Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Experimental Assessment of CO_2 Curing for Sustainable Fly Ash– Blended Concrete

Shubham Raghuvanshi
RKDF, University Bhopal
Arun Kumar Patel
RKDF, University Bhopal
Vishnu Prasad Dangi
vishnudangi1@gmail.com

RKDF, University Bhopal

Research Article

Keywords: CO_2 curing, Carbonation curing, Coal fly ash, Sustainable concrete, Accelerated carbonation, Compressive strength, CO_2 sequestration.

Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11592795/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Experimental Assessment of CO_2 Curing for Sustainable Fly Ash–Blended Concrete

Shubham Raghuvanshi,
Department of civil Engineering, RKDF, University Bhopal, India
email address- Shubhamrraghuvanshi@gmail.com ORCID- 0009-0004-9374-3969

Arun Kumar Patel
Department of civil Engineering, RKDF, University Bhopal, India
email - arunpatel123@gmail.com address or ORCID- 0000-0002-2646-9806

Vishnu Prasad Dangi (Corresponding author)
Department of civil Engineering, RKDF, University Bhopal, India
email – vishnudangi1@gmail.com ORCID- 0009-0001-6758-6507

Abstract

This study investigates the effectiveness of carbon dioxide (CO_2) curing as an alternative to conventional water curing for cement mortar incorporating coal fly ash as a partial replacement for Ordinary Portland Cement (OPC). Mortar cubes were prepared with fly ash replacement levels ranging from 0% to 25% and subjected to accelerated CO_2 curing for 6, 12, and 24 h, while corresponding specimens underwent conventional water curing for periods of up to 28 days. The performance of the specimens was evaluated in terms of compressive strength, carbonation depth, and durability-related characteristics. The results indicate that CO_2 curing promotes rapid early-age strength development through accelerated carbonation reactions and associated microstructural densification. Specimens exposed to 24 h of CO_2 curing attained compressive strengths comparable to those achieved after several days of conventional water curing. Among the investigated mixtures, approximately 5% fly ash replacement provided the most favorable strength performance under both curing regimes. At higher replacement levels (≥15%), compressive strength decreased, primarily due to the reduced proportion of cementitious clinker phases; however, CO_2 curing partially compensated for this strength reduction. Phenolphthalein analysis confirmed substantial carbonation penetration into the specimens, demonstrating the effective interaction of CO_2 with the cementitious matrix. Overall, the findings demonstrate that combining accelerated CO_2 curing with partial cement replacement using coal fly ash can provide a promising approach for developing more sustainable, low-carbon cementitious materials while improving early-age strength performance.

Keywords

CO_2 curing; Carbonation curing; Coal fly ash; Sustainable concrete; Accelerated carbonation; Compressive strength; CO_2 sequestration.

1. Introduction

The global construction industry faces growing pressure to mitigate its environmental footprint, largely driven by the substantial carbon emissions associated with cement manufacturing. The cement sector contributes approximately 9–10% of global CO_2

emissions, mainly due to limestone calcination and fossil fuel combustion during clinker production. [1]. India annual Produce, 2500 million tons of CO_2 emissions, approximately 50-60 Percentage originates from coal-based thermal power plants with a total installed capacity of more than 200 GW. [2]. India has formalized its commitment to reducing carbon emissions through the National Action Plan on Climate Change and its voluntary pledge at the Paris Agreement (COP-21) to lower carbon intensity by 30–35 Percentage by 2030. To meet the 2030 target of reduction of Co_2, India must reduce its emission intensity to 0.58 kg CO_2 per kWh, which will require a combination of strategies, including the adoption of Low Carbon Technologies (LCT).

As a result, actively exploring sustainable alternatives that can lower reducing the carbon footprint of concrete while maintaining or enhancing its performance. One promising approach is the partial replacement of cement coal fly ash This not only reduces cement consumption but also enhances the microstructural density and long-term durability of concrete [3- 4], [29-30] CO_2 curing, commonly termed carbonation curing has emerged as an innovative technique to improve the early-age performance of cement-based materials. Unlike conventional water curing, CO_2 curing involves exposing fresh or partially set concrete to a controlled concentration of carbon dioxide under specific humidity and temperature conditions. The process enhances early-age strength and durability while simultaneously enabling effective CO_2 sequestration, contributing to a more sustainable and circular construction process.. this study aims to analyse and compare the effects of CO_2 curing and conventional water curing on the mechanical, microstructural, and durability characteristics of concrete containing partial cement replacement with coal fly ash. FA has been applied in waste water treatment to remove contaminants and shows significant potential in construction, especially in cement and concrete production, where nanosized FA improves durability and reduces pore size. [5-7]. The technology is based on the concept of *CO_2 mineralization*, which involves the conversion of gaseous CO_2 into solid mineral carbonates within CO_2-cured concrete products. The mechanisms of carbonation reactions between cement hydration products and CO_2 are presented in the following equations.

Carbonation of calcium hydroxide

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad \text{..... (i)}$$

Carbonation of calcium silicate hydrates (C–S–H)

$$xCaO \cdot ySiO_2 \cdot zH_2O + xCO_2 \rightarrow xCaCO_3 + y(SiO_2 \cdot zH_2O) + (z - yt)H_2O \text{ .....(ii)}$$

"hydrated tricalcium aluminate" is fine, but it's usually written as $C_3A \cdot xH_2O$ or "ettringite/monosulfate formation."

Dicalcium silicate (C_2S) hydration

$$2(2CaO \cdot SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \ (+500\ kJ/kg) \text{ .....(iii)}$$

Tricalcium silicate (C_3S) hydration

$$2C_3S + 6H_2O \rightarrow 3C_3S_2 \cdot 6H_2O + 3Ca(OH)_2 \ (+500\ kJ/kg) \quad \text{..... (iv)}$$

Tricalcium silicate (C_3S) + calcium silicate hydrate (C–S–H) gel + crystalline calcium hydroxide ($Ca(OH)_2$)

During cement setting and hardening, exothermic hydration and hydrolysis reactions of the cementitious phases release heat.

