_3S andC_2S) from stable calcium carbonates, the absorbing order of CO_2 is $C_3S>C_2S>C_3A>C_4AF$. The water-cement ratio of 0.35-0.6 is taken into consideration. Condition for preconditioning required (Temperature = 22 + 3^0C, Relative Humidity = 55 + 10%) before carbonation. Further water curing facilities strength gain [9].

(Ahmad et al., 2017) Duration ACC increases compressive strength. The optimum pressure considered is 60 psi (414 kPa) for the duration of 10- hours which showed the best results related to strength enhancement and CO_2 uptake. The compressive strength of later CC concrete is about 200% more that of pre-CC. The CO_2 uptake was 11% [10].

(Xuan et al., 2018)Higher absorption of CO2 with the rapid rate of gas flow & normal relative humidity is mandatory to attain maturity index and strength development [11].

(Zhang & Shao, 2018) CC modifies the strength of concrete at an early stage. It is also favourable for long-term strength compared to normal concrete. CC decreases the volume of the pore of capillaries which doesn't easily allow water to access concrete and pastes. The porosity of IPC decreased by 40%, whereas with FA pastes it got reduced by 26%. Due to the filling of the pore size, there is a significant decrease in the melting point. Due to which fewer portion of pores gets freeze which mitigates the damage of ACC concrete [12].

(Sharma &Goyal, 2018)ACC increases the compressive strength of the concrete by 30% containing cement kiln dust. Without subsequent rehydration, Carbon cured concrete showed somewhat minor 7-day and 28-day compressive strength [13].

(Chen &Gao, 2019)There is a significant increase in the early strength of cement mortars. Water loss from the specimens during procuring is about 30-40%. The CC increases with a decrease in the duration of pre-curing [15].

(He et al., 2019)70 to 100% of the ultimate flexural strength can be attained within 24-hours. CC can efficiently replace autoclave curing [16].

(Meng et al., 2019)Because of the considerable intensity of hydration of OPC and the origination of CaCO3, the strength of compression of CC blocks is greater that of blocks cured with air. It also had a beneficial impact on reducing the water sorptivity of the cement block [17].

(Sharma &Goyal, 2020) ACC enhances the mechanical strength of the concrete. [18].

(Ahmad et al., 2019) The average depth of carbonation subjected to ACC was 1.5 mm for self-compacting concrete which indicates that there is less chance of corrosion of the steel bars. SCC mixtures of limestone powder cement and silica fume cement exhibited 68% & 42% increase in compressive strength after ACC for 10 hours [19].

(Chen &Gao, 2020)CC with adequate duration can modify the strength of compression of the pervious concrete.The duration of 6-hours is the most optimum. The porosity if the pervious concrete gest reduced as CC improves the bond between aggregates and paste of cement. It also decreases the adverse effect of leaching on its critical pore diameter [20].

(Qin &Gao, 2019)The loss of strength due to the inclusion of waste autoclaved aerated concrete in Portland cement gets compensated when cured with CO_2. 10-20% replacement showed the best results in terms of compressive strength. [21].

2.2 Durability

(Monkman et al., 2016) CC showed neutral to positive impact in terms of durability. CC concrete is resistant to the contracting of the hardened concrete mixture. It is also proved to be durable against the impact of freeze-thaw and also scaling of de-icing salt. The initial setting time was enhanced by 95 minutes and the final set by 103 minutes [4].

(He et al., 2019)Due to carbonate precipitation in the reinforced cement matrix, carbonated fibreboards showed better resistance to free-thaw and wet-dry cycling [16].

(Sharma &Goyal, 2020)CC facilitates lower chloride permeability and depth of carbonation. [18].

(Ahmad et al., 2019) ACC concrete exhibits the greater value of dry shrinkage than moist cured specimens. The ACC process is applicable in the precast concrete industry. CC is favourable to specimens with larger surface area with less thickness [19].

(Chen &Gao, 2020)CC can improve freeze-thaw durability [20].

(Zhang & Shao, 2016) The duration of 12-hour carbonation leads to a carbon uptake of 16% can reduce the pH of the concrete surface to 9.2 while the pH value of 13 is maintained at the core. The subsequent hydration restores the pH of the surface to 12.3 comparable to the hydration reference [22].

(Zhang & Shao, 2016)The pH of the concrete gets reduced immediately after CC. On further hydration, for 27 days the gets restored and are comparable to hydration reference. Concrete made of OPC-FA showed chloride content less than 50% compared to the hydration method. Due to the formation of a carbon-rich surface layer, it reduces corrosion risks [23].

(Liu et al., 2016) There is a formation of CaCO3 layer on cementitious material which prevents the phenomenon of disintegration thereby improving the performance of the concrete. Due to the higher temperature, the hydration rate increases. But when it is too fast large holes are formed inside the hardened paste due to which the formation of cracks takes place [5].

(Zhang et al., 2017)CC showed better results on concrete with s large surface area with thin depth. Applications of steel-reinforced members remain susceptible due to a decrease in pH and corrosion effect. The use of other waste-binders or aggregates adds benefits to the environment [24].

