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ENCAPSULATION OF LIQUEFIED CARBON DIOXIDE (CO_2) INTO CONCRETE

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ABSTRACT

The cement and concrete industries are major contributors to global carbon dioxide (CO_2) emissions, highlighting the urgent need for sustainable construction practices. This study investigates the encapsulation of liquefied CO_2 in concrete as a potential solution to reduce carbon emissions while enhancing the mechanical properties of concrete. Laboratory experiments were conducted using concrete samples with varying liquefied CO_2 dosages of 0.00%, 0.05%, 0.10%, and 0.15% by weight of cement. Compressive strength tests revealed that injecting 0.15% liquefied CO_2 yielded the highest strength, reaching 37.11 MPa at 14 days, surpassing the strength of the control samples. Tensile strength tests also indicated an improvement, with the highest recorded value of 3.834 MPa at the exact dosage of liquefied CO_2. However, water absorption tests showed minimal variations across samples, suggesting that liquefied CO_2 injection has a negligible impact on concrete permeability. Despite these improvements, challenges such as the non-uniform distribution of liquefied CO_2 and carbonation effects on surface layers were observed. The research highlights the potential of CO_2 sequestration in concrete as an environmentally friendly method to enhance the performance of concrete. Future studies should focus on refining injection techniques, evaluating long-term durability, and scaling up applications for industrial use. By optimizing the encapsulation of liquefied CO_2 in concrete, this approach contributes to sustainable construction while addressing the urgent need to reduce greenhouse gas emissions.

Keywords: *CO_2 sequestration, liquefied CO_2 injection, sustainable concrete, mechanical properties, compressive strength*

INTRODUCTION

Carbon dioxide (CO_2) emissions are a major contributor to climate change, with cement and concrete production accounting for 5–8% of global emissions. These emissions result from high-energy processes and the decarbonation of limestone. To mitigate this impact, injecting liquefied CO_2 into concrete presents a dual advantage: it traps the liquefied CO_2 within the material while enhancing its strength and durability. Studies have shown that CO_2-sequestered concrete achieves higher compressive strength in a shorter time.

However, the optimal dosage of liquefied CO_2 remains uncertain, necessitating further research to maximize benefits without compromising the quality of concrete.

Liquefied CO_2 injection into concrete is a promising approach for reducing emissions and enhancing strength, yet limited research exists on its optimal dosage. Determining the ideal amount is essential to ensure maximum stability, good workability, and effective CO_2 encapsulation. Industries, particularly those in the palm oil sector, seek sustainable solutions for CO_2 waste, but a lack of industrial-scale data hinders their adoption. This study aims to bridge these gaps by determining the optimal dosage of liquefied CO_2 for enhancing concrete properties and assessing its feasibility for commercialization.

The primary objective of this research is to investigate the differences in mechanical properties between injected CO_2 concrete and conventional concrete. Another purpose is to determine the optimal design mix for CO_2 concrete. The next objective is to assess the feasibility of liquefied CO_2 injection as a method for improving concrete properties.

This research involves laboratory experiments at UTP, focusing on mixing, injecting, and testing liquefied CO_2 in concrete at dosages of 0.00%, 0.05%, 0.10%, and 0.15% by mass of cement. The study examines compressive strength, tensile strength, water absorption, and density. It does not include CO_2 capture or liquefaction, as commercially sourced liquefied CO_2 is used. The results will help determine if CO_2 injection improves concrete performance.

LITERATURE REVIEW

Table 1 Production of CO_2 and current method to reduce CO_2 emission

Production of CO_2 and Current Method to Reduce CO_2 Emission		
Title	Source	Findings
Combining hydration and carbonation of cement using super-saturated aqueous CO_2 solution	[1]	The cement industry contributes to 90% of the emissions related to concrete, with roughly half of these emissions resulting from the decarbonation of limestone during cement production.
Global CO_2 Emission from CO_2 production	[2]	Studies have found that approximately 5 to 8% of global CO_2 emissions are attributed to the cement industry's contribution.
Properties and durability of concrete produced using CO_2 as an accelerating admixtures	[3]	Around 5% of the world's yearly CO_2 emissions come from making cement.
Carbon Dioxide Sequestered Concrete	[4]	Recycling CO_2 and permanently trapping it in concrete helps reduce greenhouse gas emissions, particularly from the construction industry.
CO_2 Capture from Cement Manufacture and Reuse in Concrete	[5]	By using less cement, CO_2 emissions are reduced by 1,260 grams per percent of cement used.

