Mechanical Properties of Concrete when cured with Carbon dioxide

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Abstract: The 5% of global CO₂ emissions are from cement industries. To reduce these emissions of CO₂ there is a necessity for sequestration of CO₂ into stable forms. The research focuses on using CO₂ as a curing agent. This paper summarizes the mechanical properties of concrete when cured in artificial CO₂ environment i.e. by using dynamic pressurized CO₂ curing chamber and Dry ice. The research includes designing a concrete mix of M25 grade as per IS 10262:2009. In this research, the effect of carbonation was analysed by CO₂ curing and dry ice curing. The experimental study on water cured, CO₂ cured and dry ice cured specimens for compressive strength, split tensile strength and flexural strength were carried out. The results show that 90% of compressive strength was achieved for 8 hours of CO₂ cured specimens when compared to 28 days of water cured specimens.

Keywords: cement industry, pollution, CO₂ sequestration, carbonation, CO₂ curing, dry ice, penetration, compression strength, split tensile strength and flexural strength.

I. INTRODUCTION

Concrete is known to possess the ability to absorb atmospheric carbon dioxide. The process of absorption of CO₂ into the concrete is called carbonation. [1] Early-age CO₂ curing develops strength, increased surface hardness, and reduced surface permeability to water, as well as the reduction of efflorescence to concrete products. [2] The reactions of carbonation between carbon dioxide and calcium compounds result in the formation of stable calcium carbonate as a permanent fixture.[3]

Don MacMaster and Oscar Tavares [3] study quantify carbon sequestration levels in concrete by creating various curing methodologies. A special CO₂ curing chamber was arranged to enable acceleration reaction by the use of carbon sequestration. The CO₂ curing chamber was arranged with a thermocouple and vacuum system, thermocouples for observing temperature and humidity and pressure. Testing samples were cast and cured in CO₂ curing chamber for 2 hours. Initially, tests were compared with traditional kiln-cured specimens at 100% CO₂ and at 20 psi of pressure. During the 2-hour curing period, continuous checking of relative humidity, temperature and weight gain were performed.

At 2-hours of CO₂ curing, the maximum temperature was reached to 30°C from 18.9°C and remained constant till the end. The relative humidity reached a maximum at the start of the curing test and decreased at 30 minutes and increase after 30 minutes until the end of the 2-hour.

Vibhas Bambroo et al., [4] conducted experimental research to find the absorption of carbon dioxide in concrete beams. For this, a metallic curing chamber is prepared with an outlet and inlet valves and a pressure gauge was attached to note the pressure inside the chamber. The samples were cast and cured in a CO₂ curing chamber for 4 hours and 8 hours and were compared with the samples that are cured in water for 28 days. After 4 hours and 8 hours of CO₂ curing the compressive strength was showed to increase by 12.3% and 27.7% and for 8 hours of CO₂ curing the flexural strength was showed to increase by 1.8% than samples cured in water.

Ming-Gin Lee [5] conducted a study on the size effect of Cylinder on the Compressive Strength of Concrete by CO₂ Curing. In this study cylinders with three different sizes were cast, cured in CO₂ and tested at various curing timings. The CO₂ cured cylinders showed higher compressive strength compared to water cured cylinders.

Y. Shao [6] investigated the viability of using reused CO₂ in concrete through the curing process. The curing process is carried to two ways Open-inlet system and closed system using pressurized flue gas of low concentration. Precast specimens are cured in the chamber, in open-inlet system CO₂ gas with high purity is passed into a closed chamber at a pressure of 21psi and in a closed system flue gas containing 14% of CO₂ is passed at a pressure of 72psi. The gas is passed in seven cycles with a time period of 30-40 minutes. The results show that the concrete products cured in CO₂ show better results for mechanical properties.

Carbonation of concrete: Carbonation shows improved strength and durability of cement products. Carbonation may not be useful in non-reinforced cement products. Carbonation process may be useful for non-reinforced cement products. But due to carbonation the pH of cement paste reduces, the steel used in concrete loses its passivity and becomes liable to corrosion. Carbonation is a process by which CO₂ reacts with water and forms Ca(OH)₂. Calcium silicate and aluminates hydrates react with CO₂ and produce calcium carbonate and hydrates of silicates and aluminates and water.