(Ghouleh et al., 2017)The carbonation process applies to GGBFS as aggregates for the concrete. The secondary carbonation of granules increases the capacity of carbon isolation in concrete. It was observed that there is good resistance against the effect of freeze-thaw[25].

(Sharma &Goyal, 2020)CC could effectively substitute steam curing for concrete pipes. Besides durability performance, it can also entrap CO_2 to reduce its footprints. Through research, it was concluded that steam curing of 2 hours at the initial stage followed by CC allows 9% of carbon uptake (by cement mass). The calcium hydroxide at the surface of the concrete gets reduced. The phenomenon modifies the resistance to sulphate, thereby maintaining an optimum value of the pH at the core which makes it less prone to acid attack. Curing of concrete with CO_2 at an earlier stage reduces the chloride ion migration due to the exclusion of hydroxyl ions and precipitation of Calcium Hydroxides within its surface. Consequently, it throttles down the conductivity of the pore solution. This test is performed using RCPT which shows lower ion migration through the surface of the concrete which indicates the improvement to resistance to ion diffusivity[26].

2.3 Densification of Concrete

(Jang & Lee, 2016) Densification of the pores in the range of (50nm to 10μm) which contributes to the strength [3].

(He et al., 2016) The reaction of non-reacted cement fragments of concrete having a water-cement ratio of 0.25 reduces the porosityand densifies the concrete [6].

(Sharma &Goyal, 2018) Transformation of $Ca(OH)_2$ to $CaCO_3$ densifies the concrete resulting reduction of porosity in the concrete. Further spraying of water reduces the porosity.[13].

2.4 Carbon Uptake

(El-Hassan & Shao, 2014)Uptake capacity of CO_2 is 22%-24% alone with initial pre-curing. Whereas 8.5% without initial curing the uptake capacity is 35% for 4-day carbonation. The CC can substitute steam curing in concrete masonry unit production to enhance and efficiently recycle cement kiln CO_2[27].

(Sharma &Goyal, 2020)Data obtained from TGA indicates the CO_2 uptake of the concrete samples is 14.1% [18].

(Xuan et al., 2018) Higher absorption of CO_2 with the rapid rate of gas flow & normal relative humidity is mandatory to attain maturity index and strength development [11].

(Guo et al., 2019)The strength of compression of aerated concrete can be increased by sequestrating CO_2 utilizing CC. Red mud, FA & GGBFS specimens are used. Duration of 4-hour curing of concrete along with red mud attained maximum CO_2 absorbing capacity of (21.9 wt.%), whereas FA (17.0 wt.%) and the GGBFS specimen (15.1%). GGBFS attained the maximum compressive strength of 7.3MPa, having 197% more than conventional curing. About 80% of CO_2 gets sequestered within 20 minutes. At around 0.1 tons of CO_2 can be indelibly embedded in a ton of aerated concrete [14].

(He et al., 2019) Maximum uptake of CO_2 with 18-hour initial hydration followed by 2 hours of carbonation is 23.2% and for 28.5% for 24 hours. Pre-conditioning helps in attaining better sequestration of CO_2. [16].

(Qin &Gao, 2019) Carbon uptake is around 11.23-19.02% for a 10-50% replacement [21].

2.5 Microscopic study

(Chen &Gao, 2019)The MIP test showed that carbonation decreases the large capillary pores, whereas water curing can dwindle the small capillary ones. Adequate pre-curing and of CC is to be done, else it will cause de-calcification of C-S-H which will cause loss of strength [15].

(Meng et al., 2019) SEM test indicates that CC has positive results as it modifies and fills the microstructure of cement, eventually at a higher temperature of 600^0C. By DTG and XRD analysis it was found that the process of CO_2 curing facilitates the consumption of Ca $(OH)_2$ to form CaCO3 which modifies the mechanical and physical properties [17].
(Sharma &Goyal, 2020)Concrete gets densified as $CaCO_3$ is produced inside voids of the concrete surface. The data obtained from TGA indicates the $_{CO2}$ uptake of the concrete samples is 14.1%[18].
(Wang et al., 2016)The application of CC can be beneficial for high-performance cement-bonded particleboard using contaminated wood. It enhances the quality of the product and reduces carbon footprint. Cement containing magnesia showed favourable results. The microscopic parameters have a significant role in the process[28].

2.6Recycled Concrete Aggregates (RCA)

(Zhan et al., 2014) CC modifies the characteristics of RA. As it densifies mortar adhered to RCA. Aggregates with smaller particle sizes got easily carbonated. There is a decrease in the pore volume of concrete. After curing is done, water absorption and porosity got reduced. The first 2-hours of curing proceeded rapidly but throttled down later[29].

