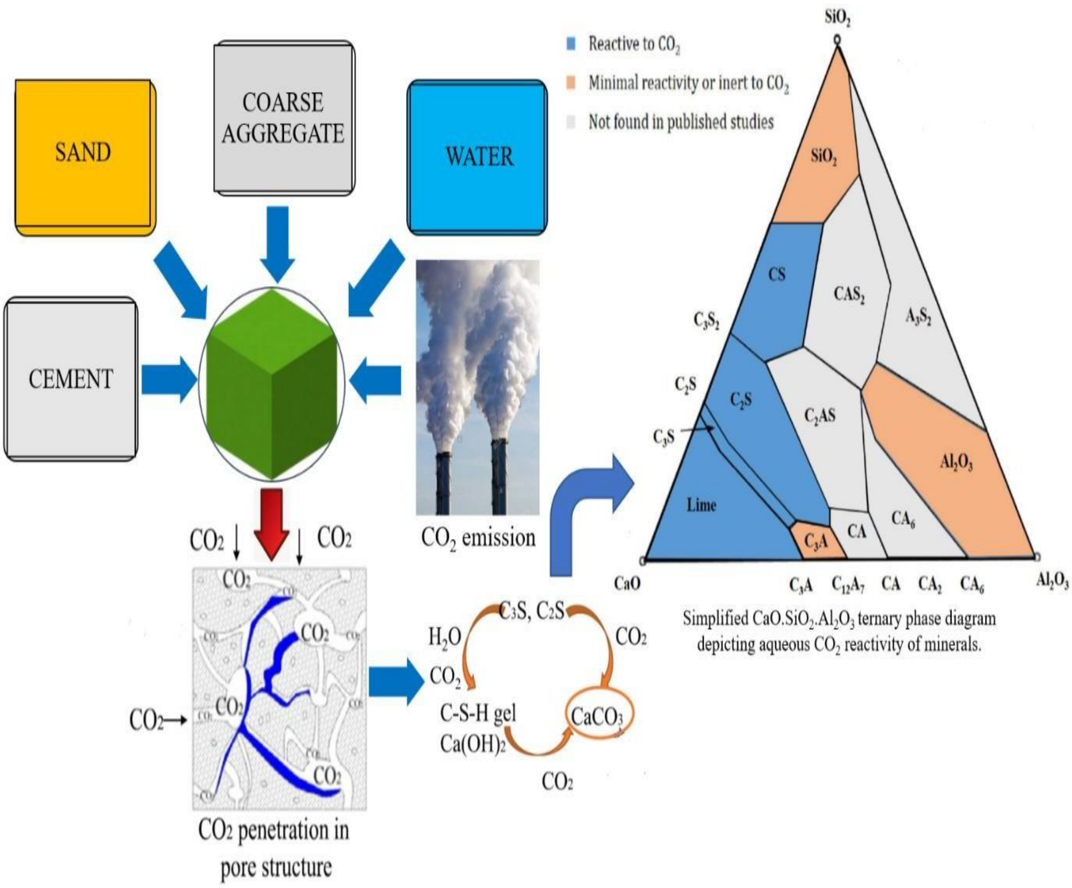
Carbon Dioxide Curing: Revolutionizing Concrete Production for Sustainable Construction

Ch.Lakshmi Sowjanya[1], Dr.K.V.G.D.Balaji[2], Dr. P.Chandan Kumar[3]

[1]Research scholar, Department of civil engineering, (GITAM) Gandhi Institute of Technology and Management (Deemed to be University), Visakhapatnam, India, soujanya.5stars@gmail.com

[2]Professor, Department of civil engineering, GITAM (Deemed to be university) Visakhapatnam, India, balajigitam@gmail.com

[3]Department of civil engineering, GITAM (Deemed to be University), Visakhapatnam, India, ppatnaik@gmail.com



GraphicalAbstract:

Abstract: The present era is characterized by heightened awareness of global warming and the significant role of carbon dioxide (CO2) emissions in its occurrence. The manufacturing of cement, a crucial component in the construction industry, contributes to approximately 7% of the total CO2 emissions through the calcination of calcium carbonate. The International Energy Agency (IEA)

[1]Research scholar, Department of civil engineering, (GITAM) Gandhi Institute of Technology and Management (Deemed to be University), Visakhapatnam, India, soujanya.5stars@gmail.com

[2]Professor, Department of civil engineering, GITAM (Deemed to be university) Visakhapatnam, India, balajigitam@gmail.com

