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A review on carbonation study in concrete

N Venkat Rao and T Meena
Department of Structural and Geo-Technical Engineering, School of Civil and Chemical Engineering, VIT University, Vellore, Tamil Nadu – 632014, India.

Email: meena.t@vit.ac.in

Abstract: In this paper the authors have reviewed the carbonation studies which are a vital durability property of concrete. One of the major causes for deterioration and destruction of concrete is carbonation. The mechanism of carbonation involves the penetration carbon dioxide (CO_2) into the concrete porous system to form an environment by reducing the pH around the reinforcement and initiation of the corrosion process. The paper also endeavours to focus and elucidate the gravity of importance, the process and chemistry of carbonate and how the various parameters like water/cement ratio, curing, depth of concrete cones, admixtures, grade of concrete, strength of concrete, porosity and permeability effect carbonation in concrete. The role of Supplementary Cementitious Materials (SCMs) like Ground granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) has also been reviewed along with the influence of depth of carbonation.

1. Introduction:

Carbonation is widely recognized as a significant cause of corrosion of reinforcement in concrete[1]. Corrosion of reinforcement is found be the major cause of deterioration of concrete structures all around the world [2, 3]. The basic mechanism involved in this process is atmosphere reacts with hydrated cement and destroys its property of alkalinity [4]. The transport properties like porosity, permeability, diffusion and capillarity show their effect on carbonation. They also effect the durability of concrete since they control the influence of chlorides. The paper reviews the effect of curing age on carbonation of concrete made of these SCM and it also identifies the relationship between permeability and curing age, strength with the depth of carbonation of concrete. Durability of concrete structures is very much important when the structures are openly exposed to the aggressive environments. Carbonation destructs the structure and reduces its service life. Carbonation is a process by which the atmosphere reacts with hydrated cement products to form calcium carbonate thereby alkalinity of the concrete is reduced [5]. In fact the negative effects of carbonation can be reduced to the maximum extent by using high strength concrete and proper compaction making the concrete denser. Carbonation can also be reduced by low water/cement ratio[1]. Low water/cement ratio and high strength concrete are possible by Self Compacting Concrete (SCC) where effect of carbonation is less comparatively. The carbonation is found to have tremendous impact on some of the engineering properties of concrete. Mostly its influence is predominant on compressive strength and hardness than any other properties. The depth of carbonation can be measured by spraying

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phenolphthalein indicator on scratched part of concrete the solution is a colorless indicator which turns purple when pH is higher than 13.

2. Carbonation process:

The process of carbonation of concrete involves the following chemical equation which clearly depicts the reaction that takes place between atmospheric CO_2 and the products of cement hydration particularly Ca $(OH)_2$.

$$Ca(OH)_2 + CO_2 \longrightarrow CaC0_3 + H_20$$

Hydration products (calcium silicate hydrate or CSH gel) and even the residual unhydrated compounds are present in all concretes.

They are

1) Tricalcium silicate (C_3S)
2) Dicalcium silicate (C_2S)

These compounds react with CO_2 as shown in the following reactions:

$$CSH + 3CO_2 \longrightarrow (3CaCO_3\ 2SiO_2 + 3H_2O)$$

$$C_3S + 3CO_2 \longrightarrow H_2OSiO_2\ H_2O + 3CaCO_3$$

$$C_2S + 2CO_2 \longrightarrow H_2O\ SiO_2\ H_2O + 2CaCO_3.$$

3. Factors affect rate of carbonation:

The following factors have a significant effect on the rate of carbonation [6].

3.1 External factors:

- Ambient relative humidity
- Concentration of carbon dioxide
- Surface protection

3.2 Internal factors:

- Grade of concrete
- Permeability of concrete
- Depth of cover to reinforcement
- Water-cement ratio

3.3 Other factors:

- Time of exposure
- Orientation of building

4. Constituents influence carbonation:

4.1 Effect of water/cement ratio:

From various research studies it was identified that water/cement ratio has a profound effect on carbonation irrespective of the mix design [1]. Water/cement ratio was found to be most authentic and reliable parameter that helps in predicting the resistance of normally vibrated concrete to carbonation [7, 8]. It has been concluded by the earlier research studies that the carbonation depth is directly related to water/cement ratio and it is identified that depth of carbonation increases with increase in water/cement ratio. It is also directly related to the age of the concrete. It has also been found that depth of carbonation has been reduced greatly by reducing water/cement ratio. It is observed at low values of water/cement ratio the depth of carbonation is low but there seems a continuous increase in depth of carbonation at higher values of water/cement ratios. Some of the researchers have concluded that carbonation decreases with decrease in water/cement ratio in some tropical arid regions.