Table 2 Compressive strength of concrete

Compressive Strength of Concrete		
Title	Source	Findings
Carbon Dioxide Sequestered Concrete	[4]	CO_2-sequestered concrete with accelerated carbonation gained strength more rapidly than regular concrete over a 7-day period. By day 28, both methods showed higher compressive strength than normal concrete.
On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete	[3]	The baseline concrete had an average strength of 36.5 MPa at 7 days and 44.9 MPa at 28 days. Concrete with CO_2 averaged 39.0 MPa at 7 days (7% higher) and 48.4 MPa at 28 days (8% higher).
Properties and durability of concrete produced using CO_2 as an accelerating admixtures	[3]	The compressive strength tests on CO_2-injected concrete showed that the lowest dose (0.05% per weight of cement) gave the best results, with a 14% strength increase after 1 day, 10% after 3 days, 1% after 7 days and 3% after 28 days.
Sustainable Ready Mix Concrete Production Using Waste CO_2: A Case Study	[6]	The historical data shows an average compressive strength of 16.4 MPa at 7 days and 27.1 MPa at 28 days. In the CO_2- injected batches with reduced binder, the strength averaged 15.5 MPa at 7 days and 27.9 MPa at 28 days. This means the CO_2 helped maintain the strength at similar levels.

Table 3 Amount of injected CO_2 into concrete

Amount of Injected CO_2 into Concrete		
Title	Source	Findings
On carbon dioxide utilization as a means to improve the sustainability of ready-mixed concrete	[7]	The dose of CO_2 varied slightly from batch to batch, but can be generalized as 0 .15% by weight of cement.
Properties and durability of concrete produced using CO_2 as an accelerating admixture	[7]	From the table, it is evident that three different dosages of CO_2 were used: 0.05%, 0.15%, and 0.30% by weight of the cement.
Sustainable Ready Mix Concrete Production Using Waste CO_2: A Case Study	[6]	The CO_2 utilization approach used a dosage rate of 0.11% CO_2 by weight of cement.

METHODOLOGY

Research Methodology

This study investigates the mechanical properties of concrete injected with liquefied CO_2 at varying dosages of 0.00% (control), 0.05%, 0.10%, and 0.15% by mass of cement. Concrete mixes were batched by weight, with no admixtures used, to ensure an accurate assessment of the effects of liquefied CO_2. Compressive strength tests were conducted at 7 and 28 days, while tensile strength, water absorption, and density tests were performed at 28 days.

