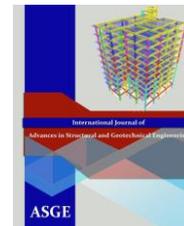




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## Prevention of Carbonation of RC Structures (Critical Review)

Kamal G. Sharobim<sup>1</sup>, Mohamed I. Fouad<sup>2</sup>

<sup>1</sup>Professor, Faculty of Engineering, Suez Canal University, Egypt  
E-mail: [k\\_sharobim@hotmail.com](mailto:k_sharobim@hotmail.com)

<sup>2</sup>Postgraduate Student, Faculty of Engineering, Suez Canal University, Egypt  
E-mail: [eng.mohamed.ibrahim12@gmail.com](mailto:eng.mohamed.ibrahim12@gmail.com)

### ABSTRACT

Carbonation of concrete is traditionally defined as the chemical reaction between atmospheric carbon dioxide and the products of cement hydration, particularly calcium hydroxide. This phenomenon will reduce an alkaline pH of concrete of approximately 12.6, whereas the carbonated concrete is more neutral with a pH value which may decrease to 8.3. The degradation mechanism which threatens the reinforcement is corrosion, but the alkaline environment will safeguard the protective film as the pH of the surrounding solution remains within certain limits. Carbonation is a threat as it lowers pH and so may bring the steel within the corrosion boundary. Thus, carbonation may be a factor in the initiation of corrosion. Carbonation itself does not attack the reinforcement but it may contribute significantly to a lowering of the defense mechanism inherent in the synergetic relationship between steel reinforcement and concrete. This paper presents literature review of different methods which can be used to prevent the carbonation of concrete of existing structures and new one. The prevention methods include the use of protective coatings, anti-carbonation coatings and admixtures. From the literature review, it can be concluded that carbonation of concrete can be eliminated and prevented by using some anti-carbonation coatings. Also, using of protective coatings and/or cement plastering will reduce the carbonation depth. Moreover, concrete quality and good construction practices are governing factors on the rate of carbonation. The treatment of existing carbonated reinforced concrete structures is discussed.

**Keywords:** Carbonation of Concrete, Cracks, Prevention, Anti-carbonation, Prevention Coating.

### INTRODUCTION

Carbon dioxide (CO<sub>2</sub>) forms about 0.03 percent of the atmosphere and reacts with calcium hydroxide and to lesser extent with the calcium silicate hydrates to form calcium carbonate (CaCO<sub>3</sub>). Lea [1], among other, notes that the reaction only takes place in the presence of moisture. This prompts the description that carbon dioxide penetrates as carbonic acid in the free water of concrete. Only a small amount of the carbon dioxide reacts with the water to form carbonic acid. As little as 0.1% is thought to dissociate into hydrogen and carbonate ions, the remainder is present as carbon dioxide molecules unchanged in solution [2]. Meyers [3] has shown that carbonation of other hydroxides and hydrated compounds is possible but probably plays a small part in the overall process. Research concerning the effects of carbon dioxide on cementitious systems is proceeding at an unprecedented rate at present. This may be gauged by the number of published papers on the topic per decade over the last one hundred years (from 1880 to 1980) was presented by Mark Richardson [4], which includes a total of 706 papers. However, during the last 10 years, research in the field of carbonation of concrete has increased dramatically and reaching about 770 papers during 2010-2019 only [5]. Japanese researchers opened the debate on the effect of carbon dioxide regarding the durability of

reinforced concrete. Hamada recalls that exposure tests were initiated in 1907 by Riki Sano who measured twenty years of carbonation, then theory and formula were established by Shozo Uchida and Minoru Hamada in 1928 [6]. During the following decade exposure tests were carried out in Japan and Taiwan by Hamada, Ohno, Nakamura, Kishitani, Nishi, and Koh [7]. Early conclusions were that carbonation was influenced by the degree of compaction, climate, voids, water-cement ratio, and amount of filler in blended cement. This paper will discuss the effect of some important factors affecting the rate of carbonation and the methods which can be used to eliminate and prevent the carbonation of concrete, and how to treat the carbonated RC concrete.

**FACTORS AFFECTING RATE OF CARBONATION**

In the consideration of how to minimize the detrimental effects of carbonation, some knowledge is required of influencing factors and their relative importance. Some factors can be considered as external factors such as ambient relative humidity, carbon dioxide concentration and surface protection. Other factors can be considered as internal factors such as concrete grade, permeability of concrete and water cement ratio [8,9]. Other factors such as time of exposure and orientation of building are also important. Kishitani et al. [10] presented many of the factors influencing carbonation of concrete in their series "Durability of Concrete Structures Carbonation". Fig. 1 shows the summary of these factors. Also, some influences identified by Mark Richardson

[4] through field observation and literature reference are presented in his text "Carbonation of concrete" from these investigations, it was noticed that the most important factors are climate and exposure conditions, w/c ratio, curing time, permeability and diffusivity of concrete, surface concrete quality and inclination, age of concrete, strength, cracking, and carbon dioxide concentration.