4.2 Effect of water/binder ratio:
It has been found that water/binder ratio has a significant effect on depth of carbonation. Water/binder ratio plays a vital role in defining the relationship between compressive strength and permeability of concrete. Water/binder ratio at lower levels does not influence carbonation depth but higher ratios influence other properties [9]. Carbonation depth increases with increase in water/binder ratio [10].
Hence it was found that carbonation depth is directly proportional to water/binder ratio[11]. Slump values also had a tremendous impact on carbonation depth, increase in slump increases depth of carbonation. Fly Ash (FA) has also had a greater effect on carbonation depth and strength of concrete. High levels of water/binder ratio with fly ash have a substantial effect on all the properties.

4.3 Effect of Admixtures:
As it was observed from the previous studies strength of concrete reduces with increased depth of carbonation. Many of the industrial by-products like GGBS, SF, FA, Metakaolin etc are increasingly used in constructions as they contribute to the improvement of various other properties [12]. They improve strength of concrete and results in reduction of carbonation depth, replacement of cement also facilitate some benefits like reduction of shrinkage, expansion etc. Some of the studies revealed that lower levels of replacement i.e. 0-30% replacements observed beneficial rafter than higher replacements like beyond 60%. The compressive strength is improved by 30% replacement of FA. It was identified from previous studies the depth of carbonation of High Volume Fly Ash (HVFA) with 90 days curing period is nearly equal to plain concrete. It is true that FA increases carbonation depth, but with HVFA with curing period 90 days reduces the carbonates depth[13].

4.3.1 Ground granulated blast furnace slag (GGBS):
The strength of the concrete and porosity chiefly depends on water/cement ratio and supplementary cementitious materials like GGBS, Silica fume, etc used [11,9]. More particularly GGBS and Silica fume used as cement replacement materials in concrete [14]. GGBS and Silica fume form less porous and offer good binding strength in concrete. The depth of carbonation depends on strength and porosity of the concrete [5].

4.3.2 Silica fume (SF):
Silica fume is very effective in reducing permeability of cement in paste form and in concrete it also reduces porosity [15]. It plays very significant role in the process of development of high strength and high performance concrete. The concrete made of SF will have very good bond strength and offers resistance to abrasion [16]. The compressive strength will also be improved with the addition SF. The increase in compressive strength is also accompanied by increase in carbonation depth. When SF reacts with calcium hydroxide the pH value of pore solution is reduced and it indicates the initiation of carbonation process [17]. The previous studies have revealed the fact that beyond 10% replacement of silica fume will show its affect on carbonation and is also responsible for corrosion [18].

4.4 Effect of porosity:

As per previous studies increase in porosity results in increasing depth of carbonation It means that when water content is increased porosity also increased which results in increase of depth of carbonation [15]. When water content is reduced porosity is also reduced this results in reduction of depth of carbonation. Further it was observed that carbonation depth is increased in the environment where CO_2 presence is more [19].

4.5 Effect of cover:
The depth of carbonation is reduced primarily when the reinforcement is provided with substantial cover as per design specifications. Protected surfaces resist the diffusion of CO_2 thereby reduce the effect of carbonation [20]. The effect of carbonation is more on the non protective areas rather than protected areas. It was proved by the earlier studies that plastering helps to the great extent in reducing carbonation affect. Previous studies have shown that both amount of carbonation and depth of carbonation are drastically reduced when proper plastering is provided [10]. Application of surface coating reduces carbonation levels to the maximum extent. It was suggested by previous studies that the cover thickness up to 40mm would be very effective in reducing the effect of carbonation [10]. Double layer protective coatings were found very effective in preventing the diffusion of $CO_{2.}$ Application of surface coatings is a fundamental preventive and remedial measure to reduce the intensity of carbonation. Earlier researchers have found and suggested that a minimum of 25mm cover thickness is to be provided for effective prevention of carbonation. Replacement of FA is also found to be effective in reducing the intensity of carbonation [21].