The increase in molar volume resulting from the carbonation of cement hydrates leads to a reduction in porosity. This chemical reaction is robust and enhances the strength of fresh CO_2-cured concrete, producing components that meet or exceed industry-standard performance metrics. and this enhance the mechanical characteristic of cement composites [8-9].Carbon Capture Plant (CCP) – The CO_2 Concrete technology converts carbon dioxide emissions into CO_2-cured concrete products, which can replace traditional concrete with a significantly lower CO_2 footprint. This technology is based on the concept of *CO_2 mineralization*, in which gaseous CO_2 is transformed into solid mineral carbonates within the concrete matrix.

The primary focus of this research is on the environment, construction, and building technology aimed at enhancing the natural world as well as building materials. A technical specification of cement mortar incorporating the use of coal fly ash as a partial cement replacement has been developed to comply with ASTM specifications. This aims to contribute to the industry's efforts in environmental preservation, encourage the government to address waste disposal in landfills, and promote sustainable practices. Additionally, the study seeks to provide new insights to contractors and developers on improving construction methods and services through the utilization of recycled coal fly ash, while maintaining optimal product performance and supporting recycling objectives. In a conventional cement mortar, tests were conducted in the laboratory, where precise and comprehensive data were collected. Some of the key findings from the study are summarized as follows:

(a) The incorporation of coal fly ash as a partial substitute for cement is feasible in producing cement mortar cubes.

(b) The key indicators of coal fly ash quality as a replacement material in cement mortar cubes include particle size, shape, and texture; resistance to crushing; absorption and surface moisture; grading; behaviour under heating and cooling; and its lightweight characteristics.

(c) Coal fly ash is classified as a miscellaneous construction material suitable for various non-structural applications.

(d) The cement mortar cube is considered non–load-bearing, as its 28-day compressive strength shows improvement compared with the conventional cement mortar mix, even with the partial substitution of cement.

Combining coal fly ash with CO_2 concrete technology can yield the following advantages:

- **I.** Direct utilization of CO_2 from carbon-capture systems (e.g., amine strippers) can be used for curing the cement mortar cubes, which increases the compressive strength compared to conventional mortar mixes.
- **II.** The CO_2 curing of mortar cubes is carried out at ambient pressure and temperature, which significantly lowers external energy requirements.
- **III.** The material formulation requires reduced or even no Ordinary Portland Cement (OPC) while still achieving or exceeding industry standards for mechanical performance.

1.1 **Objectives: -** This study aims to achieve the following objectives:

i. To investigate the use of coal fly ash as a sustainable partial replacement for cement in concrete and to evaluate the effects of CO_2 curing on its mechanical properties and compressive strength.
ii. To compare the performance of CO_2-cured and conventionally cured ash-blended concrete in terms of strength development, microstructural characteristics, and durability.

2. Literature Review

Previous research has demonstrated the effectiveness of mineral carbonation for CO_2 sequestration and strength enhancement in cementitious materials. Wie et al. [10] reported improved early-age strength and carbon storage capacity when carbonated CFBC ash was used as a partial cement replacement. Miao et al. [11] investigated aqueous mineral carbonation of municipal solid waste incineration fly ash, achieving carbonation efficiencies exceeding 78% under optimized conditions. Heejung Jun et al. [12]showed that accelerated CO_2 curing significantly improved the mechanical performance of FBC ash–blended cementitious composites, particularly in CaO-rich systems, due to extensive $CaCO_3$ formation. Other studies have explored the use of agro-waste ashes and recycled materials in concrete, demonstrating their potential for sustainable construction when used within optimal replacement limits. Jia et al. [13] reviewed CO_2 carbonation solidification technologies for industrial solid wastes, with a focus on coal fly ash. The study summarizes early- and later-stage carbonation mechanisms, including CO_2 diffusion, dissolution, and $CaCO_3$ formation, and highlights the role of early-age carbonation in microstructure densification, strength development, and long-term stability. The authors also discuss CO_2 sequestration potential and practical challenges of integrating carbonation curing with industrial CO_2 capture. However, they point out that comparative studies between CO_2 curing and conventional

curing, particularly at short curing durations, remain limited, underscoring the need for further experimental investigation. Franco-Quiñonez et al. [14] Studies have investigated sustainable concrete using rice husk ash, PET, and tire rubber as partial substitutes for fine aggregates. The results show improved sustainability and resource efficiency, maintaining adequate mechanical and durability performance at optimal replacement levels, though higher substitutions can reduce strength. Jeong et al. [15] Studies have investigated integrated carbon capture, utilization, and storage (CCUS) through CO_2 mineralization, employing fly ash, bottom ash, and exhaust gases from circulating fluidized bed combustion. The study highlights effective CO_2 sequestration and solid waste valorisation, demonstrating potential for industrial-scale emission reduction.

Tantri et al. [16] has investigated self-compacting concrete incorporating calcined and uncalcined cashew nut-shell ash in conjunction with recycled concrete aggregates. Using the Bailey grading technique, the study shows sustainable utilization of agro-industrial and construction waste while maintaining workability and mechanical performance. Dixit et al. [17] The feasibility of CO_2 sequestration in ultra-high-performance concrete has been examined via pressurized CO_2 curing. Results indicate enhanced early-age strength and densified microstructure, demonstrating the dual benefits of carbon sequestration and improved material properties. Liu et al. [18] demonstrated that flue gas carbonation curing significantly improves CO_2 uptake and enhances the compressive strength of cement-based materials, highlighting the dual benefits of carbon sequestration and early-age mechanical performance for sustainable construction applications [19] Ting et al. assessed the potential for CO_2 sequestration in Malaysia's cement industry, evaluating strategies for Carbon capture, utilization, and storage implemented at the industrial scale. The study highlights opportunities for integrating CO_2-mineralization technologies and sustainable practices to reduce emissions while maintaining cement production efficiency, emphasizing the importance of policy support and technological adoption for large-scale decarbonization. Qin et al. [20] provide a comprehensive overview of industrial decarbonization, covering materials, methods, and technological developments. The book discusses CO_2 capture, utilization, and storage strategies, including cement and concrete applications, highlighting innovations in sustainable materials and processes. It emphasizes integrating decarbonization techniques to reduce industrial emissions while maintaining productivity and efficiency. Although CO_2 curing has been widely studied in concrete, research specifically focused on cement mortar remains limited, creating several important research gaps. Most existing studies on CO_2 curing of mortar primarily address early-age strength enhancement, while the long-term mechanical performance and durability of CO_2-cured mortar are not well established. The influence of CO_2 curing on pore structure refinement, permeability, and microcrack development in mortar, which differs significantly from concrete due to the absence of coarse aggregates, has not been thoroughly investigated. Additionally, the optimal CO_2 curing parameters (concentration, pressure, exposure time, and humidity) for mortar mixes of varying cement–sand ratios remain unclear. There is insufficient understanding of how CO_2 curing affects the carbonation depth, pH reduction, and potential implications for bond strength with reinforcement or masonry units when mortar is used in practical applications. Furthermore, limited studies explore the interaction of CO_2 curing with modified mortars, such as those containing supplementary cementitious materials or chemical admixtures. The lack of standardized testing procedures and comparative durability data for CO_2-cured mortar restricts its broader application, highlighting the need for systematic and long-term experimental research in this area.