(Zhan et al., 2016)Due to the reduction in permeability, the apparent density increases from 2995 to 2222 kilograms per meter cube after CO_2 curing. The degree of CO_2 depends upon the use of RA. It compensates for the dropping of strength due to the inferior grade of the RA. Extremely wet or dry conditions are unfavorable to CC. Pre-treating of concrete blocks is required to reduce its moisture content. 2-hour CC gives the same output in terms of quality when compared with the steam curing[30].

(Pan et al., 2017)Properties of RCA originated from demolished concrete. gets enhanced when pre-soaked and CC. Condition for CC includes 0.04-0.05 molecular per kg Ca (OH)2 with 70% concentration with 5% humidity. After curing is done, it was evaluated the RCA in powder form decreased from 14.2% to 9.1%, whereas the absorption of water got reduced from 4.35% to 1.65%. The crushing value reduces to 13% from 18%, whereas the ratio of water- demand reduces (1.17 to 1.10). The rate of increase in compressive strength is (0.95-1.04)[31].

(Xuan & Poon, 2019)The sequestration of $_{CO2}$ in recycled coarse aggregate takes place at a higher rate at the initial phase (<5 hours) followed by a slower rate. The carbon uptake depends upon the conditions of carbonation and the characteristics of RCA. The accelerated carbonation modifies the properties of RCA including mechanical. Physical and microstructural features. The water absorption reduces whereas fines enhance by 10%. The permeability also gets reduced[32].

III. Research Gaps, Status And Future Trends

From the literature review, it was concluded that despite having numerous advantages application of CC to the reinforced structures. This is because at the initial stage the pH gets reduced which makes it prone to corrosion. But it was observed that further hydration restores the pH of the concrete and has a sign to make it applicable in the future. Utilization of other wastes like ferrochrome ash, rice husk ash in concrete using CC will help in analyzing its characteristics and properties.

It has established that steam curing can be replaced by this method. Sequestration of CO_2makes the concrete green as collected liquified CO_2 gets entrapped and embedded permanently into it. In current practice, this method has shown good results when incorporated with other industrial by-products. Red mud has the highest CO_2 uptake, whereas GGBS showed the highest 1-day compressive strength. It is due to the reaction of aluminium and precipitated calcium carbonate. It also compensates for the loss of strength when recycled coarse aggregate is used in place of natural aggregate.

CC has a promising future as it utilizes CO_2 which is a major greenhouse gas that contributes to global warming. In comparison to steam curing, it is less expensive, therefore it turns out to be frugal. Reinforced bars may be used in this form of curing as the core of the concrete remains alkaline after the curing is done.

IV. Discussion

In general, carbonation is coined as a detrimental aspect of concrete in which CO_2 present in the environment penetrates the concrete and reacts with calcium hydroxide to form calciumcarbonates. In this phenomenon, the alkalinity of concrete gets reduced which makes the reinforcement prone to corrosion. However, it was observed that prolong exposure of CO_2 at an earlier stage of concrete showed positive results in terms of mechanical strength, durability, Microscopic structure.

1. $3(3CaO\cdot SiO_2) + (3-x)\ CO_2 + yH_2O \rightarrow xCaO\cdot SiO_2\cdot yH_2O + (3-x)\ CaCO_3$
2. $2(2CaO\cdot SiO_2) + (2-x)\ CO_2 + yH_2O \rightarrow xCaO\cdot SiO_2\cdot yH_2O + (2-x)\ CaCO_3$

The CO_2 dissolves rapidly which rapidly generates carbonic acid that mixes with water due to which hydration of C3S and C2S takes place. In this process, CaCO3 acts as nucleation sites and the zone of C-S-H.

V. Conclusion

With all the research and data, it is quite evident that the process of curing with liquifiedCO_2 has got advantages over conventional forms of curing. This technology can be adopted and practiced in the construction sector to achieve the best results in terms of improving the properties of concrete. The key points associated in this review are:

1. The infused CO_2 gets mineralized and turns into stone which doesn't leave the concrete even after pulverization.
2. On the application of CC at an early age, the mechanical properties of concrete like compressive strength attains a higher value as the porosity gets reduced.
3. The duration of curing showed better results overpressure in terms of carbon uptake. Short-term carbonation doesn't fully react to all C_2S and C_3S grains. Curing of concrete for a period of 6-hours at 30-60 psi or 0.2 MPa is considered to give the best results.
4. Carbonation of adequately moistened C_2S and C_3S occurs rapidly within a few minutes to hours. Extensive Carbonation of C-S-H involves the decalcification effect, eventually transforming to $CaCO_3$ and SiO_2.
5. Continuous exposure to moist or humid environment post carbonation allows for the subsequent hydration of residual unreacted portion.
6. Initially the pH at the surface of concrete declines but on further hydration, it gets restored. as the core remains alkaline.
7. It was concluded that it also makes the concrete greener and more durable in aspects like Chloride penetration, freeze-thaw, salt-scaling.
8. Modifies the properties of mortar adhered to recycled coarse aggregate as it increases its apparent density. On the other hand, water absorption reduces and the ratio of compressive strength throttles up. The duration of 2-hour is regarded as the most optimum duration for giving better results.

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