An Alternative Technique for Accelerated Carbonation of Normal Concrete

Bura Akshay Ramesh1,a, B. Kondraivendhan2,b

1,2 Applied Mechanics Department, Sardar Vallabhbhai National Institute of Technology, Surat, Ichchhanath, Gujarat-395007, India.

a akshayrbura@gmail.com, b kondraivendhan78@gmail.com

Abstract. Carbonation is a continuous process in concrete structures and taking place for large period of time. The present study investigates accelerated carbonation effect on normal concrete with the help of Ammonium Bicarbonate (\(\text{NH}_4\text{HCO}_3\)) solution. Normal concrete specimens were exposed to carbonated water curing for different durations after initial 28 days of normal water curing. The effect of carbonated water curing on concrete specimens was studied with the help of carbonated water curing test and pH profiling test. From the results, it was observed that the compressive strength of normal concrete specimens increased and pH value increased along the depth from the surface with prolonged carbonated water curing.

1. Introduction

Concrete is the most frequently used building material in the civil engineering industry for many years throughout the world. Production of cement is energy intensive and one of the major contributors of \(\text{CO}_2\) emission sources in the world. Depending on the production technology, the \(\text{CO}_2\) emission ranges from 0.73 to 0.99 t of \(\text{CO}_2\) per 1 t of cement. More than one half of this amount is caused by calcinations, which is integral part of the cement production. Looking at the amount of \(\text{CO}_2\) production by the concrete industry, it is highly desirable to find a way to reduce the quantity of \(\text{CO}_2\) emissions from concrete production. Therefore, there are lots of attempts to use supplementary cementitious materials (SCMs) which can replace at least a part of cement in concrete by more environmental friendly materials. The most common representatives of SCM are industrial by-products such as fly-ash, silica fume or blast furnace slag [1]. Apart from lowering the \(\text{CO}_2\) emissions by the construction industry, Carbon Capture and Storage (CCS) techniques have gained importance over the last few decades. A well equipped CCS unit can reduce the \(\text{CO}_2\) emissions by 80 – 90 %. Among the various CCS techniques, accelerated carbonation curing (ACC) is considered to be an effective \(\text{CO}_2\) sequestration technique that can be adopted for precast concrete units. ACC is different from the carbonation of mature concrete which is considered detrimental to reinforced concrete. The major difference between the two carbonation procedures is its time of application, while the former is intentionally applied within 24 hours of concrete casting; the latter is a normal reaction of cement paste with the atmospheric \(\text{CO}_2\) for a prolonged period [2]. Carbonation of cement pastes naturally occurs in atmospheric conditions because \(\text{CO}_2\) dissolves in the interstitial solution of the pores of a hardened cement matrix shown by Eq. 1.

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \rightarrow 2\text{H}^+ + \text{CO}_3^{2-}
\]
In the presence of portlandite, the carbonation reaction occurs as shown in Eq. 2, prior to the formation of calcium silicate hydrate (C-S-H) and Aft and Afm.

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \quad (2)
\]

Furthermore, the decalcification of C-S-H can occur after the complete carbonation of portlandite, because the stability of C-S-H is highly associated with the alkalinity of the pore solution [3]. The purpose of the present study is to examine the effect of an alternative accelerated carbonation technique using Ammonium Bicarbonate (NH\textsubscript{4}HCO\textsubscript{3}).

2. Experimental program
In current investigation, experimental study was carried out to analyze an alternative technique for accelerated carbonation of normal concrete. Normal concrete samples were exposed to carbonated water curing for different age periods. The change in compressive strength and pH values were studied after carbonation curing.

3. Materials
Cement used in current study was OPC (Grade 53) confirming to IS: 12269-1987 [4]. Concrete was prepared by using crushed coarse aggregates of size 20 mm MSA (Maximum size of aggregate) and 10 mm MSA. The specific gravity of 20 mm MSA and 10 mm MSA were 2.69 and 2.67 respectively. Locally available natural river sand confirming to Zone II as per IS: 2386-1963 (Part-I) was used as fine aggregate for preparation of concrete mix [5].

4. Mix proportion
In present work, concrete mix design was done in line with DOE method guidelines as per SP23-1982 [6]. Concrete specimens with a constant water-to-cement (W/C) ratio of 0.55 were fabricated. Using W/C ratio and water content of mix proportion, the total binder content was calculated as 309 kg/m\textsuperscript{3}. Fine aggregate content was taken as 38% of mass of total aggregate. The ratio of 20 mm MSA and 10 mm MSA coarse aggregate were established at 60% and 40% by the total mass of coarse aggregate respectively. The mix proportion of normal concrete is detailed in table 1.

| Ordinary Portland cement (kg/m\textsuperscript{3}) | Water content (kg/m\textsuperscript{3}) | Fine aggregate (kg/m\textsuperscript{3}) | Course aggregate (kg/m\textsuperscript{3}) |
|-----------------------------------------------|----------------------------------------|-----------------------------------------|-------------------------------------------|
| 309                                          | 170                                    | 724                                     | 710                                       |
|                                              |                                        |                                         | 474                                       |