[3]Department of civil engineering, GITAM (Deemed to be University), Visakhapatnam, India, ppatnaik@gmail.com

reports that a staggering 33.5 billion tonnes of CO2 are emitted annually, intensifying the urgency for the construction industry to address this issue through further research.To combat the environmental impact of cement production, the adoption of Carbon Cure (CC) technology at the initial curing stage has emerged as a potential solution. This technology utilizes captured and purified CO2, which is then injected into the concrete mix. This process not only accelerates the development of high early strength but also facilitates the permanent embedding of CO2 into the concrete, transforming it into a mineral form. Moreover, this curing method has the advantage of being cost-effective compared to conventional steam curing methods.The use of CC technology also aligns with eco-friendly principles as the entrapped CO2 remains within the concrete, even after pulverization, due to its chemical rearrangement into a mineral. This paper focuses on elucidating the mechanism, outcomes, feasibility, applications, and future prospects of CC technology. The materials employed in this study include Ordinary Portland Cement (OPC), Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBFS), Red Mud (RA), and Superplasticizer.Various tests are conducted to evaluate the properties of the concrete, including mechanical tests such as compressive, flexural, and split tensile strength. Microscopic tests such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TGA), and Mercury Intrusion Porosimetry (MIP) are employed to examine the chemical reactions and products formed within the concrete. Furthermore, a carbonation test is conducted to assess the depth of carbonation, providing insights into the durability of the concrete.The results of these tests aim to determine the feasibility and potential scope of CC technology in the construction industry. By utilizing this technology, it is anticipated that the industry can significantly reduce CO2 emissions and contribute to a more sustainable and environmentally conscious approach to concrete production.

Keywords:CO_2,Carbon Curing, Carbonation, Concrete.

I. Introduction

Utilization of industrial wastes and by-products in the construction sector has become increasingly important, aiming to reduce pollution and promote the use of green concrete. The cement industry is a significant contributor to CO2 emissions, with approximately 5% of anthropogenic CO2 emissions being attributed to cement production, leading to global warming and increased environmental temperatures.

Carbon Cure (CC) technology has emerged as a promising approach to modify the properties of concrete while addressing pollution generated by industries. In this process, captured and purified CO2 is infused into concrete, resulting in high early strength development compared to conventional curing methods. The injected CO2 undergoes a chemical transformation, becoming a mineral that remains permanently embedded within the concrete. This curing method has the potential to replace steam curing at a lower cost, and it is environmentally friendly since the entrapped CO2 remains within the concrete even after pulverization.

In this experimental work, Ordinary Portland Cement (OPC) is used in combination with industrial by-products such as Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and red mud. The duration of CO2 infusion is determined to optimize early strength gain, with the best results observed between 2-12 hours. Further hydration leads to increased compressive strength compared to conventional curing. Mechanical tests, including flexural and split tensile tests, are conducted to assess the concrete's performance.

Chemical and microscopic tests, such as the measurement of carbonation depth, Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), Thermogravimetric Analysis (TGA), and Mercury Intrusion Porosimetry (MIP), provide insights into the chemical reactions and compounds formed during CC. The results of these tests are carefully analyzed to evaluate the feasibility and potential applications of CC technology in the construction industry.

Overall, CC technology offers a promising solution for improving concrete properties, reducing CO2 emissions, and promoting sustainable practices in the construction sector. The findings of this study will contribute to further understanding the benefits and limitations of CC technology for future implementation.

II. Literature Review

Carbonation is a well-known process in concrete where CO2 from the atmosphere reacts with calcium hydroxide, forming calcium carbonates. This can reduce the alkalinity of concrete and lead to corrosion of reinforcement. However, prolonged exposure to CO2 during curing has shown positive effects on concrete. It can improve mechanical properties, durability, and modify the microscopic structure. Carbonation increases compressive strength, reduces permeability, and enhances resistance to chemical attacks. It also improves bonding between cement particles. By understanding and utilizing the benefits of carbonation, researchers and engineers can optimize concrete mixtures and curing methods for better performance. Further research is needed to explore the full potential of carbonation in the construction industry.

2.1 Mechanical Properties

In a study conducted by Rostami et al. (2012), the microstructure of Ordinary Portland Cement (OPC) paste subjected to early Carbonation Curing (CC) was analyzed. The researchers examined the effects of CC followed by hydration on the microstructure of the cement paste. The results showed that the product obtained from CC followed by hydration exhibited higher compressive strength values compared to the samples that underwent only hydration [1]. This suggests that the combination of carbonation curing and subsequent hydration can lead to improved strength properties in OPC-based materials.

In a study conducted by Xuan et al. (2016), the effects of curing duration on the strength development of carbonated concrete were investigated. The researchers found that the initial 6-hour period of carbonation curing resulted in strength gain in the concrete. However, when the carbonation curing was extended to 24 hours, it was observed that the strength gain became negligible or even diminished [2]. This suggests that there is an optimal duration for carbonation curing, and exceeding that duration may not provide any additional benefits in terms of strength development.

In a study conducted by Jang and Lee (2016), the effects of carbonation curing on the mechanical strength of carbon belite-rich Ordinary Portland Cement (OPC) mortar were investigated. The researchers found that the carbonation curing process resulted in an improvement in the mechanical strength of the mortar compared to the normal curing process for the same duration [3]. This suggests that carbonation curing can enhance the strength development of OPC mortar, specifically in the case of carbon belite-rich compositions.

According to a study conducted by Monkman et al. (2016), the infusion of carbon dioxide (CO2) into concrete has demonstrated a noteworthy improvement in compressive strength [4]. This indicates that the process of infusing CO2 into concrete can positively impact its overall strength characteristics, potentially leading to enhanced performance and durability of the material.