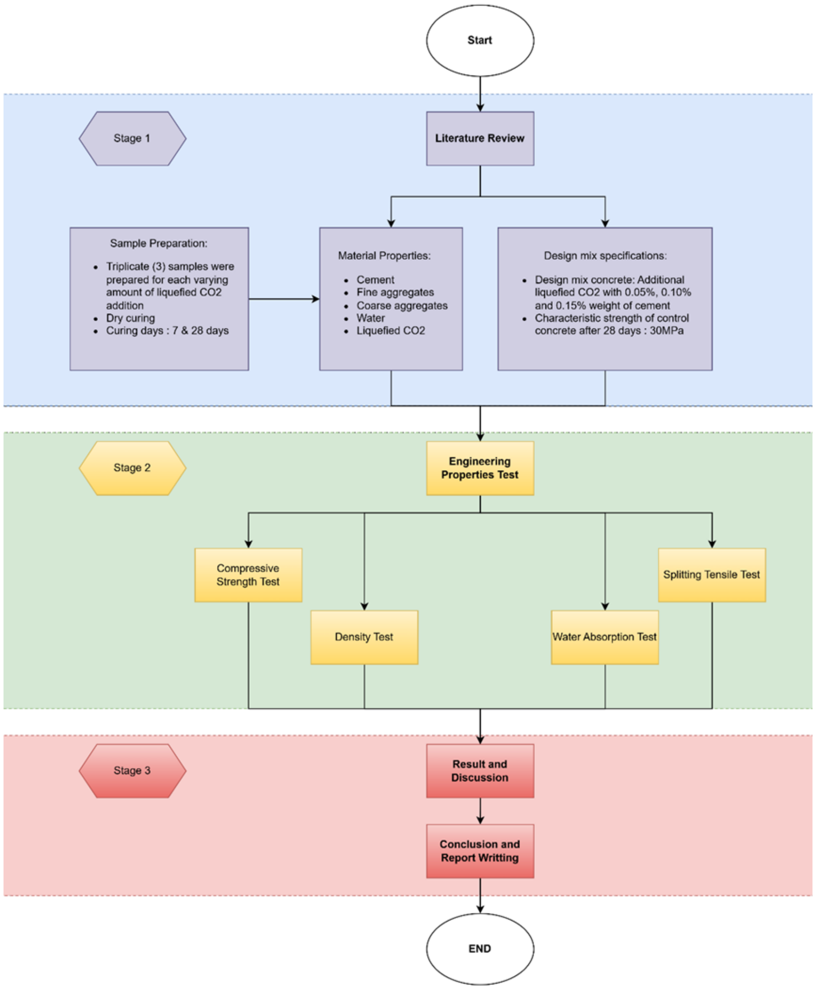

Figure 1 Research methodology flowchart

The materials used were fine aggregates, coarse aggregates, water, and OPC 42.5 grade cement, with liquefied CO_2 as the manipulated variable. The target compressive strength for the control concrete was 30 MPa at 7 and 28 days. A controlled water-to-cement ratio ensured workability and consistency in strength across samples.

Sample Preparation

Batching was conducted manually, maintaining accurate material proportions to ensure uniformity. The mixing process involved adding dry materials first, followed by water and liquefied CO_2 injection at designated dosages. The concrete was mixed until it reached a uniform consistency and then tested for workability using a slump test.

Samples were molded in 100 mm steel cubes and 100 mm × 200 mm cylindrical molds, with three samples per dosage, totaling 48 samples. These include 12 cube samples for compressive strength at 7 and 28 days, 12 cube samples for the water absorption test, and 12 cylindrical samples for the splitting tensile strength test, totaling 36 samples. For the density test, the same cylindrical samples were tested before the splitting tensile strength test. The curing process employed a dry curing method to prevent liquefied CO_2 from leaking into the water, ensuring accuracy. 7-day cured samples were used for compressive strength tests, while 28-day cured samples were used for tensile strength, density, and water absorption tests. Samples were stored in the curing room at Block 14, Universiti Teknologi PETRONAS (UTP).

Experimental Investigation

Compressive Strength Test (Test on Hardened Concrete)

The compressive strength test measures the maximum axial load that a concrete sample can withstand before failure, as specified in ASTM C39. Hardened concrete cubes (100 mm × 100 mm) are tested after 7 and 28 days of dry curing. Each sample is subjected to a uniform load in a compression testing machine until failure, and the strength is calculated.

Water Absorption Test

The water absorption test, as specified in ASTM C1585, assesses concrete porosity and durability. Hardened cube samples (100 mm × 100 mm) that have been cured for 28 days are submerged in water for 24 hours. Weight measurements before and after immersion determine the water absorption rate.

Splitting Tensile Test

According to ASTM C496, this test evaluates the tensile strength of concrete using 28-day-cured cylindrical samples (100 mm × 200 mm). A split-tensile machine applies a uniform load until failure, and the strength is calculated.

Density Test

Following standard procedures, this test measures the density of concrete to assess its compactness. Sample weight and volume are recorded to calculate density, comparing control and liquefied CO_2 concrete samples.