3. Materials Properties and Sample Preparation

The materials required for this study include OPC 43-grade cement, coal fly ash, fine and coarse aggregates, and water.

3.1 OPC 43-Grade Cement – Ordinary Portland Cement (OPC- 43 Grade) is one of the most commonly used types of cement in concrete construction. Chemical tests were carried out in accordance with IS: 4032-1985 [[21]while physical tests were performed as per IS: 4031 (Part 5)-1988 [22] The chemical and physical properties of OPC 43-Grade cement are summarized in Table 1 and Table 2, respectively.

Table 1 summarizes the chemical composition (%) of OPC 43-Grade cement and coal fly ash.

Chemical Components (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	$SiO_2+Al_2O_3+Fe_2O_3$
Coal Fly ash	47.22	19.33	3.57	2.27	0.57	73.21
Cement	26.23	4.55	5.32	56.23	1.18	34.68

Table 2 Presents the physical properties of OPC 43-Grade cement and coal fly ash

Physical Properties	Specific gravity	Fineness modulus	Consistency
Coal Fly ash	1.78	9.33%	33.57
Cement	3.14	5.54%	39.32

Coal Fly Ash (CFA) – Coal fly ash (CFA) is a fine, powdery material produced during the combustion of coal in power plants. It is carried out of the combustion chamber with flue gases and subsequently captured by pollution-control equipment. CFA is the principal industrial byproduct generated from the combustion of solid fuels. In this study, coal fly ash obtained from the carbon capture plant at RKDF University, Bhopal, was used. The chemical and physical properties of coal fly ash and OPC 43-Grade cement are summarized in Table 1 and Table 2, respectively.

Fine aggregate (FA) - Primarily natural river sand, consists of clean, well-graded particles that pass through a 4.75 mm sieve.

Table 3 Summarizes the physical properties of fine aggregate (FA).

Physical Properties	Specific gravity	Bulk Density (kg/m^3)	Water Absorption (%)	Fineness Modulus
Fine Aggregate	2.78	9.33%	0.73	2.65

4. Methodology

The research methodology is divided into two sections, as shown in Fig. 1.