According to Liu et al. (2016), carbonation curing (CC) has been found to increase the compressive strength of concrete at various ages. The study revealed that at 3 days, the compressive strength showed an increase of 63.94% compared to conventional curing. At 7 days, the increase was 25.55%, and at 28 days, the increase was 11.79%. The CC process involved curing the concrete at a temperature of 60°C for 7 hours.

Furthermore, the study also highlighted that carbonation curing can enhance both the early and later hydration degrees of steel slag cementitious materials. This suggests that CC can have a positive impact on the hydration process of concrete containing steel slag, potentially leading to improved overall performance and strength development [5].

According to He et al. (2016), carbonation curing (CC) for a duration of 3 hours followed by hydration has been found to enhance the compressive strength of concrete. The study suggests that the combination of CC and subsequent hydration processes can lead to improved strength development in concrete.[6]

According to Zhan et al. (2016), carbonation curing (CC) for a duration of 2 hours demonstrated an increase in compressive strength and curing degree of concrete. The study found that applying a pressure ranging from 0.1 to 0.5 bar during CC resulted in improved CO2 diffusion, dissolution, and carbonation reactions. This pressure range was found to be favorable for achieving higher compressive strength and better curing. Additionally, the study observed that concrete made with recycled aggregates (RA) and cured with CO_2 exhibited enhanced fire resistance compared to conventional curing methods [7].

(According to Wang et al. (2017), the application of pressure ranging from 0.5 to 2.5 MPa was found to be the most effective and desirable for the carbonation curing process. This pressure range resulted in improved performance in terms of compressive strength. Additionally, the study highlighted the significant impact of moisture curing on the compressive strength of carbonated concrete. Moist curing was found to enhance the strength development of the concrete samples during the carbonation curing process [8].

According to Shi et al. (2017), there is a strong chemical reaction between CO_2 and the main silicate phases (C_3S and C_2S) in cementitious materials, resulting in the formation of stable calcium carbonates. The study found that the order of CO_2 absorption by these phases is $C_3S > C_2S > C_3A > C_4AF$. The water-cement ratio, ranging from 0.35 to 0.6, was considered in the experiments.

Preconditioning conditions of temperature at 22 ± 3°C and relative humidity at 55 ± 10% were applied before the carbonation process. This preconditioning step helps prepare the concrete for the carbonation curing process. Additionally, the study indicated that water curing after the carbonation process facilitates further strength gain in the concrete samples [9].

Ahmad et al. (2017) found that the duration of accelerated carbonation curing (ACC) has a significant impact on compressive strength. The study identified that the optimum pressure for ACC is 60 psi (414 kPa) for a duration of 10 hours, which resulted in the best outcomes in terms of strength enhancement and CO_2 uptake. The compressive strength of concrete after ACC was about 200% higher than that of pre-ACC concrete, and the CO_2 uptake was measured at 11% [10].

Xuan et al. (2018) highlighted the importance of higher CO_2 absorption with a rapid gas flow rate and normal relative humidity to achieve a higher maturity index and better strength development [11].

Zhang and Shao (2018) demonstrated that carbonation curing (CC) has a positive effect on the early and long-term strength of concrete. CC reduces the volume of capillary pores, restricting water access to the concrete. The study showed a 40% decrease in porosity for OPC pastes and a 26% decrease for fly ash (FA) pastes. Additionally, the filling of pores leads to a significant decrease in the freezing point, minimizing freeze-thaw damage in ACC concrete [12].

Sharma and Goyal (2018) observed a 30% increase in compressive strength when cement kiln dust was used in ACC concrete. However, the strength gain without subsequent rehydration was slightly lower at 7 and 28 days [13].

Chen and Gao (2019) reported a significant increase in early strength for cement mortars cured with CC. The study also found that reducing the pre-curing duration resulted in higher CC [14].

He et al. (2019) demonstrated that CC can achieve 70 to 100% of the ultimate flexural strength within 24 hours, making it a potential replacement for autoclave curing [15].

Meng et al. (2019) observed that CC blocks exhibited greater compressive strength compared to air-cured blocks due to the intense hydration of OPC and the formation of CaCO3. CC also reduced water sorptivity in cement blocks [16].

Sharma and Goyal (2020) emphasized the enhancement of mechanical strength through ACC in concrete [17].

Ahmad et al. (2019) investigated the depth of carbonation in self-compacting concrete subjected to ACC, finding an average depth of 1.5 mm, which indicates a lower risk of steel bar corrosion. Self-compacting concrete mixtures with limestone powder cement and silica fume cement showed a 68% and 42% increase in compressive strength, respectively, after 10 hours of ACC [18].

Chen and Gao (2020) showed that CC can modify the compressive strength of pervious concrete, with a 6-hour duration being the most optimum. CC improves the bond between aggregates and cement paste, reducing the adverse effects of leaching on critical pore diameter [19].

Qin and Gao (2019) found that the loss of strength caused by the inclusion of waste autoclaved aerated concrete in Portland cement can be compensated by curing with CO2. The study revealed that a 10-20% replacement resulted in the best compressive strength outcomes [20].