Modifications to Experimental Procedure

Due to equipment limitations, the liquefied CO_2 injection method was modified from mixing-stage injection to injection after concrete was poured into molds. The original plan required a closed mixer to stabilize liquefied CO_2; however, due to unavailability and high costs, CO_2 was instead injected into the molded concrete.

This modification prevented workability assessment during mixing, so slump tests were conducted to ensure consistency (50–60 mm slump values). The testing period was also reduced from 28 to 14 days due to time constraints. To ensure safety, all CO_2-related equipment (cylinders, injectors, and pressure regulators) was inspected by university safety staff. Despite these modifications, the methodology remained scientifically valid, and future studies could revisit mixing-stage CO_2 injection if suitable equipment becomes available.

RESULT AND DISCUSSION

Compressive Strength Performance of Concrete with Varying Liquefied CO_2 Injection for 7 and 14 days

The compressive strength test at 7 and 14 days shows that 0.15% liquefied CO_2 achieved the highest strength (33.99 MPa and 37.11 MPa), while 0.05% CO_2 had the lowest (28.47 MPa and 33.55 MPa). Control samples (0.00% CO_2) recorded 32.23 MPa and 34.93 MPa, slightly lower than 0.10% CO_2 but higher than 0.05% CO_2. This suggests that optimal CO_2 dosage enhances strength, while insufficient amounts may weaken it due to incomplete carbonation reactions. The trend indicates a proportional increase in compressive strength as CO_2 dosage rises from 0.00% to 0.15%. This relationship demonstrates that higher CO_2 levels accelerate the formation of calcium carbonate ($CaCO_3$) through carbonation of calcium hydroxide ($Ca(OH)_2$) within the cement matrix. The newly formed $CaCO_3$ fills micro-pores and refines the microstructure, resulting in a denser and stronger composite. However, excessive CO_2 can disrupt the hydration reaction by prematurely consuming $Ca(OH)_2$, which is crucial for forming calcium silicate hydrate (C–S–H), the primary phase responsible for providing strength. Thus, the improved strength at 0.15% reflects a balance between carbonation and hydration reactions.

Several factors influenced the results. Hydration disruption at 0.05% CO_2 may have weakened early strength, while higher dosages (0.10%–0.15%) improved strength through calcium carbonate formation, refining the microstructure. Compaction and vibration inconsistencies may have introduced air voids or segregation, which can affect the strength. Additionally, variations in CO_2 injection and testing may have caused minor discrepancies.

Overall, these findings confirm that controlled CO_2 injection enhances concrete strength by promoting the formation of secondary C–S–H gel and reducing pore connectivity. This mechanism aligns with other studies, suggesting that moderate carbonation densifies the matrix without compromising cement hydration.

Water Absorption Performance of Concrete with Different Amount of Liquefied CO_2 Injections

The water absorption test at 14 days showed minimal variation across all samples, with absorption values ranging from 0.04 kg to 0.0467 kg. The lowest absorption was recorded for 0.00%, 0.05%, and 0.10% CO_2 samples at 0.04 kg, while the highest was in 0.15% CO_2 samples at 0.0467 kg.

The marginal increase at higher CO_2 dosages suggests that carbonation occurs primarily at the surface, resulting in denser outer layers but limited penetration depth. This surface densification slightly alters porosity without significantly influencing bulk permeability. The formation of $CaCO_3$ crystals within internal pores reduces water ingress, demonstrating that CO_2 encapsulation contributes positively to the durability of the concrete. Therefore, the results indicate that CO_2-treated concrete retains its impermeability despite the occurrence of carbonation reactions. The insignificant rise in absorption at 0.15% may be attributed to the formation of microcracks due to localized carbonation stress, which does not compromise the overall performance.