1. CO_2 captured from a Carban Capture plant and utilized for Concrete curing.

2. Sample preparation through mix design.



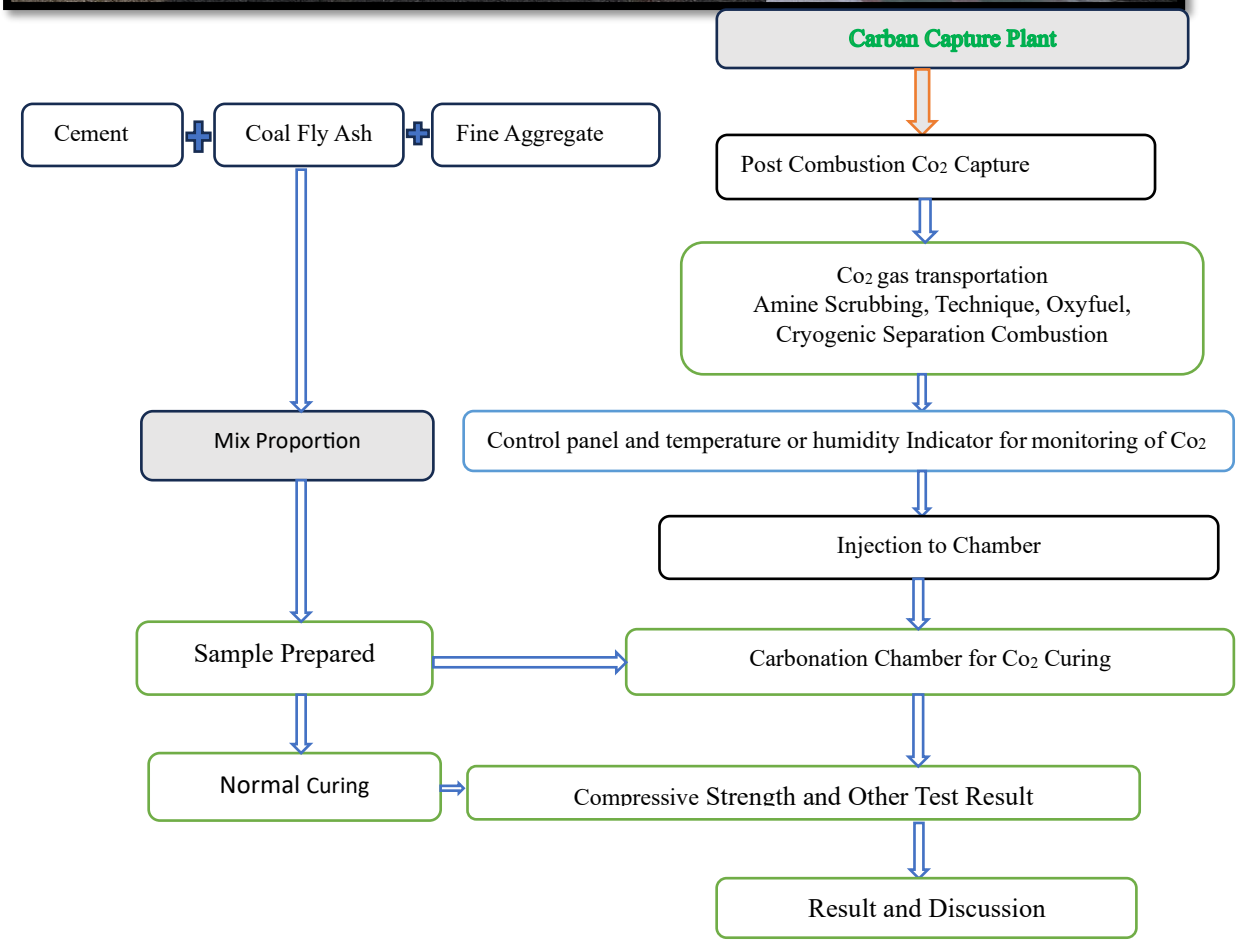

Figure 1 Carban Capture Plant at RKDF University Bhopal

Natural sand plays a critical role in enhancing the finish, strength, and durability of cement mortar and concrete. Its characteristics—including particle size distribution, shape, texture, and moisture content—significantly affect workability, bonding, and overall performance. Proper selection of natural sand helps reduce shrinkage, improve compaction, and contribute to the long-term stability and structural quality of the mix. The physical properties of the fine aggregate used in this study are summarized in Table 3.

4.1 CO_2 capture from cement plant emissions and its utilization for concrete curing.

The study applies Carbon Capture, Utilization, and Storage (CCUS) principles to capture carbon dioxide (CO_2) from cement plant flue gases.. Multiple capture technologies are considered to isolate CO_2 efficiently Figure 1: Carbon Capture Plant at RKDF University, Bhopal. which based on the following working principal:

i. **Amine Scrubbing Technique**: Flue gases are passed through amine-based solvents, such as monoethanolamide (MEA), which selectively absorb CO_2. The solvent is subsequently regenerated by thermal treatment to release high-purity CO_2 [23]
ii. **Oxyfuel Combustion**: Combustion is carried out using nearly pure oxygen instead of air, resulting in a flue gas stream rich in CO_2 and water Vapour which is generated Solar thermal process. After condensation, a concentrated CO_2 stream is obtained [24]
iii. **Cryogenic Separation and Advanced Methods**: Cryogenic cooling, membrane separation systems, and novel solvents are reviewed as alternative capture approaches for improved efficiency and reduced energy demand. [25-26]

The RKDF CCUS plant demonstrates CO_2 capture from flue gas and other industrial emissions using chemical or physical absorbents, with a regeneration unit to release and recycle CO_2. It serves as a facility for research and educational purposes, enabling the study of carbon capture processes and efficiency.

4.1.1 Carbonation Curing of Concrete

Concrete specimens are prepared using OPC and conventional aggregates. Fresh concrete samples are cast in Molds and demoulded after initial setting to facilitate early-age carbonation in carbonation chamber as shown in figure 3(a). The procedure involved in curing as follows

i. The demoulded The specimens were placed in a controlled carbonation curing chamber.
ii. High concentrations of CO_2, either purified or from cement plant flue gas, were introduced during the early curing stage, usually within 24 hours after casting.
iii. The exposure duration was optimized based on experimental observations, with curing periods of 6, 12, and 24 hours adopted in this study.



Figure 1 (a) Carbonation chamber for cement mould curing

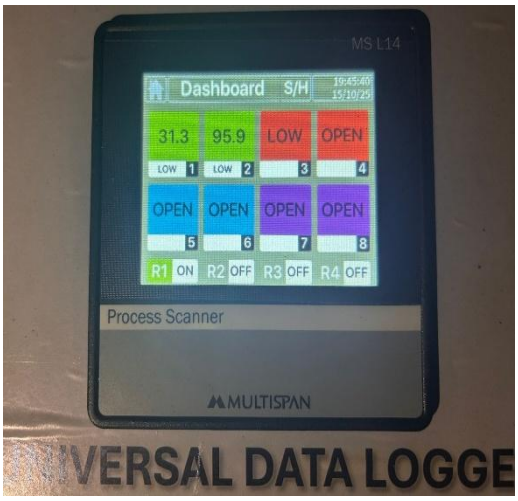

Figure 2 (b) Temperature and Humidity Indicator Device

Figure 2 (a) shows that the chamber is constructed from steel to prevent gas leakage and is equipped with internal metallic racks for uniformly placing mortar or concrete cubes. These racks ensure adequate circulation of CO_2 around all specimen surfaces. The chamber allows regulation of key ey curing parameters, such as CO_2 concentration, relative humidity, temperature, and curing duration, govern the effectiveness of carbonation. In carbonation curing, carbon dioxide reacts with calcium hydroxide and other calcium-bearing hydration products within the cement matrix, resulting in the formation of stable calcium carbonate. This reaction densifies the microstructure, reduces pore volume, and enhances early-age strength development. The chamber is primarily used for early-age curing, typically ranging from 6 to 24 hours, after which specimens may be subjected to further curing or testing.

The device shown in Fig. 2(b) is a Universal Data Logger used for monitoring and displaying environmental parameters such as temperature and humidity. It features a digital colour display that provides real-time readings and system status in an easy-to-understand dashboard format. The temperature is displayed as 31.3 °C, while the humidity level is shown as 95.9% RH. Different coloured blocks indicate the condition of each channel. The device supports multiple input channels (labelled 1 to 8), making it suitable for monitoring several sensors simultaneously.

4.1.1.2 Carbonation Reaction Mechanism

During carbonation curing, CO_2 reacts with calcium silicates and hydration products in cement to form stable calcium carbonate ($CaCO_3$). This reaction accelerates mineral carbonation and densifies the concrete microstructure, improving strength and durability.