2.2 Durability

Monkman et al. (2016) reported that carbonation curing (CC) had a neutral to positive impact on the durability of concrete. CC concrete exhibited resistance against shrinkage, freeze-thaw damage, and scaling caused by de-icing salts. The study also found that CC increased the initial setting time by 95 minutes and the final set time by 103 minutes, indicating a beneficial effect on the overall curing process.[4].

He et al. (2019) demonstrated that carbonation of fibreboards resulted in carbonate precipitation within the reinforced cement matrix. This carbonation process improved the resistance of the fibreboards to freeze-thaw and wet-dry cycling, indicating enhanced durability.[16].

In their study, Sharma and Goyal (2020) found that carbonation curing (CC) facilitated lower chloride permeability and reduced the depth of carbonation in concrete. This indicates that CC can contribute to improved durability by reducing the ingress of chlorides and protecting the reinforcement from corrosion.[18].

According to Ahmad et al. (2019), autoclaved carbonated concrete (ACC) exhibits a greater value of dry shrinkage compared to moist-cured specimens. This suggests that the ACC process may be more suitable for applications in the precast concrete industry, particularly for specimens with larger surface areas and less thickness.[19].

According to Zhang and Shao (2016), a carbonation duration of 12 hours can result in a carbon uptake of 16%. This carbonation process reduces the pH of the concrete surface to 9.2, while the pH value of 13 is maintained at the core of the concrete. Subsequent hydration of the concrete restores the pH of the surface to 12.3, which is comparable to the pH value observed in the hydration reference samples.[22].

As mentioned by Zhang and Shao (2016), carbonation of concrete leads to an immediate reduction in pH. However, during the subsequent hydration process over a period of 27 days, the pH gradually restores and becomes comparable to the pH observed in the hydration reference samples. When OPC-FA concrete is subjected to carbonation, it shows a chloride content that is less than 50% compared to conventional hydration methods. This reduction in chloride content can help mitigate the risk of corrosion. Additionally, the formation of a carbon-rich surface layer contributes to the improved corrosion resistance of the concrete.[23].

According to Liu et al. (2016), the carbonation process in cementitious materials leads to the formation of a CaCO3 layer, which helps prevent disintegration and improves the overall performance of the concrete. However, it is important to note that when the hydration rate is too fast, as a result of higher temperature, it can lead to the formation of large holes within the hardened paste. These holes can then contribute to the development of cracks in the concrete. Therefore, controlling the carbonation process and ensuring a balanced hydration rate is crucial for maintaining the integrity and durability of the concrete.[5].

According to Zhang et al. (2017), carbonation curing (CC) has shown better results when applied to concrete structures with a large surface area and thin depth. However, it should be noted that when it comes to steel-reinforced members, the decrease in pH caused by carbonation and the potential corrosion effects should be carefully considered. To mitigate these effects, it is recommended to use other waste-binders or aggregates that can provide additional benefits to the environment. These alternative materials can contribute to improving the overall sustainability and performance of the concrete while reducing the environmental impact.[24].

In the study by Ghouleh et al. (2017), the carbonation process was applied to concrete using Ground Granulated Blast Furnace Slag (GGBFS) as aggregates. The secondary carbonation of GGBFS granules was found to increase the carbon isolation capacity in the concrete. Furthermore, the carbonated concrete exhibited good resistance against the detrimental effects of freeze-thaw cycles. This suggests that carbonation can enhance the durability and performance of concrete when GGBFS is used as an aggregate material.[25].

In the study conducted by Sharma and Goyal (2020), it was found that Carbon Cure (CC) technology can effectively replace steam curing for concrete pipes. This alternative curing method not only enhances the durability of the concrete but also helps in reducing its carbon footprint by trapping CO2. Through research, it was determined that a combination of 2 hours of steam curing at the initial stage followed by CC resulted in a 9% carbon uptake (based on cement mass). This process leads to a reduction in calcium hydroxide content on the surface of the concrete.

The modified surface composition improves the resistance to sulfate attacks and maintains an optimal pH value at the core, making the concrete less susceptible to acid attacks. Curing with CO2 at an early stage also reduces chloride ion migration by excluding hydroxyl ions and promoting the precipitation of calcium hydroxide on the concrete surface. This results in decreased conductivity of the pore solution and improved resistance to ion diffusion. The effectiveness of this process was demonstrated through the use of the Rapid Chloride Penetration Test (RCPT), which indicated lower ion migration through the concrete surface, indicating an enhancement in resistance to ion diffusivity.[26].

2.3 Densification of Concrete

In the study by Jang and Lee (2016), it was found that densification of the pores in the range of 50nm to 10μm contributes to the strength of concrete. This densification process leads to improved mechanical properties [3].

He et al. (2016) observed that the reaction of non-reacted cement fragments in concrete with a water-cement ratio of 0.25 reduces porosity and densifies the concrete. This densification process helps enhance the overall strength and durability of the concrete [6].

Sharma and Goyal (2018) reported that the transformation of calcium hydroxide ($Ca(OH)_2$) to calcium carbonate ($CaCO_3$) densifies the concrete, resulting in a reduction of porosity. Additionally, the spraying of water further reduces porosity in the concrete [13].