This slight increase suggests that higher CO_2 dosage may influence porosity due to excessive carbonation reactions. The limited depth of CO_2 penetration may have confined its effect to the surface, leading to similar absorption values across all samples. Additionally, the optimized water-to-cement ratio ensured controlled porosity, thereby reducing the impact of CO_2 on permeability. Proper compaction and uniform curing conditions also contributed to the consistency in absorption rates.

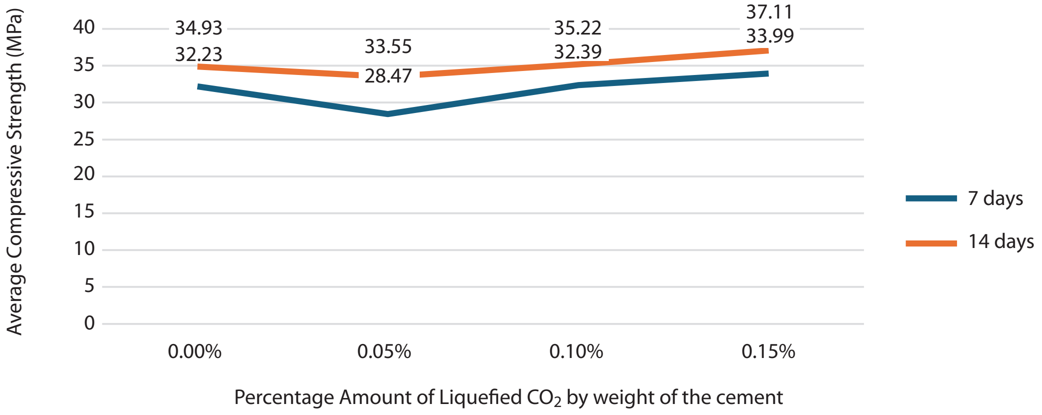

Figure 2 Compressive strength test graph data

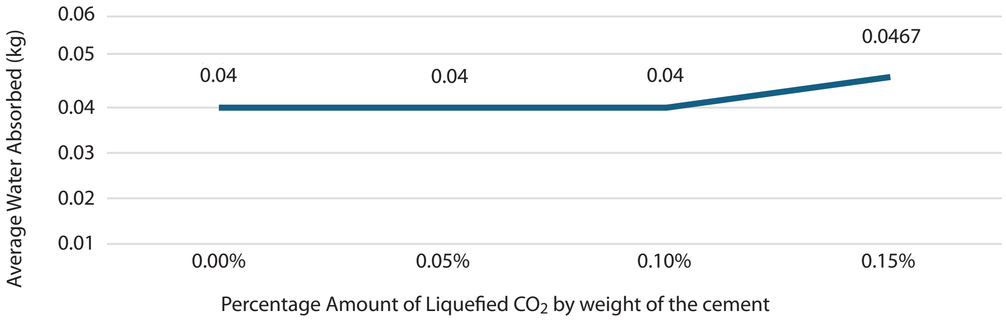

Figure 3 Water absorption test graph data

Overall, CO_2 injection had minimal impact on water absorption, with only a slight increase at 0.15% CO_2. This indicates that CO_2 encapsulation enhances strength without compromising durability, making it a practical approach for improving concrete.

Influence of Liquefied CO_2 Injection on the Splitting Tensile Strength of Concrete

The splitting tensile test was conducted after 14 days of dry curing to evaluate the concrete's ability to resist tensile forces. The control samples (0.00% CO_2) recorded an average tensile strength of 3.334 MPa, while the highest strength was observed in 0.15% CO_2 samples at 3.834 MPa. The 0.05% and 0.10% CO_2 samples recorded 3.263 MPa and 3.668 MPa, respectively. The results indicate a drop at 0.05% CO_2, followed by an increase at 0.10% and 0.15% CO_2, suggesting a moderate positive effect of CO_2 injection on tensile strength.