The key reactions are:

1. Reaction with calcium hydroxide (portlandite):

$$\mathrm{Ca(OH)_2} + CO_2 \rightarrow CaCO_3 + H_2O$$

2. Carbonation reaction with calcium silicate hydrate (C–S–H)

$$CaO \cdot SiO_2 \cdot H_2O + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot H_2O$$

4.1.1.3 Normal curing of cement moulds

Normal curing of cement moulds refers to the controlled maintenance of moisture and temperature conditions to ensure proper hydration of freshly cast cement specimens to allow complete hydration of cement particles. After casting, the moulds are usually kept submerged in water, in a damp room, or covered with wet cloth for a specific period, typically 7 to 28 days. This prevents shrinkage and cracking, premature drying, while promoting uniform strength development. Proper normal curing ensures that the cement achieves its maximum tensile and compressive strength, durability, and long-term stability. It is an essential step for producing high-quality concrete and reliable structural performance.

4.1.2 Evaluation of Carbonation Curing Effects

i. **Mechanical Performance Assessment: -** The compressive strength of carbonation-cured concrete specimens is evaluated and compared with that of conventionally cured specimens to assess the strength enhancement resulting from carbonation curing. [27]
ii. **Carbon Sequestration Potential: -** The amount of CO_2 sequestered within the concrete matrix is estimated based on mass gain measurements and carbonation depth analysis, establishing concrete as a potential carbon sink [28]

4.1.3 Environmental and Practical Assessment: - The effectiveness of utilizing captured CO_2 in carbonation curing is evaluated in terms of emission reduction potential for the cement industry. The scalability and economic feasibility of integrating carbonation curing with CCUS infrastructure are also examined to assess its suitability for large-scale implementation.

4.2 Mix Proportion: - The cement mortar mix was designed by partially replacing cement with coal fly ash contents of 0%, 5%, 10%, 15%, 20%, and 25% by weight of cement were used to evaluate their effects on mortar properties. The total binder content was kept constant at 600 g, while the fine aggregate (sand) content was fixed at 1800 g for all mixes. A water-to-cement ratio of 0.45 was maintained to ensure consistent workability., resulting in a water content of 270 g for each mix. The material quantities for all mix proportions are provided in Table 4. Three samples were prepared for each mix to ensure consistency. This methodology allows a systematic evaluation of the impact of coal fly ash as a partial cement replacement on mortar performance.

Table 4 Mix Proportions of Cement Mortar Incorporating Coal Fly Ash as Partial Cement Replacement

Three samples were prepared for each mix; all material quantities are given in grams (g).				
Ratio %	Cement	Ash	Sand	W/C (0.45)
0	600	-	1800	270
5	570	30	1800	270
10	540	60	1800	270
15	510	90	1800	270
20	480	120	1800	270
25	450	150	1800	270

4.2.1 Sample Preparation: - The cement mortar samples were prepared using ordinary Portland cement (OPC), with partial replacement by coal fly ash as a partial replacement (Sample Preparation, as shown in Fig. 3). Standard graded fine aggregate was used throughout the study. Fresh mortar was cast into standard cube moulds of 70.6 × 70.6 × 70.6 mm and compacted on a vibrating table to remove entrapped air and ensure proper consolidation. After casting, the specimens were covered to prevent moisture loss and allowed to set at room temperature for an initial period. For each mix, three cubes were prepared for CO_2 curing at 6, 12, and 24 hours (total 9 cubes per mix), and four cubes were prepared for water curing at 1, 3, 7, 14, and 28 days (total 20 cubes per mix). The demoulded specimens were then subjected to either conventional water curing or carbonation curing according to the experimental program. For carbonation curing, the samples were placed in a carbonation chamber and exposed to a controlled CO_2 environment for the specified durations before further testing.



Figure 2 Samples After Preparation

5. Result and Discussion

5.1 Compressive Strength: - The compressive strength data for the cement mortar specimens, summarized in Table 5, highlight the influence of CO_2 curing durations (6, 12, and 24 hours) across different coal fly ash replacement levels. The data highlight how curing duration and replacement level influence strength development in the specimens.

Table 5 Compressive strength test results in MPa after CO_2 curing in Hours

Compressive strength test Results (MPa)			
Replacement %	**Co_2 Curing in Hours**		
	6 hr.	**12 hr.**	**24 hr.**
0 %	12.50	14.86	20.80
5 %	12.86	14.90	19.90
10 %	11.60	13.63	18.84
15 %	10.40	10.28	17.63
20 %	9.86	9.33	16.33
25 %	8.60	8.40	15.26