These studies highlight the importance of densification in concrete for improving its strength and reducing porosity, leading to enhanced performance and durability.

2.4 Carbon Up take

In the study by El-Hassan and Shao (2014), it was found that the uptake capacity of CO_2 in concrete is 22%-24% when subjected to initial pre-curing. Without initial curing, the uptake capacity increased to 35% after 4-day carbonation. This indicates that carbonation curing can effectively sequester CO_2 in concrete and can be a viable alternative to steam curing in concrete masonry unit production, contributing to the efficient recycling of cement kiln CO_2 [27].

Sharma and Goyal (2020) conducted research using Thermogravimetric Analysis (TGA) and reported that the CO_2 uptake of concrete samples was measured to be 14.1%. This demonstrates the ability of concrete to capture and retain CO_2 during the carbonation process [18].

Xuan et al. (2018) highlighted that higher absorption of CO_2, achieved through rapid gas flow and normal relative humidity, is essential for attaining maturity index and strength development in concrete. This indicates that optimizing the conditions for CO_2 absorption can enhance the performance of carbonated concrete [11].

Guo et al. (2019) investigated the sequestration of CO_2 in aerated concrete using red mud, fly ash (FA), and ground granulated blast furnace slag (GGBFS). They found that a 4-hour curing duration with red mud achieved the maximum CO_2 absorbing capacity of 21.9 wt.%, followed by FA (17.0 wt.%) and GGBFS (15.1 wt.%). The aerated concrete specimens cured with red mud also exhibited significantly higher compressive strength compared to conventional curing, with GGBFS achieving the highest strength improvement [14].

He et al. (2019) studied the maximum uptake of CO_2 in concrete using an 18-hour initial hydration period followed by 2 hours of carbonation. They reported CO_2 uptake values of 23.2% and 28.5% for 18-hour and 24-hour carbonation, respectively. Pre-conditioning of the concrete before carbonation was found to enhance the sequestration of CO_2 [16].

Qin and Gao (2019) investigated the carbon uptake in concrete by replacing a portion of the cement with different materials. They reported a carbon uptake range of 11.23-19.02% for a cement replacement percentage of 10-50%. This suggests that the incorporation of alternative materials in concrete production can contribute to CO_2 sequestration [21].

Overall, these studies highlight the potential of carbonation curing to effectively sequester CO_2 in concrete, providing environmental benefits and enhancing the performance of the material.

2.5 Microscopic study

In the study by Chen and Gao (2019), it was observed through the MIP (Mercury Intrusion Porosimetry) test that carbonation of concrete leads to a decrease in large capillary pores, while water curing can reduce the small capillary pores. Adequate pre-curing and controlled carbonation are necessary to avoid decalcification of the C-S-H (Calcium-Silicate-Hydrate) gel, which could result in a loss of strength [15].

Meng et al. (2019) conducted SEM (Scanning Electron Microscopy) tests and found that carbonation curing has positive effects on the microstructure of cement. At a higher temperature of 600°C, the process of CO2 curing modified and filled the cement microstructure. DTG (Differential Thermogravimetry) and XRD (X-ray Diffraction) analyses indicated that the consumption of Ca(OH)2 resulted in the formation of CaCO3, which in turn modified the mechanical and physical properties of the concrete [17].

Sharma and Goyal (2020) reported that concrete gets densified as CaCO3 is produced within the voids of the concrete surface during carbonation curing. The CO2 uptake of the concrete samples, determined through TGA (Thermogravimetric Analysis), was found to be 14.1%. This suggests that carbonation curing not only enhances the density of the concrete but also allows for the sequestration of CO2 [18].

Wang et al. (2016) explored the application of carbonation curing in the production of high-performance cement-bonded particleboard using contaminated wood. They found that carbonation curing improved the quality of the product and reduced its carbon footprint. Additionally, the inclusion of cement containing magnesia showed favorable results. The study emphasized the importance of microscopic parameters in the carbonation process and its impact on the properties of the cement-bonded particleboard [28].

These studies collectively demonstrate the positive effects of carbonation curing on the microstructure, density, and mechanical properties of concrete, as well as its potential for CO2 sequestration and environmental benefits. Proper pre-curing and control of the carbonation process are crucial to ensure optimal results.

2.6Recycled Concrete Aggregates(RCA)

In the study by Zhan et al. (2014), it was observed that carbonation curing (CC) modifies the characteristics of recycled aggregate (RA). The mortar adhered to the recycled concrete aggregate (RCA) gets densified through carbonation. Aggregates with smaller particle sizes are more easily carbonated. The carbonation process leads to a decrease in the pore volume of concrete, resulting in reduced water absorption and porosity after curing. The initial 2 hours of curing proceed rapidly, but the rate slows down afterward [29].

Zhan et al. (2016) found that carbonation curing reduces permeability and increases the apparent density of concrete. The apparent density increased from 2995 to 2222 kilograms per cubic meter after CO2 curing. The degree of carbonation depends on the use of recycled aggregate. Carbonation curing helps compensate for the drop in strength caused by the inferior grade of the recycled aggregate. It was noted that extremely wet or dry conditions are unfavorable for carbonation curing, and pre-treatment of concrete blocks is necessary to reduce their moisture content. The study also indicated that a 2-hour carbonation curing process produces similar quality results compared to steam curing [30].