5. Preparation of specimens
Concrete mixture was prepared as per the guidelines provided by IS 456-2005 in concrete mixer [7]. Immediately after mixing, the fresh concrete was placed in cube specimens of size 150 mm \times 150 mm \times 150 mm and vibrated in 3 layers for better compaction. After casting, all the specimens were kept in laboratory environment for 24 hours. All the specimens were demolded after 24 hours and kept in moist curing for the period of 27 days in normal water. Further, concrete specimens were subjected to carbonated water curing after 28 days of initial normal water curing. Carbonation can be induced in concrete specimens by using carbonated water curing as an alternative accelerated carbonation technique. At room temperature, Bakharev et al. (2001) used 0.352 M NaHCO\textsubscript{3} solution as carbonated water curing on alkali activated slag concrete [8]. In current study, 0.352 M solution of Ammonium bicarbonate (NH\textsubscript{4}HCO\textsubscript{3}) was used as carbonated water curing to induce accelerated carbonation in
concrete specimens. After every 7 days, carbonated water was renewed to maintain constant carbonated ions ($CO_3^{2-}$) concentration in curing regime. Compressive strength and pH tests were performed on all the concrete specimens after 6 months of carbonated water curing.

6. Test procedure

6.1. Compressive strength

The test for compressive strength was carried out at the curing ages of 7, 14, 28, 56, 90 and 180 days after initial 28 days of normal water curing. Effect of accelerated carbonation on compressive strength was examined by further curing the concrete specimens in carbonated water beyond initial 28 days of normal water curing. Cube specimens of size 150 mm × 150 mm × 150 mm were used to perform the test in compression testing machine at the rate of 140 kg/cm$^2$/min. For each curing age three samples of concrete specimens were tested and the average of the three was reported as the compressive strength.

6.2. pH profiling of concrete samples

The measurement of pH is essential in studies related to carbonation. Due to carbonation curing, pH drop may occur in pore solution which can be harmful to the rebar preset in reinforced concrete structures. pH of each concrete specimen was measured at discrete layer (0-5, 5-10, 10-15 and up to 25-30 mm from the surface). Concrete powder samples were collected by drilling the concrete specimens at different depth intervals from the surface. For Suspension method of pH determination, concrete powder sample of 4 g was mixed with 80 ml of distilled water in an air tight container. After 24 hours of storage the solution was then tested on a digital pH meter. An apparent pH profile was generated by testing all concrete samples obtained at different depth intervals.

7. Results and discussion

7.1. Compressive strength

The average compressive strength of normal concrete cured in carbonated water at the ages of 7, 14, 28, 56, 90 and 180 days after initial 28 days of normal water curing is shown in figure. 1. It is observed that the compressive strength of normal concrete specimens increased as the duration of carbonated water curing increased. When the specimens were exposed to carbonation curing after initial 28 days of normal water curing, higher compressive strength results were achieved. The carbonation reaction leads to conversion of products from hydration reaction into C-S-H gel or CaCO$_3$. This leads to an increase in the rate of hydration and an accelerated strength gain. Accelerated carbonation curing generates CaCO$_3$ particles in matrix, which fill the pores and reduce the porosity by improving the compressive strength [9]. Thus it can be concluded that prolonged carbonation curing can play an effective role in improving compressive strength with age.
Figure 1. The compressive strength of normal concrete specimens cured in carbonated water with respect to curing duration.

7.2. pH Profiling

Figure 2 present the pH profile of concrete powder samples obtained at various depth intervals from the surface of specimens.

From the results it can be observed that pH value was lower at the surface of concrete specimens. After 180 days of carbonated water curing, the pH value of concrete specimens varies from 11.9 to 12.2 between top of the surface to the depth of 30 mm. These reductions in pH value of concrete sample were due to direct exposure of \( \text{CO}_3^{2-} \) ions to the concrete specimens in accelerated carbonation.
curing condition. Due to accelerated carbonation curing, pH value of normal concrete reduced due to continuous reduction of calcium hydroxide into CaCO$_3$ as a carbonation reaction product [10].

8. Conclusion
The effect of accelerated carbonation curing on the normal concrete has been evaluated with the help of compressive strength and pH profiling. Based on the experimental results, the following conclusions can be drawn.
1) Accelerated carbonation curing technique increases the compressive strength of normal concrete, due to continuous production of additional C-S-H gel and CaCO$_3$ upon carbonation.
2) The porosity of the concrete specimens decreased upon accelerated carbonation curing, because of densification caused by CaCO$_3$ generation.
3) The pH profiling of normal concrete samples varied depending on curing duration and extend of carbonation from the surface of concrete specimens.
4) The pH value of the concrete samples increased along the depth intervals from the surface due to less carbonation reaction in greater depths.

9. References
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