The improvement trend follows the same pattern as compressive strength, confirming the beneficial role of $CaCO_3$ formation in enhancing bonding between cement paste and aggregates. The carbonation reaction forms fine crystalline products that fill internal voids, improving tensile strength and crack resistance. The strength drop at 0.05% CO_2 can be explained by insufficient carbonation, where CO_2 fails to react fully with the available Cafully $(OH)_2$, producing weak, porous zones instead of dense interfaces. Hence, the tensile behavior supports the hypothesis that optimal CO_2 levels encourage balanced microstructural refinement through the coexistence of partial carbonation and hydration.

The carbonation reaction between CO_2 and calcium compounds likely contributed to the formation of additional binding phases, thereby improving concrete strength. However, the increase was relatively small, indicating a limited overall impact. The decrease at 0.05% CO_2 may be due to incomplete carbonation reactions or non-uniform CO_2 distribution since the injection occurred after pouring, affecting only the outer layers rather than the entire concrete matrix.

Additionally, experimental inconsistencies, such as variations in CO_2 injection rates, mold handling, or slight timing differences, may have contributed to the variation in results. This highlights the need for precise control over the CO_2 injection process to ensure reliable outcomes.

Effect of Liquefied CO_2 Dosage on the Density of Concrete: A Comparative Study

The density test at 14 days showed a slight increase in density with higher CO_2 dosages. The control samples recorded a density of 2231.42 kg/m^3, while the highest density was observed in the 0.15% CO_2 samples at 2325.05 kg/m^3. The 0.05% and 0.10% CO_2 samples had densities of 2309.98 kg/m^3 and 2319.11 kg/m^3, respectively. The trend suggests that CO_2 injection enhances density, likely due to carbonation reactions that form calcium carbonate, thereby reducing voids and increasing compactness. However, the differences remain relatively small, suggesting that CO_2 injection does not drastically alter overall density.

This trend correlates with the microstructural compaction caused by carbonation, where CO_2 reacts to form solid $CaCO_3$, which occupies void spaces and reduces total porosity. Higher density is thus a reflection of reduced pore volume and improved particle packing efficiency. The minor variation across samples suggests that although the carbonation effect is present, it is not excessive enough to cause brittleness or surface

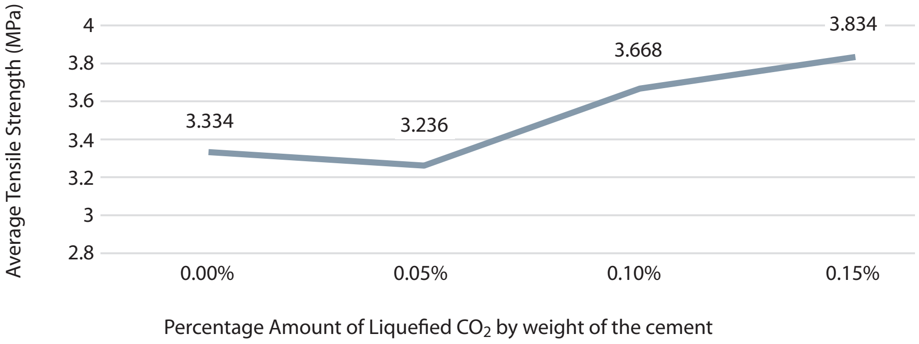

Figure 4 Splitting tensile strength test graph data

cracking. Therefore, the observed density increase confirms that liquefied CO_2 contributes to a denser, more compact concrete structure, supporting the strength findings.

Several factors may have influenced the results. Inadequate mixing time and substandard mixing equipment may have contributed to uneven aggregate distribution, which in turn affects density. Compaction inconsistencies, such as over-vibration causing segregation or under-vibration leaving air voids, also contributed to variations. Additionally, inefficient CO_2 absorption may have resulted in an uneven distribution within the concrete matrix, which could impact density measurements.

Overall, the findings confirm that CO_2 injection slightly increases concrete density, aligning with existing research. However, further studies are needed to assess its long-term impact on durability and mechanical performance.

Determination of Optimum CO_2 Concrete Mix Design

The optimum liquefied CO_2 dosage was determined by evaluating compressive strength, tensile strength, density, and water absorption at 0%, 0.05%, 0.10%, and 0.15% CO_2 by weight of cement. The results showed that 0.15% CO_2 achieved the highest compressive and tensile strength, along with increased density, without significantly affecting water absorption.

