



Comparative study of accelerated carbonation of plain cement and fly-ash concrete



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ABSTRACT

Accelerated carbonation of plain cement concrete and concrete with fly-ash replacing cement partially, is discussed in the present paper. Mechanical properties such as compressive strength, flexural strength, modulus of elasticity, durability aspects such as depth of carbonation and porosity of carbonated concrete are studied. To study the influence of water binder ratio on the above-mentioned properties, water-binder ratios of 0.35, 0.50 and 0.65 are used. It is observed that the mechanical properties of carbonated concrete have increased with the duration of carbon dioxide exposure. So did the depth of carbonation, whereas the volume of permeable voids has reduced leading to the decrease in porosity. An expression to predict the depth of carbonation of fly-ash concrete has also been developed.

1. Introduction

Carbonation of concrete is the term used to illustrate the effect of carbon dioxide (CO_2) on concrete. This process is facilitated by the ingress of CO_2 into concrete through its pores. When carbon dioxide (CO_2) from atmosphere comes in contact with the hydration products of cement, it changes the physical and chemical properties of the concrete [1–3]. Carbonation of cementitious materials is responsible for lowering of pH value because of which the concrete becomes less alkaline, hence the process of carbonation of concrete some times are referred to as neutralization.

CO_2 diffuses through the surface of the concrete through its interconnected capillary pores and dissolute as HCO_3^- and CO_3^{2-} ions depending upon the pH of the pore solution. When carbon dioxide comes into contact with water, which is at a pH of 7, bicarbonates are formed. The pH value of pore solution of concrete is around 12.5–13 [4]. This is because of the dissolution of $\text{Ca}(\text{OH})_2$ which leads to the presence of hydroxyl ions in the pore water. Because the pore solution of the concrete has a high pH in the presence of calcium hydroxide, the bicarbonates finally dissociate into carbonate ions. The hydration products of cement such as $\text{Ca}(\text{OH})_2$ dissolute to release Ca^{2+} and hydroxyl ions which react with carbonate ions and precipitate as CaCO_3 [5]. This process consumes Ca^{2+} ions, thereby dissolution of the calcium hydroxide. The solubility of CaCO_3 is much lower than that of $\text{Ca}(\text{OH})_2$, thus $\text{Ca}(\text{OH})_2$ will dissolve and CaCO_3 is formed until all of $\text{Ca}(\text{OH})_2$ is consumed [6].

Hence it is inevitable that the structures made of concrete are prone

to carbonation, but the question is the duration at which the process takes to initiate. The pH value of pore solution of concrete falls to around 9 to 8.3 [7]. Initially, a thin layer of carbonated concrete is developed on the surface owing to the CO_2 diffusion through the surface that is directly in contact with the atmosphere, but the further propagation of CO_2 is a complex mechanism as the lesser porous carbonated layer makes it difficult for the further CO_2 to diffuse into the fresh concrete. This process depends on the permeability of carbonated concrete and the amount of hydration products available [8].

In blended concretes where cement is replaced by mineral admixtures, the reactions that involve un-hydrated constituents and calcium silicate hydrate (C-S-H) are also crucial because the end products are calcium carbonate and hydrated silica [8]. The C-S-H will dissolve when the pH value and Ca^{2+} ions concentration drops, due to consumption of $\text{Ca}(\text{OH})_2$. Monosulphate and Ettringite will decompose at a pH of 11.6 and 10.6, respectively. After this, most of the Ca^{2+} ions from C-S-H bind to CaCO_3 leaving only some Ca^{2+} ions in silica gel [6]. This changes the composition of C-S-H, resulting in the lower CaO/SiO₂ ratio. When the molar ratio value of CaO/SiO₂ is less than 1.2, rapid decalcification of C-S-H is accompanied by carbonation shrinkage [9]. A molar ratio value of CaO/SiO₂ of cement in carbonated zone is 0.85 and in the un-carbonated zone is 1.65 [10].

Though there are many methods to locate the carbonation front, the one that involves phenolphthalein indicator is more prominent than the rest. This method is most predominantly used in the fields to locate the ingress of CO_2 . The indicator changes the color of concrete to purple when the pH value of pore solution of concrete is above 9. The

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CO₂ ingress does not advance at a constant rate because of the non-homogeneity of the material and also due to the fact that once the concrete has densified in the carbonated zone, it prevents further propagation of carbon dioxide into concrete. There are several factors that influence the propagation of carbonation into the concrete that either individually or combined, affect the CO₂ front. The primary factors that play the key role are permeability of concrete, pozzolanic material, moisture in concrete, CO₂ concentration and duration of exposure [11,12].