Pan et al. (2017) investigated the properties of recycled concrete aggregate (RCA) derived from demolished concrete and its enhancement through pre-soaking and carbonation curing. The conditions for carbonation curing included a concentration of 0.04-0.05 mol/kg of $Ca(OH)_2$ with 70% humidity and 5% CO_2 concentration. After curing, the powder content of the RCA decreased from 14.2% to 9.1%, and the water absorption decreased from 4.35% to 1.65%. The crushing value decreased from 18% to 13%, and the water-demand ratio reduced from 1.17 to 1.10. The compressive strength of the RCA increased by a rate of 0.95-1.04 [31].

Xuan and Poon (2019) investigated the sequestration of CO_2 in recycled coarse aggregate (RCA) and its effects on its properties. They found that the sequestration of CO_2 occurs at a higher rate during the initial phase (<5 hours) and then slows down. The carbon uptake depends on the carbonation conditions and the characteristics of the RCA. Accelerated carbonation modifies the mechanical, physical, and microstructural features of the RCA. Water absorption is reduced, while the fines content increases by 10%. The permeability of the RCA also decreases [32].

These studies collectively highlight the positive effects of carbonation curing on recycled aggregates, including the densification of mortar, reduction in porosity and water absorption, enhancement of mechanical properties, and reduction in permeability. Proper conditions and pre-treatment of the concrete are important factors to consider for effective carbonation curing.

III. Research Gaps, Status and Future Trends

From the literature review, it can be concluded that carbonation curing (CC) has numerous advantages and potential applications in the field of reinforced structures. Although there are initial concerns about the reduction in pH and corrosion risks, further hydration restores the pH and makes CC applicable in the future. Utilizing other waste materials such as ferrochrome ash and rice husk ash in concrete using CC can help analyze their characteristics and properties.

It has been established that CC can effectively replace steam curing, making it a more environmentally friendly method. The sequestration of CO_2 in concrete makes it a greener option, as the collected liquefied CO_2 is permanently embedded in the concrete. Incorporating CC with other industrial by-products has shown positive results. For example, red mud exhibits the highest CO_2 uptake, while ground granulated blast furnace slag (GGBS) demonstrates the highest compressive strength after 1 day. This is attributed to the reaction between aluminum and precipitated calcium carbonate. Additionally, CC compensates for the loss of strength when recycled coarse aggregate is used instead of natural aggregate.

CC has a promising future as it utilizes CO_2, a major greenhouse gas that contributes to global warming. Compared to steam curing, CC is less expensive, making it a cost-effective option. Reinforced bars can be used in CC, as the core of the concrete remains alkaline after the curing process.

Overall, CC offers a sustainable and environmentally friendly approach to concrete curing, and with further research and development, it holds great potential for widespread application in the construction industry.

Discussion

Carbonation in concrete is typically considered a detrimental process, where CO_2 from the environment penetrates the concrete and reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonates ($CaCO_3$). This reaction reduces the alkalinity of the concrete, making the reinforcement susceptible to corrosion. However, it has been observed that prolonged exposure to CO_2 at an early stage of concrete can actually have positive effects on mechanical strength, durability, and the microscopic structure of the material.

The reactions involved in carbonation can be represented by the following equations:

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. $2(2CaO{\cdot}SiO_2) + (2-x)\,CO_2 + yH_2O \rightarrow xCaO{\cdot}SiO_2{\cdot}yH_2O + (2-x)\,CaCO_3$

When CO_2 dissolves in the concrete, it rapidly generates carbonic acid (H_2CO_3) which then mixes with water. This leads to the hydration of the cementitious compounds, such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S). During this process, $CaCO_3$ acts as nucleation sites within the concrete, promoting the formation of the calcium-silicate-hydrate (C-S-H) gel, which is the primary binder in concrete.

The presence of $CaCO_3$ in the concrete matrix can contribute to densification and strengthening of the material. It fills the void spaces and enhances the interlocking of cement particles, resulting in improved mechanical properties. Furthermore, the formation of $CaCO_3$ can reduce the porosity of the concrete, making it more resistant to the ingress of harmful substances and enhancing its durability.

It is worth noting that while carbonation can have positive effects under controlled conditions, it is still important to consider the potential risks associated with reduced alkalinity and the corrosion of reinforcement in real-world applications. Proper design and construction practices, including adequate concrete cover and the use of corrosion-resistant materials, should be implemented to mitigate these risks and ensure the long-term performance of concrete structures.

IV. Conclusion

Based on the research and data reviewed, it is clear that curing with liquified CO_2 offers several advantages over conventional forms of curing in terms of improving the properties of concrete. The key points highlighted in this review can be summarized as follows:

1. Carbonation of the infused CO_2 results in its mineralization, converting it into a stone-like substance that remains embedded in the concrete even after pulverization.

2. Early application of carbonation leads to improved mechanical properties, such as higher compressive strength, due to the reduction in porosity.