II. RESEARCH SIGNIFICANCE

CO₂ emissions in the environment is increasing day by day. This increase in concentration has been reached the permissible limit standards and is leading to global warming. 5% of the global CO₂ emissions are from the cement industry. The research focused on reducing CO₂ emissions by sequestering them inside the concrete.
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Carbonation is an accelerated curing process that injects CO₂ gas into the curing chamber and transforms the gaseous CO₂ into solid calcium carbonates (CaCO₃) at ambient temperature, diffuses the carbon dioxide into the fresh concrete under low pressure.

Ca(OH)₂ + CO₂ → CaCO₃ + H₂O
C₃S + 3CO₂ + H₂O → C-S-H + 3CaCO₃
C₂S + 2CO₂ + H₂O → C-S-H + 2CaCO₃

A. Preparation of Curing Chamber
A metallic curing chamber of sizes 1000mmx500mmx500mm with an outlet and inlet and withholding pressure of 2kg/cm² was prepared. To know the pressure that is maintained in the chamber, a pressure gauge was fixed.

B. Aggregates

The fine aggregate used in the research was of zone2 of confirming IS 383-1970. The physical properties of FA are listed below in the table
Coarse aggregate used in this was angular of size 12.5mm confirming to IS 383-1970. The physical properties of Coarse aggregate are listed below in the table

Table: 2 Test results of aggregates

| S.NO | Description                        | Fine aggregate | Coarse aggregate |
|------|------------------------------------|----------------|------------------|
| 1    | Specific gravity of fine aggregate | 2.55           | 2.61             |
| 2    | Water absorption of fine aggregate | 0.76           | 0.55             |
| 3    | Bulk density of compacted aggregates | 1.62          | 1.61             |
| 4    | Bulk density of loosely packed aggregates | 1.44         | 1.49             |
| 5    | Fineness modulus of Fine Aggregates | 2.11           | 7.2              |

IV. CONCRETE MIX DESIGN
Concrete mix design is done as per IS 10262. The mix quantities are listed in the table below:

Table: 3 MIX PROPORTIONS

| Grade designation | Cement (kg/m³) | F.A (kg/m³) | C.A. (kg/m³) | w/c ratio | Target strength |
|-------------------|----------------|-------------|--------------|-----------|----------------|
| M25               | 300            | 738.7       | 1233.7       | 0.47      | 31.6           |

V. EXPERIMENTAL PROCEDURE
The testing specimens for compressive strength, split tensile strength flexural strength was cast. The specimens are cured in water and tested for 1day, 7days, and 28days. The specimens are cured in CO₂ curing chamber and Dry ice for 4, 6, 8 hours and tested for compression strength, split tensile strength and flexural strength. The specimens are cured in CO₂ and dry ice for 4, 6, and 8 hours and in water for 28days and tested for compressive strength. The results of CO₂ and Dry ice cured are compared with water cured.

A. Tests on fresh properties of concrete
Concrete is said to be workable when it is easily placed homogeneously without Segregation. Workability of freshly mixed concrete commonly determined by slump cone test and compaction factor.
- The slump cone value is 30mm.
- Compaction factor value is 0.86.

B. CURING SETUP
a) Water curing setup
The cubes, cylinders, and beams are cast and cured for 1day, 7days, and 28days and tested.

b) Dry ice curing and CO₂ curing setup
The cubes, cylinders, and beams are cast and cured for 2hours- 8hours. For dry ice curing artificial CO₂ curing, the environment was created by using dry ice. The specimens are kept in Thermocole box along with dry ice and it should be
airtight with masking tape to avoid contact with the outside temperature. The casted specimens are placed in carbonation chamber and pure CO₂ gas is passed into chamber at a pressure of 2kg/cm² and cured for 2hours-8hours in CO₂ curing chamber and tested for mechanical properties. The specimens are cured in CO₂ and Dry ice for 4 hours, 6 hours and 8 hours and in water after 28 days and tested for compressive strength.