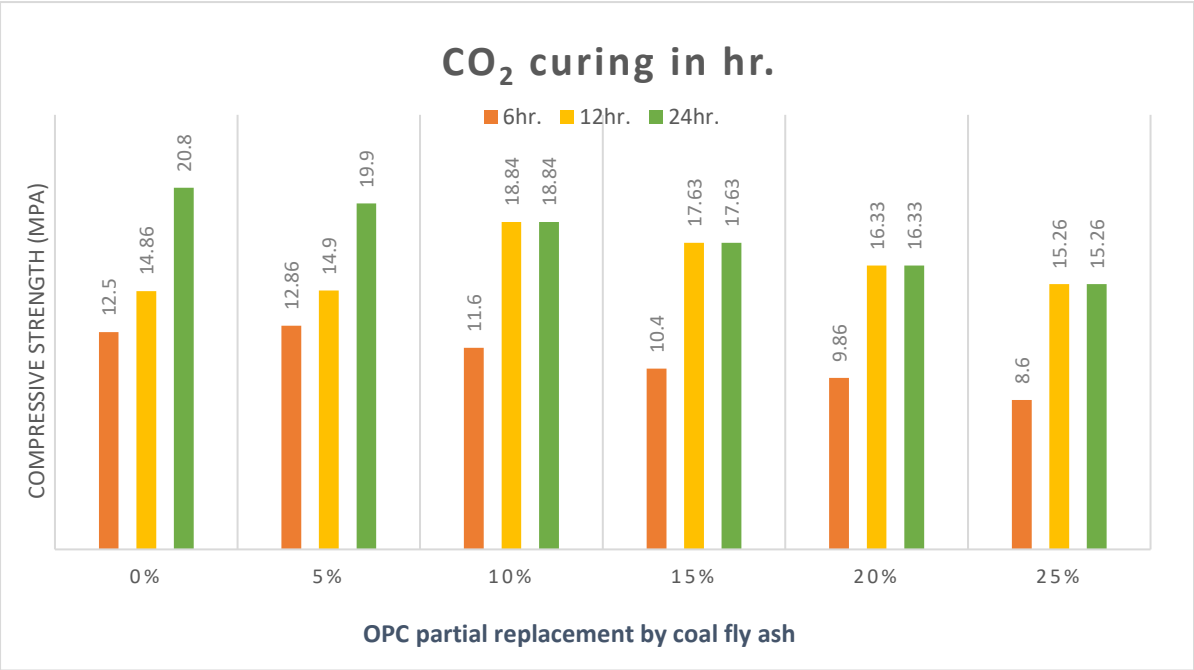

Figure 4 Represented compressive strength test result after CO_2 curing

From the experimental results, it is observed that compressive strength increases with longer CO_2 curing durations for all coal fly ash replacement levels. The maximum compressive strength of 20.80 MPa was recorded for the control mix (0% replacement) after 24 hours of CO_2 curing, highlighting the effectiveness of extended CO_2 curing in enhancing strength development.

As the coal fly ash replacement percentage increases from 0% to 25%, a gradual reduction in compressive strength is observed across all curing durations. At 5% replacement, the compressive strength values remain comparable to the control mix, showing only a slight decrease. However, beyond 10% replacement, a noticeable reduction in strength occurs, particularly at higher replacement levels (15–25%). For the 25% replacement mix, the lowest compressive strengths of 8.60 MPa, 8.40 MPa, and 15.26 MPa were recorded after 6, 12, and 24 hours of CO_2 curing, respectively. This reduction can be attributed to the decreased availability of cementitious material, which limits the formation of strength-contributing compounds.

Overall, the results indicate that CO_2 curing enhances compressive strength with increasing curing time, although higher coal fly ash replacement levels reduce the magnitude of strength gain. while higher replacement percentages negatively influence strength development. An optimum replacement level of up to 5% can be considered without significant loss in compressive strength under CO_2 curing conditions.

Table 6 Compressive Strength Results (MPa) after Normal Curing for Different Days

Compressive strength test Results (MPa)					
Replacement %	**Normal Curing in Days**				
	1 Days	**3 Days**	**7 Days**	**14 Days**	**28 Days**
0 %	7.80	9.20	11.50	13.60	22.60
5 %	7.90	9.10	11.30	13.76	23.80
10 %	7.40	8.90	10.90	12.50	22.33
15 %	7.33	7.90	10.33	11.90	21.25
20 %	7.10	6.60	9.80	10.30	20.13
25 %	6.52	5.90	8.90	9.43	18.94

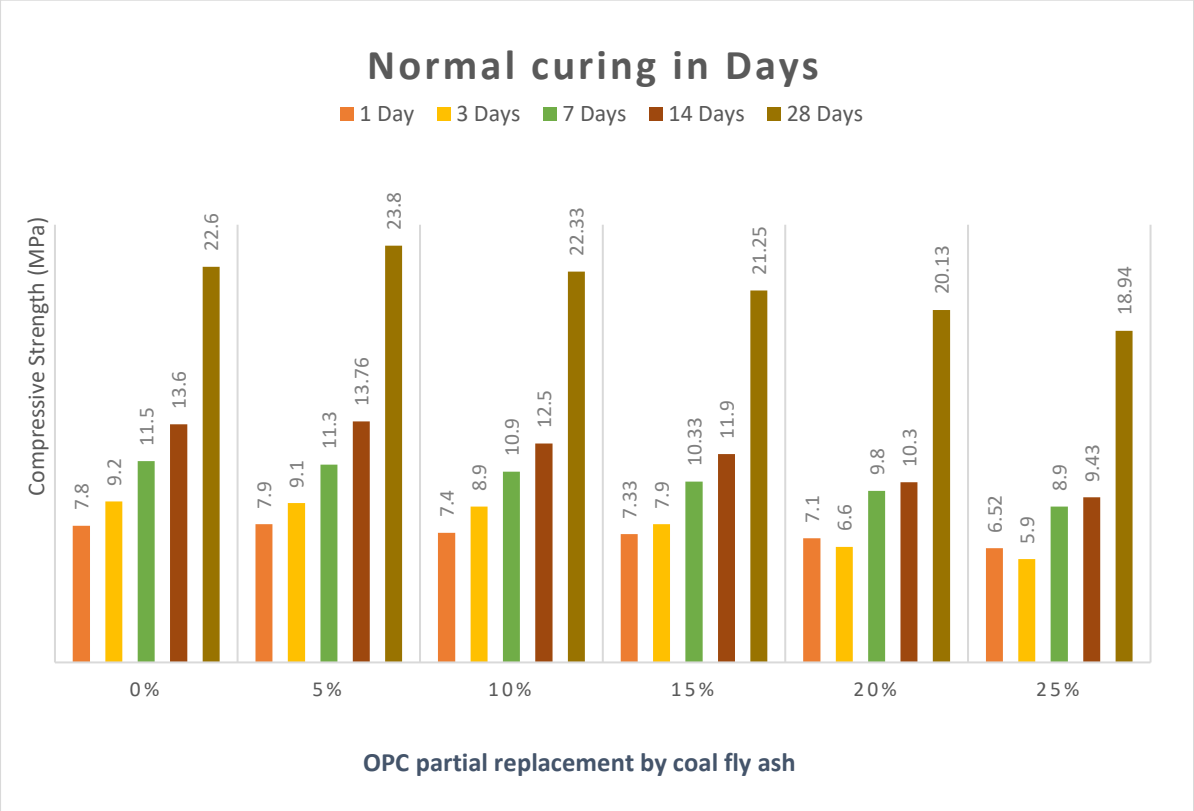

Figure 5 Represented compressive strength test result after Normal curing.