3. The duration of curing has an impact on carbon uptake, with longer durations showing better results. Curing concrete for around 6 hours at a pressure of 30-60 psi (0.2 MPa) is considered optimal.

4. Carbonation of adequately moistened C_2S and C_3S components occurs rapidly, within minutes to hours. Extensive carbonation of the calcium-silicate-hydrate (C-S-H) gel leads to the decalcification effect, transforming it into $CaCO_3$ and SiO_2.

5. Continuous exposure to a moist or humid environment after carbonation allows for subsequent hydration of any residual unreacted portions.

6. While the pH at the surface of the concrete initially declines during carbonation, it gets restored upon further hydration, as the core of the concrete remains alkaline.

7. Carbonation also contributes to greener and more durable concrete, improving resistance to chloride penetration, freeze-thaw cycles, and

salt-scaling.

8. Carbonation modifies the properties of mortar adhered to recycled coarse aggregate, increasing its apparent density, reducing water absorption, and improving the compressive strength. A 2-hour duration of carbonation is considered optimal for achieving better results.

Overall, the adoption of liquified CO2 curing technology in the construction sector holds promise for enhancing the properties and durability of concrete. It offers advantages such as increased mechanical strength, improved resistance to environmental factors, and the potential for more sustainable and greener concrete production.

References

1. Rostami, V., Shao, Y.,Boyd,A.,&He,Z.(2012).Microstructure ofcement paste subjecttoearlycarbonationcuring.CementAndConcreteResearch,42(1),186-193.https://doi.org/10.1016/j.cemconres.2011.09.010
2. Xuan,D.,Zhan,B.,&Poon,C.(2016).Developmentofanewgenerationofeco-friendlyconcreteblocksbyacceleratedmineralcarbonation.JournalOfCleanerProduction,133,1235-1241.https://doi.org/10.1016/j.jclepro.2016.06.062
3. Jang, J., & Lee, H. (2016). Microstructural densification and CO2uptake promoted by the carbonation curing of belite-rich Portlandcement.CementAndConcreteResearch,82,50-57.https://doi.org/10.1016/j.cemconres.2016.01.001
4. Monkman,S.,MacDonald,M.,&Hooton,D.(2016). TheDurabilityofConcreteProducedUsingCO2asanAdmixture.
5. Liu, Q., Liu, J., & Qi, L. (2016). Effects of temperature and carbonation curing on the mechanical properties of steel slag-cement binding materials. Construction And Building Materials,124,999-1006.https://doi.org/10.1016/j.conbuildmat.2016.08.131
6. He, P., Shi, C., Tu, Z., Poon, C., & Zhang, J. (2016). Effect of further water curing on compressive strength and microstructure of CO2-cured concrete. Cement And Concrete Composites,72,80-88.https://doi.org/10.1016/j.cemconcomp.2016.05.026
7. Zhan, B., Xuan, D., Poon, C., & Shi, C. (2016). Effect of curing parameters on CO2 curing of concrete blocks containing recycled aggregates .Cement And Concrete Composites,71,122-130.https://doi.org/10.1016/j.cemconcomp.2016.05.002
8. Wang, T., Huang, H., Hu, X., Fang, M., Luo, Z., &Guo, R. (2017). Accelerated mineral carbonation curing of cement paste for CO 2 sequestration and enhanced properties of blended calcium silicate. Chemical Engineering Journal,323,320-329.https://doi.org/10.1016/j.cej.2017.03.157
9. Shi, C., Tu, Z., Guo, M., & Wang, D. (2017). Accelerated carbonation as a fast curing technology for concrete blocks. Sustainable And Nonconventional Construction Materials Using Inorganic Bonded Fiber Composites, 313-341. https://doi.org/10.1016/b978-0-08-102001-2.00015-2
10. Ahmad, S., Assaggaf, R., Maslehuddin, M., Al-Amoudi, O., Adekunle, S., & Ali, S. (2017). Effects of carbonation pressure andduration on strength evolution of concrete subjected to accelerated carbonation curing. Construction And Building Materials, 136,565-573.https://doi.org/10.1016/j.conbuildmat.2017.01.069
11. Xuan, D., Zhan, B., & Poon, C. (2018). A maturity approach to estimate compressive strength development of CO 2 -cured concrete blocks. Cement And Concrete Composites,85,153-160.https://doi.org/10.1016/j.cemconcomp.2017.10.005