4.6 Evaluation of Depth of Carbonation:
The phenolphthalein indicator method is a very popular method for measuring the depth of carbonation of concrete which involves spraying of solution on the concrete surface shows a change in color depending on the pH factor [22]. The measurement was carried out immediately after the broken surface was exposed and after applying phenolphthalein indicator, which lose their colour, are to be judged as carbonated [23]. Hand microscope is also a popular method which is being used to measure the depth of carbonation [24]. It is necessary to record the average depth and maximum depth of penetration [8]. The depth of carbonation is measured from the surface of the sample.

4.7 Effect of curing period:
Curing of concrete has an important contribution that influences many properties of concrete. It shows direct impact on strength and service life of the concrete [10]. Heat of hydration is an exothermic reaction which takes place in concrete and liberates heat energy. Due to this process cracks are developed in structures subsequently and strength of the concrete is decreased [25,26]. Proper curing is required to prevent this unwanted effect on concrete [27,28]. It is observed from the previous studies that the strength of the concrete is increased with curing periods. Increase in curing period results in reduction of permeability [29]. Increase in curing period increases strength of concrete and decreases depth of carbonation. The addition of mineral admixtures like GGBS and SF reduces the permeability and in turn the depth of carbonation is decreased [30]. Hence it was concluded that curing period has direct impact on permeability, strength of concrete and depth of carbonation.

4.8 Effect of compressive strength:
The strength of concrete depends on various factors such as mix proportion of the concrete, water/cement ratio, quantity of cement content, method and degree of compaction, type of curing and period of curing. From the earlier studies it was proved that the strength of concrete has direct influence on carbonation. Increase in compressive strength reduces depth of carbonation [15]. It is observed that SCC offers very

good resistance to porosity rather than normally vibrated concrete (NVC). Depth of carbonation is also decreased in case of self compacting concrete. SCC made of GGBS and SF offers good resistance to the carbonation effect. SCC is proved as the best concrete which reduces the depth of carbonation to the maximum levels. Mineral admixtures like GGBS and SF reduce porosity and increase strength of concrete and it leads to the reduction of carbonation effect [31].

4.9 Effect of grade of concrete:
Previous studies revealed the fact that the extent of carbonation is limited to surface layers of concrete. Increase in depth of concrete is also very slow and it may not exceed 20 mm in 50 years, whereas in porous concrete the depth of carbonation may be increased to 100 mm in 50 years since dense concrete prevent the diffusion of CO_2 effectively rather than porous concrete[32,33].

Table 1: Depth of carbonation

Age in years	**Depth of Carbonation (mm)**	
	M_{20}	**M_{40}**
2	**5.0**	**0.5**
5	**8.0**	**1.0**
10	**12.0**	**2.0**
50	**25.0**	**4.0**

5. Conclusions:

General conclusions are drawn from the extensive review of literature on carbonation on concrete:

1. The influence of water/cement ratio is very much significant on the strength of the concrete since the strength of the concrete depends on water/cement ratio. The depth of carbonation depends on water/cement ratio higher water/cement ratio contributes to higher carbonation depth.
2. Increase in curing period reduces the carbonation depth. The resistant power of the concrete to carbonation is increased with sufficient and substantial curing periods.
3. To improve the resisting power of the plain concrete at least 7 days curing is mandatory.
4. Additions of admixtures modifies the pore structure of the concrete and reduce the porosity.
5. If porosity increases carbonation depth also increases hence a linear relationship exist between accelerated carbonation and porosity.
6. Addition of SCMs like GGBS and SF reduce the porosity of concrete and reduce the depth of carbonation.
7. The application of surface coatings and provision of proper cover considerably reduces the rate of carbonation. The service life of the concrete can be enhanced.
8. The compressive strength also depends on water/binder ratio and mineral admixtures both higher and lower water/binder ratio affects the properties of concrete.
9. The use of SCC has been proved to be the best to improve the durability characteristic of concrete in relation to the carbonation of concrete.

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