Table 4. Results of water cured specimens

| Time intervals | Compressive strength(Mpa) | Split tensile strength (Mpa) | Flexural strength (Mpa) |
|----------------|---------------------------|-----------------------------|------------------------|
| 1 day          | 14.3                      | 1.57                        | 2.14                   |
| 7 days         | 19.31                     | 2.6                         | 3.33                   |
| 28 days        | 33.23                     | 3.6                         | 3.6                    |

Fig 2. Specimens cured in Dry ice

Fig 3. Specimens in the carbonation chamber

VI. RESULTS AND DISCUSSIONS

A. Water cured Results

The compressive strength, Split tensile strength and Flexural strength results of specimens cured in water are tested for 1 day, 7 days and 28 days are tabulated below.

Fig 4. Compressive strength results of water cured specimens

The compressive strength results of water cured are tabulated and shown in the above figure. From the above figure, the design compressive strength is achieved for 1 day and 28 days. As the curing age increases, the strength of concrete increases by 64% and 7% for 1 day and 28 days curing compared to design strength and for 7 days the strength achieved was nearer to design strength of concrete.

Fig 5. Split tensile strength results of water cured specimens

The split tensile strength results of water cured are tabulated and shown in the above figure. From the figure, it was observed that split tensile strength results for 1 day, 7 days and 28 days curing was 1.57Mpa, 2.6Mpa and 3.6Mpa.
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Fig 6. Flexural strength results of water cured specimens
The Flexural strength results of water cured are tabulated and shown in the above figure. From the figure, it was observed that Flexural strength results for 1 day, 7 days and 28 days curing 2.14 Mpa, 3.33 Mpa and 3.6 Mpa.

B. CO₂ cured and Dry ice cured Results
The Compressive strength, Split tensile strength and Flexural strength results of CO₂ cured and Dry ice cured specimens that are tested for 2 hours, 4 hours, 6 hours and 8 hours are tabulated below:

Table 5. Compressive strength results for CO₂ cured and dry ice cured specimens

| Time intervals | CO₂ cured(Mpa) | Dry ice cured(Mpa) |
|----------------|---------------|-------------------|
| 2 hours        | 1.77          | 1.32              |
| 4 hours        | 2.43          | 1.86              |
| 6 hours        | 2.63          | 2.05              |
| 8 hours        | 3.23          | 2.52              |

Fig 7. Compressive strength results for CO₂ cured
The compressive strength results of CO₂ cured are tabulated and shown in the above figure. From the above figure, it was found that 82% of compressive strength was achieved for 8 hours of CO₂ curing compared to 28 days water cured specimens.

Table 6. Split tensile strength results for CO₂ cured and dry ice cured specimens

| Time intervals | CO₂ cured(Mpa) | Dry ice cured(Mpa) |
|----------------|---------------|-------------------|
| 2 hours        | 19.6          | 17.13             |
| 4 hours        | 20.5          | 17.93             |
| 6 hours        | 22.03         | 20.43             |
| 8 hours        | 28.73         | 26.13             |

Fig 8. Compressive strength results for Dry ice cured specimens
The compressive strength results of CO₂ cured are tabulated and shown in the above figure. From the above figure, it was found that 90% of compressive strength was achieved for 8 hours of CO₂ curing compared to 28 days water cured specimens.

Fig 9. Split tensile strength results for CO₂ cured specimens
The split tensile strength results of CO₂ cured are tabulated and shown in the above figure. From the figure, it was observed that split tensile strength results for 2 hours, 4 hours, 6 hours and 8 hours curing was 1.77 Mpa, 2.43 Mpa, 2.63 Mpa and 3.23 Mpa respectively. It was found that 92% of tensile strength was achieved for 8 hours of CO₂ curing when compared to specimens cured in water for 28 days.
Fig 10. Split tensile strength results for Dry ice cured specimens

The split tensile strength results of Dry ice cured are tabulated and shown in the above figure. From the figure, it was observed that split tensile strength results for 2hours, 4hours, 6hours and 8hours curing was 1.32 Mpa, 1.86 Mpa, 2.05 Mpa and 2.52 Mpa respectively. It was found that 72% of tensile strength was achieved for 8 hours of Dry ice curing compared to 28days water cured specimens.