Table 6 Presents the compressive strength test results of specimens subjected to normal curing for different periods of 1, 3, 7, 14, and 28 days, with varying coal fly ash replacement percentages. The compressive strength values are reported in megapascals (MPa). The results show that compressive strength increases with curing age for all replacement levels, a trend attributed to the continued hydration of cement, which progressively forms strength-

contributing compounds over time. The highest compressive strength values were consistently observed at 28 days of curing for all mixes. The control mix (0% replacement) achieved a compressive strength of 22.60 MPa at 28 days, serving as a reference for comparison. A slight improvement in strength was noted at 5% replacement, which recorded the highest 28-day strength of 23.80 MPa. This suggests that a small amount of coal fly ash replacement may enhance particle packing and contribute positively to strength development under normal curing conditions.

As the coal fly ash replacement percentage increased beyond 10%, a gradual reduction in compressive strength was observed across all curing ages. At 10% replacement, the 28-day compressive strength was 22.33 MPa, which is comparable to that of the control mix. However, further increases to 15%, 20%, and 25% replacement resulted in noticeable strength reductions, particularly at later curing ages. This reduction at higher replacement levels can be attributed to the lower cement content, which limits the availability of hydration products responsible for strength development.

The lowest compressive strength values were recorded at 25% replacement, with strengths of 6.52 MPa at 1 day and 18.94 MPa at 28 days. Despite the reduction, strength development with curing age was still evident, highlighting the continued hydration process.

5.2 Co_2 Penetration test: Phenolphthalein testing was employed to assess carbonation penetration in the cement mortar samples. In this test, the pink or purple regions indicate uncarbonated, highly alkaline concrete, while the Gray areas represent carbonated zones where CO_2 penetration has lowered the pH. The results of this analysis, presented in Figure 6, illustrate the depth of CO_2 penetration in the cement mortar samples, offering a clear visual assessment of the extent of carbonation under different curing conditions.



Figure 6 CO_2 Penetration Depth in Cement Mortar via Phenolphthalein Test

. The measured carbonation depth varied across samples, generally ranging from 8 to 12 mm. CO_2 penetration depth is a critical parameter for evaluating the effectiveness of carbonation curing and its influence on concrete durability. Controlled carbonation curing has been shown to enhance the mechanical performance of concrete while enabling the permanent sequestration of CO_2 within the cementitious matrix, thereby contributing to emission mitigation.

6. Conclusions

The following are conclusions drawn

(i) This study demonstrates that CO_2 curing significantly enhances early-age compressive strength of fly ash–blended cement mortar compared to conventional curing. An optimum fly ash replacement level of approximately 5% provides comparable or improved strength performance under both curing regimes. Although higher replacement levels reduce strength due to cement dilution, CO_2 curing partially compensates for this loss through accelerated carbonation. The integration of coal fly ash utilization with CO_2 curing presents a promising approach for producing sustainable, low-carbon construction materials while facilitating effective CO_2 sequestration.

(ii) Conventional water curing played a crucial role in sustaining long-term hydration and promoting strength development in cement mortar. Specimens subjected to normal curing exhibited a gradual and continuous increase in compressive strength with curing age, achieving their maximum strength at 28 days. The observed behaviour is a result of continued hydration of cementitious constituents, leading to the progressive development of calcium silicate hydrate (C–S–H) gel and improved interfacial bonding within the cement matrix. The results confirm that conventional curing remains effective for long-term performance, particularly for mixes with higher cement content, and provides a reliable benchmark for evaluating the efficiency of alternative curing techniques such as CO_2 curing.

Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethics Approval, Consent to Participate, and Consent to Publish

Not applicable.

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Consent to Publish

The authors confirm that all authors have read and approved the manuscript and consent to its publication.

Consent to Participate

Not applicable. This study does not involve human participants or animals.

Authors' Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by all authors. The first draft of the manuscript was written by Shubham Raghuvanshi, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

[1] Ige, O. E., Von Kallon, D. V., & Desai, D. (2024). Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technologies and Environmental Policy, 26*(579–597). https://doi.org/10.1007/s10098-023-02683-0

[2] Sethi, V. K., & Vyas, S. (2017). An innovative approach for carbon capture & sequestration on a thermal power plant through conversion to multi-purpose fuels – A feasibility study in Indian context. *Energy Procedia, 114*, 1288–1296. https://doi.org/10.1016/j.egypro.2017.03.1240

[3] Zhang, L., Zha, X., Ning, J., & Li, W. (2023). Research status on the application technology of early age carbon dioxide curing. *Buildings, 13*(4), 957. https://doi.org/10.3390/buildings13040957

[4] França, S., Sousa, L. N., Saraiva, S. L. C., Ferreira, M. C. N. F., Silva, M. V. d. M. S., Gomes, R. C., Rodrigues, C. d. S., Aguilar, M. T. P., & Bezerra, A. C. d. S. (2023). Feasibility of Using Sugar Cane Bagasse Ash in Partial Replacement of Portland Cement Clinker. *Buildings*, 13(4), 843. https://doi.org/10.3390/buildings13040843

[5] Alterary, S. S., & Marei, N. H. (2021). *Fly ash properties, characterization, and applications: A review*. *Journal of King Saud University – Science, 33*(6), Article 101536. https://doi.org/10.1016/j.jksus.2021.101536

[6] Wan Yun, H. (2022). A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2emissions future. *Carbon Capture Science & Technology, 3*, 100044. https://doi.org/10.1016/j.ccst.2022.100044

[7] Hewlett, P. C., & Liska, M. (Eds.). (2019). *Lea's Chemistry of Cement and Concrete* (5th ed.). https://doi.org/10.1016/C2013-0-19325-7

[8] Cho, S., Lee, N., & Kim, M. O. (2025). A comprehensive review on CO_2utilization in cement and concrete: From microstructural transformations to structural applications. *Case Studies in Construction Materials, 23*, e05265. https://doi.org/10.1016/j.cscm.2025.e05265

[9] Sethi, V. K., & Vyas, S. (2017). An innovative approach for carbon capture & sequestration on a thermal power plant through conversion to multi-purpose fuels – A feasibility study in Indian context. *Energy Procedia, 114*, 1288–1296. https://doi.org/10.1016/j.egypro.2017.03.1240