This dosage achieves a synergistic balance between the hydration of cement and the carbonation of calcium hydroxide. The resulting concrete exhibits enhanced compressive and tensile strengths due to the formation of finely distributed $CaCO_3$ within pores. The negligible effect on water absorption indicates that this dosage does not compromise the pore structure or durability, making it suitable for practical application in sustainable construction.

Compressive and tensile strength tests confirmed that 0.15% CO_2 concrete outperformed other mixes, while

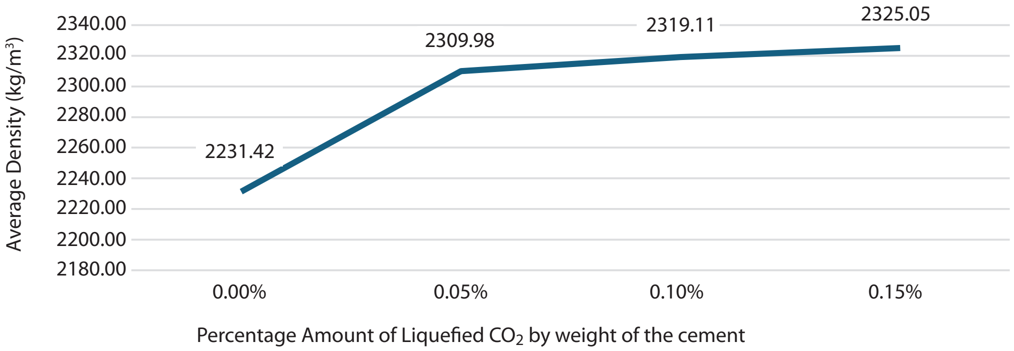

Figure 5 Density test graph data

the density test indicated improved microstructural compactness at higher CO_2 dosages. The water absorption test revealed minimal variation, suggesting that CO_2 injection had no significant impact on permeability. Based on these findings, 0.15% liquefied CO_2 was identified as the optimal dosage for enhancing strength and durability.

CONCLUSION AND RECOMMENDATION

Conclusion

This study demonstrated the potential of liquefied CO_2 injection in concrete as a sustainable solution for reducing CO_2 emissions while enhancing mechanical properties. The findings confirmed that compressive and tensile strengths improved, particularly at dosages of 0.10% and 0.15% CO_2, with 0.15% yielding the highest strength. Density increased with higher CO_2 dosages, indicating better microstructural compactness, while water absorption remained largely unaffected, suggesting minimal impact on permeability.

The optimal design mix was identified as 0.15% liquefied CO_2, achieving maximum strength and density without compromising durability. These results highlight the feasibility of CO_2 encapsulation in concrete as an innovative method for industrial applications, offering both environmental benefits and high-performance materials.

Recommendation for Future Works

Extending Testing Duration

Testing should be extended to 28 days or beyond (50–60 days) to assess long-term strength development and durability.

Microstructural Analysis

Future studies should incorporate microscopic analysis to understand the chemical interactions between liquefied CO_2 and cementitious compounds, so that the reaction of CO_2 with concrete can be proven in terms of microstructure.

Optimization of Liquefied CO_2 Injection Method

Research should explore the use of liquefied CO_2 injection at various stages, such as during mixing, by utilizing a closed mixer to ensure uniform distribution and maximize reaction efficiency.

Durability and Environmental Performance Assessment

Further testing under freeze-thaw cycles, chemical exposure, and carbonation depth analysis is necessary to validate the long-term durability and environmental resilience of the material.

Large-Scale Application and Structural Assessment

Future research should evaluate the use of liquefied CO_2 concrete in structural elements, such as beams and columns, to assess its practicality in real-world construction projects.

Economic and Sustainability Assessment

A cost-benefit and life cycle analysis should be conducted to determine the economic feasibility and environmental impact of using liquefied CO_2 in concrete for large-scale applications.

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