Table 7. Flexural strength results for CO₂ cured and dry ice cured specimens

| Time intervals | CO₂ cured(Mpa) | Dry ice cured(Mpa) |
|----------------|----------------|--------------------|
| 2 hours        | 2.63           | 1.91               |
| 4 hours        | 2.77           | 2.14               |
| 6 hours        | 2.83           | 2.57               |
| 8 hours        | 3.38           | 3.04               |

Fig 11. Flexural strength results for CO₂ cured specimens

The Flexural strength results of CO₂ cured are tabulated and shown in the above figure. From the figure, it was observed that flexural strength results for 2hours, 4hours, 6hours and 8hours curing was 2.63, 2.77, 2.83 and 3.38 respectively. It was found that 89% of Flexural strength was achieved for 8 hours of CO₂ curing compared to 28days water cured specimens.

Table 8. Compressive strength results of CO₂ cured and dry ice cured specimens

| Time intervals  | CO₂ cured         | Dry ice cured       |
|-----------------|-------------------|---------------------|
| 4h + 28 days water | 32.2              | 33.5                |
| 6h + 28 days water | 33.7              | 35.72               |
| 8h + 28 days water | 35.5              | 37.4                |

Fig 12. Flexural strength results for Dry ice cured specimens

The Flexural strength results of Dry ice cured are tabulated and shown in the above figure. From the figure, it was observed that flexural strength results for 2hours, 4hours, 6hours and 8hours curing was 1.91, 2.14, 2.57 and 3.04 respectively. It was found that 80% of Flexural strength was achieved for 8 hours of CO₂ curing compared to 28days water cured specimens.

Fig 13. Compressive strength results of CO₂ + water cured and Dry ice + water cured specimens

The compressive strength results of CO₂ + water cured and Dry ice + water cured are tabulated and shown in the above figure. The results show that the target strength is reached in both curing conditions but the strength of concrete slightly decreases when cured in CO₂ (4h, 6h, 8h) + water (28 days) when compared with specimens cured in Dry ice (4h, 6h, 8h) + water (28 days).

C. TEST FOR CARBONATION

Phenolphthalein indicator solution was used to find the depth of carbonation. Concrete having higher pH due to formation of Calcium hydroxide when cement reacts with water. When phenolphthalein solution is added it turns pink.
However it remains colourless, it indicates that concrete has undergone carbonation. The concrete specimens cured in water and CO<sub>2</sub> are tested for phenolphthalein are shown in figure below and the penetration depths are shown.

Fig 12. Phenolphthalein test for water cured and CO<sub>2</sub> cured specimens

Fig 13. Graph shows CO<sub>2</sub> penetration vs. duration of CO<sub>2</sub> cured specimens

From the above figure, it is shown that average penetration of CO<sub>2</sub> has occurred at 2 hours of CO<sub>2</sub> curing was 17mm and for water cured specimens it found to be negligible when compared to CO<sub>2</sub> cured specimens. As time increases the porosity decreases in concrete and it needs a lot more pressure to sequester carbon dioxide inside it which is not possible to maintain at this level.

VII. CONCLUSIONS

The results from the experimental study carried out for evaluating the mechanical properties of specimens cured in water, CO<sub>2</sub> and Dry ice. The CO<sub>2</sub> and Dry ice cured specimens achieved early strength when compared to water cured specimens are summarized below:

- Compressive strength of CO<sub>2</sub> cured specimens for 8 hours duration has achieved 90% of the strength when compared with respect to water cured specimens.
- Split tensile strength of the CO<sub>2</sub> cured specimens for 8 hours duration has achieved 92% of tensile strength when compared with the specimens cured in water.
- Flexural strength of the CO<sub>2</sub> cured specimens for 8 hours duration has achieved 89% of flexural strength when compared with the specimens cured in water.
- The CO<sub>2</sub> and Dry ice cured specimens have achieved slightly higher compressive strength with an increase in the curing age of 8 hours when compared with water cured specimens.
- The compressive strength of CO<sub>2</sub> cured (4h, 6h, 8h) + water (28days) and Dry ice cured (4h, 6h, 8h) + water (28 days) specimens achieved target strength but the strength of CO<sub>2</sub> cured specimens slightly decreases when compared with Dry ice cured specimens.

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