The process of carbonation produces calcium carbonate (CaCO₃) as the end product, which occupies more volume compared to Ca(OH)₂. Hence the decrease in permeability of concrete may be expected. This decrease in permeability (or porosity) is the reason why mechanical properties of the carbonated concrete are higher than that of a non-carbonated one. It is to be noted here that the depth of carbonation is limited by the amount of Ca(OH)₂ available for the reaction and hence the decrease in porosity is expected till a certain depth depending on the duration. The influence of carbonation on the porosity of concrete has been reported controversially. Though there is a general agreement that the decrease in porosity due to formation of calcite is observed, the permeability of concrete made with blast furnace slag is reported due to carbonation [13,14]. Ngala and Page [15] observed redistribution of pore sizes in concrete due to carbonation; the proportion of larger pores increased significantly for mineral admixture concrete.

This paper presents the influence of accelerated carbonation on few mechanical properties and durability studies of plain cement concrete and concrete with cement replaced by fly-ash up to 30% by weight. Because the concentration of CO₂ in the atmosphere is 0.03–0.04%, the process of natural carbonation would take a decade to be detected [16]. Moreover concrete is not a highly porous material; the chances of rapid ingress of CO₂ are very unlikely and depend mostly on the permeability of concrete. To overcome this difficulty and accelerate the process in this investigation, concrete samples are exposed to a CO₂ concentration of 5% by volume. Compressive strength, flexural strength, modulus of elasticity, the volume of permeable voids, and depth of carbonation of these concrete samples exposed to accelerated carbonation are measured at pre-determined intervals for over 12 months.

2. Materials and methodology

2.1. Materials

2.1.1. Cement

Ordinary Portland cement (Grade 43) was used in the present research. The chemical and physical characteristics of the cement are mentioned in Table 1 and Table 2, respectively. The physical tests of cement have been determined in accordance to the standard procedure specified in IS 4031 [17].

2.1.2. Fly-ash

Class F fly-ash from the Suratgarh super thermal power plant, India, has been used for the present research. The chemical and physical properties of the same are presented in Table 3 and Table 4,

Table 1

Chemical composition of cement.

Chemical composition	OPC 43 grade (%)
SiO ₂	20.27
Al ₂ O ₃	5.32
Fe ₂ O ₃	3.56
Al ₂ O ₃ + Fe ₂ O ₃	8.88
CaO	60.41
MgO	2.46
SO ₃	3.17
Loss on ignition	3.55

Table 2

Physical characteristics of cement.

Physical Characteristics	OPC 43 grade
Density (kg/m ³)	3090
Specific gravity	3.15
Fineness (%)	8
Normal consistency (%)	33

Table 3

Chemical composition of Fly-ash.

Chemical composition	Value (% by mass)
SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	90
SiO ₂	55.2
CaO	2.7
MgO	1.2
Na ₂ O	0.5
Total Chlorides, Cl	0.04
Sulphur Trioxide (SO ₃)	< 0.01
Loss on Ignition	1.8

Table 4

Physical properties of Fly-ash.

Property	Test value
Fineness, m ² /kg	334
Soundness, %	0.03
Specific gravity	2.7

respectively.

2.1.3. Aggregates

Crushed basalt was used as coarse aggregate and sand was used as fine aggregate. The specific gravity and size range of the aggregates is mentioned in Table 5.

2.1.4. Concrete mix proportions

Three water-binder ratios, 0.35, 0.50 and 0.65 are selected for this study, each designed in proportion to attain a strength of 30–35 MPa. The design mix proportions of the concrete for the selected water-binder ratios are presented in Table 6. The optimum dosage of fly-ash as replacement of cement has been determined by trial and error method and was fixed to 30% by weight of cement. Various dosages of fly ash from 10% to 70% replacement by weight of cement have been considered for the trial and error to determine the optimum dosage. This dosage was fixed for the percentage replacement of fly ash that yielded maximum compressive strength at the end of 56-day curing period. The design mixes MO1, MO2, MO3 represent mixes with ordinary portland cement with a water-binder ratios of 0.35, 0.50 and 0.65 respectively, while the design mixes designated as MF1, MF2 and MF3 represent mixes with fly ash as partial replacement of cement with 0.35, 0.50 and 0.65 respectively.

2.2. Exposure environment

To overcome the difficulties of natural carbonation that would consume few years of exposure, the concrete specimens are cured in an

Table 5

Aggregates size and specific gravity.

Physical characteristics	Fine aggregate	Coarse aggregate
Size range (mm)	0.075–4.75	12.5–20
Specific gravity	2.42	2.77

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