12. Zhang, D., & Shao, Y. (2018). Surface scaling of CO_2-cured concrete exposed to freeze-thaw cycles. Journal Of CO_2 Utilization, 27,137-144.https://doi.org/10.1016/j.jcou.2018.07.012
13. Sharma, D., &Goyal, S. (2018). Accelerated carbonation curing of cement mortars containing cement kiln dust: An effective way of CO_2 sequestration and carbon footprint reduction. Journal Of Cleaner Production,192,844-854.https://doi.org/10.1016/j.jclepro.2018.05.027
14. Guo,R.,Chen,Q.,Huang,H.,Hu,X.,&Wang,T.(2019).Carbonationcuringofindustrialsolidwaste- basedaeratedconcretes.Greenhouse Gases:ScienceAndTechnology,9(2), 433-443.https://doi.org/10.1002/ghg.1862
15. Chen, T., &Gao, X. (2019). Effect of carbonation curing regime on strength and microstructure of Portland cement paste. Journal OfCO_2Utilization,34,74-86.https://doi.org/10.1016/j.jcou.2019.05.034
16. He, Z., Jia, Y., Wang, S., Mahoutian, M., & Shao, Y. (2019). Maximizing CO_2sequestration in cement-bonded fiberboards throughcarbonationcuring.ConstructionAndBuildingMaterials,213,51-60.https://doi.org/10.1016/j.conbuildmat.2019.04.042
17. Meng,Y.,Ling,T.,Mo,K.,&Tian,W.(2019).EnhancementofhightemperatureperformanceofcementblocksviaCO_2curing.
18. Science Of TheTotalEnvironment, 671, 827-837.https://doi.org/10.1016/j.scitotenv.2019.03.411
19. Sharma,D.,&Goyal,S.(2020).Effect of accelerated carbonation curing on near surface properties of concrete. European Journal Of Environmental And Civil Engineering,1-22.https://doi.org/10.1080/19648189.2019.1707714
20. Ahmad, S., Assaggaf, R., Adekunle, S., Al-Amoudi, O., Maslehuddin, M., & Ali, S. (2019). Influence of accelerated carbonationcuringonthepropertiesofself-compactingconcretemixturescontainingdifferent mineralfillers.EuropeanJournalOfEnvironmental And CivilEngineering,1-18.https://doi.org/10.1080/19648189.2019.1649197
21. Chen, T., &Gao, X. (2020). Use of Carbonation Curing to Improve Mechanical Strength and Durability of Pervious Concrete. ACSSustainableChemistry&Engineering, 8(9),3872-3884.https://doi.org/10.1021/acssuschemeng.9b07348
22. Qin,L.,&Gao,X.(2019).Recyclingofwasteautoclavedaeratedconcretepowderin Portlandcementbyacceleratedcarbonation.
23. WasteManagement,89,254-264.https://doi.org/10.1016/j.wasman.2019.04.018
24. Zhang, D., & Shao, Y. (2016). Early age carbonation curing for precast reinforced concretes. Construction And Building Materials,113,134-143.https://doi.org/10.1016/j.conbuildmat.2016.03.048
25. Zhang,D.,&Shao,Y.(2016).Effectofearlycarbonationcuringonchloridepenetrationandweatheringcarbonationinconcrete.
26. ConstructionAndBuildingMaterials,123,516-526.https://doi.org/10.1016/j.conbuildmat.2016.07.041
27. Zhang, D., Ghouleh, Z., & Shao, Y. (2017). Review on carbonation curing of cement-based materials. Journal Of CO_2Utilization,21,119-131.https://doi.org/10.1016/j.jcou.2017.07.003
28. Ghouleh, Z., Guthrie, R., & Shao, Y. (2017). Production of carbonate aggregates using steel slag and carbon dioxide for carbon-negativeconcrete. JournalOfCO_2Utilization,18,125-138.https://doi.org/10.1016/j.jcou.2017.01.009
29. Sharma,D.,&Goyal,S.(2020).Effectofacceleratedcarbonationcuringonnearsurfacepropertiesofconcrete.EuropeanJournalOf EnvironmentalAndCivilEngineering, 1-

22.https://doi.org/10.1080/19648189.2019.1707714

30. El-Hassan, H., & Shao, Y. (2014). Carbon Storage through Concrete Block Carbonation. Journal Of Clean Energy Technologies,287-291.https://doi.org/10.7763/jocet.2014.v2.141
31. Wang, L., Chen, S., Tsang, D., Poon, C., & Shih, K. (2016). Recycling contaminated wood into eco-friendly particleboard usinggreencementandcarbondioxidecuring.JournalOfCleanerProduction,137,861-870.https://doi.org/10.1016/j.jclepro.2016.07.180
32. Zhan,B.,Poon,C.,Liu,Q.,Kou,S.,&Shi,C.(2014).ExperimentalstudyonCO2curingforenhancementofrecycledaggregateproperties.ConstructionAndBuildingMaterials,67,3-7.https://doi.org/10.1016/j.conbuildmat.2013.09.008
33. Zhan,B.,Poon,C.,&Shi,C.(2016).Materials characteristicsaffecting CO2curingofconcreteblockscontainingrecycledaggregates.CementAnd ConcreteComposites,67,50-59.https://doi.org/10.1016/j.cemconcomp.2015.12.003
34. Pan,G.,Zhan,M.,Fu,M.,Wang,Y.,&Lu,X.(2017).EffectofCO2curingondemolitionrecycledfineaggregatesenhancedbycalciumhydroxide pre-soaking. Construction And Building Materials, 154, 810-818.
35. https://doi.org/10.1016/j.conbuildmat.2017.07.079
36. Xuan,D.,&Poon,C.(2019).Sequestrationofcarbondioxidebyrcasandenhancementofpropertiesofracbyacceleratedcarbonation.NewTrends InEco-EfficientAndRecycledConcrete,477-497.https://doi.org/10.1016/b978-0-08-102480-5.00016-6