[10] Wie, Y. M., Lee, K. G., & Lee, K. H. (2024). Characteristics of circulating fluidized bed combustion (CFBC) ash as carbon dioxide storage medium and development of construction materials by recycling carbonated ash. *Materials, 17*(17), 4359. https://doi.org/10.3390/ma17174359

[11] Miao, E., Du, Y., Zheng, X., Zhang, X., Xiong, Z., Zhao, Y., & Zhang, J. (2023). CO_2 sequestration by direct mineral carbonation of municipal solid waste incinerator fly ash in ammonium salt solution: Performance evaluation and reaction kinetics. *Separation and Purification Technology, 309*, 123103. https://doi.org/10.1016/j.seppur.2023.123103

[12] Jun, H., Han, S., Wi, S., & Yoon, J. (2026). Influence of CO_2curing on carbonation depth, phase composition, and micro-mechanical properties of FBC ash-blended cementitious materials. *Construction and Building Materials, 506*, 144872. https://doi.org/10.1016/j.conbuildmat.2025.144872

[13] Jia, Q., Shen, L., Zhou, Z., et al. (2025). *Carbonation solidification of industrial solid wastes including coal fly ash*. *Energy & Fuels*. https://doi.org/10.1021/acs.energyfuels.5c04093

[14] Franco-Quiñonez, V., Garcia-Troncoso, N., Valverde-Burneo, D., & Segura, I. (2025). Sustainable concrete using rice husk ash, PET, and tire rubber as fine aggregate substitutes. *Construction and Building Materials, 504*, 144675. https://doi.org/10.1016/j.conbuildmat.2025.144675

[15] Jeong, E., Jung, S.-H., & Shin, H.-S. (2024). The integrated approach of carbon capture, utilization, and storage via CO_2mineralization for the removal of fly ash, bottom ash, and exhaust gas—A case study of circulating fluidized bed combustion. *Science of the Total Environment, 945*, 174104. https://doi.org/10.1016/j.scitotenv.2024.174104

[16] Tantri, A., Nayak, G., Shenoy, A., et al. (2022). Implementation assessment of calcined and uncalcined cashew nut-shell ash with total recycled concrete aggregate in self-compacting concrete employing Bailey grading technique. *Innovative Infrastructure Solutions, 7*, 305. https://doi.org/10.1007/s41062-022-00907-8

[17] Dixit, A., Du, H., & Pang, S. D. (2021). *Carbon capture in ultra-high performance concrete using pressurized CO_2 curing.* **Construction and Building Materials**, **288**, 123076. https://doi.org/10.1016/j.conbuildmat.2021.123076

[18] Liu, L., Liu, Y., Tian, X., & Chen, X. (2022). *Superior CO_2 uptake and enhanced compressive strength for carbonation curing of cement-based materials via flue gas*. **Construction and Building Materials, 346**, 128364. https://doi.org/10.1016/j.conbuildmat.2022.128364

[19] Ting, K. L., Vallyutham, K., Phoon, C. H., Manokaran, P. K. (2023). *Prospect of CO_2 sequestration in Malaysia cement industry*. **IOP Conference Series: Earth and Environmental Science, 1135**(1), 012049. https://doi.org/10.1088/1755-1315/1135/1/012049

[20] Qin, X., Bill Jin, X., Ida Chen, F., Shi, D., & Shekhawat, D. (Eds.). (2025). *Industrial Decarbonization: Materials, Methods, and Developments*. CRC Press. https://doi.org/10.1201/9781003655442

[21] Bureau of Indian Standards. (1985). *IS 4032:1985 – Specification for Ordinary and Rapid Hardening Portland Cement*. New Delhi: BIS.

[22] Bureau of Indian Standards. (1988). *IS 4031 (Part 5):1988 – Methods of Physical Tests for Hydraulic Cement – Determination of Initial and Final Setting Times*. New Delhi: BIS.

[23] Rochelle, G. T. (2009). *Amine scrubbing for CO_2 capture from flue gas*. (as summarized in industrial literature on aqueous amine absorption).

[24] Yuan, Y., Wang, L., Zhuang, Y., Wu, Y., & Bi, X. (2024). *Energy and economic assessment of oxy-fuel combustion CO_2 capture in coal-fired power plants*. **Energies, 17(18)**, 4626. https://doi.org/10.3390/en17184626

[25] Sreenath, S., & Sam, A. A. (2023). *Hybrid membrane-cryogenic CO_2 capture technologies: A mini-review.* **Frontiers in Energy Research, 11**, 1167024. doi:10.3389/fenrg.2023.1167024

[26] Song, C., Liu, Q., Deng, S., Li, H., & Kitamura, Y. (2019). *Cryogenic-based CO_2 capture technologies: State-of-the-art developments and challenges.* **Renewable and Sustainable Energy Reviews, 101**, 265–278.

[27] Li, Z., He, Z., & Chen, X. (2019). The performance of carbonation-cured concrete. *Materials, 12*(22), 3729. https://doi.org/10.3390/ma12223729

[28] Seo, J. H., Amr, I. T., Park, S. M., Bamagain, R. A., Fadhel, B. A., Kim, G. M., Hunaidy, A. S., & Lee, H. K. (2018). CO_2 uptake of carbonation-cured cement blended with ground volcanic ash. *Materials, 11*(11), 2187. https://doi.org/10.3390/ma11112187

[29] Kene, S. D., & Patel, A. (2024). *Paver blocks made up of fly ash, rice husk ash, and plastic*. In *AIP Conference Proceedings* (Vol. 2974). American Institute of Physics Inc. https://doi.org/10.1063/5.0184195

[30] Kene, S. D., & Patel, A. (2022). Experimental overview on paver block using fly ash, rice husk ash and plastic. *European Journal of Advances in Engineering and Technology, 9*(4s), 87–92. In *Proceedings of the International Conference on Tech Trends in Science & Engineering (ICTTSE 2022)*, Suryodaya College of Engineering & Technology, Suryodaya Polytechnic, Nagpur, Maharashtra, India.