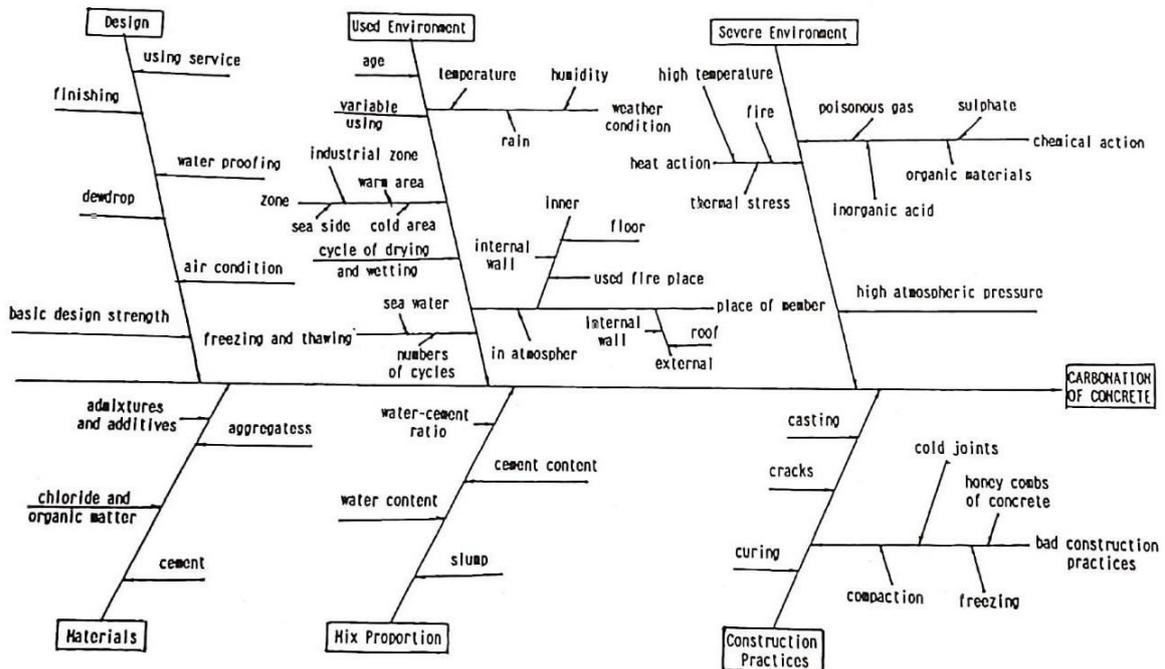


Fig.1 Summary of factors influence carbonation identified by Mark Richardson [4]

**Climate and Exposure Conditions**

Carbonation is decisively affected by the subsequent delivery of CO<sub>2</sub>, which diminishes as the moisture content increases. Many research [10-13] indicate that the carbonation rate is increased when it is taken place in the open air at a relative humidity (RH) between 50-70%. In

addition, increased CO<sub>2</sub> contents, as might occur for example in garages, smokestacks, or road underpasses, contribute to accelerated carbonation. The air temperature is also, have a direct effect on rate of carbonation of concrete. The rate of carbonation is increase with increasing the temperature. The influences of temperature (10 °C, 20 °C and 30 °C) on concrete carbonation were studied by Ying Chen et al. [9] using an accelerated carbonation test. The concrete was exposed to different CO<sub>2</sub> concentration for 28 days at different temperatures. Fig. 2 shows the changes of carbonation depth of concrete, after 28 days under 70% relative humidity. The carbonation depths are increased with increasing the temperature and concentration of CO<sub>2</sub> concentration. Also, the depth of carbonation is affected by RH as shown in Fig.3. The higher depth of carbonation was obtained at RH between 65-75%.

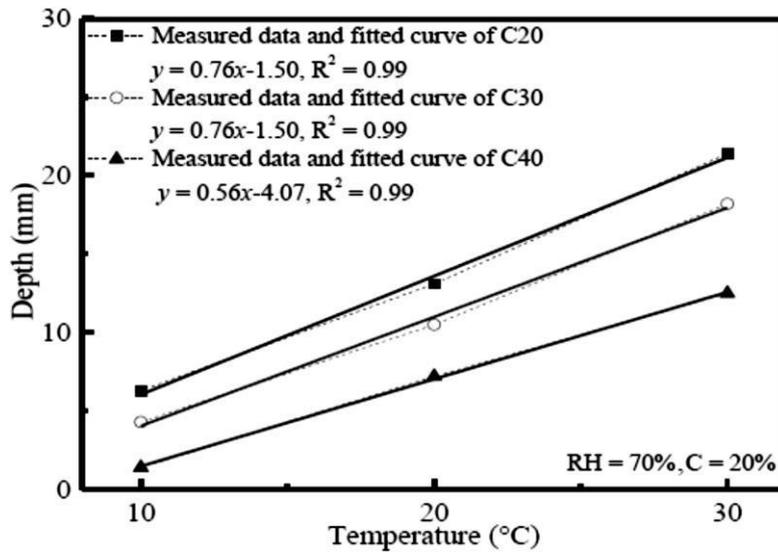


Fig. 2 Relationship between temperature and carbonation depth of concrete [9]

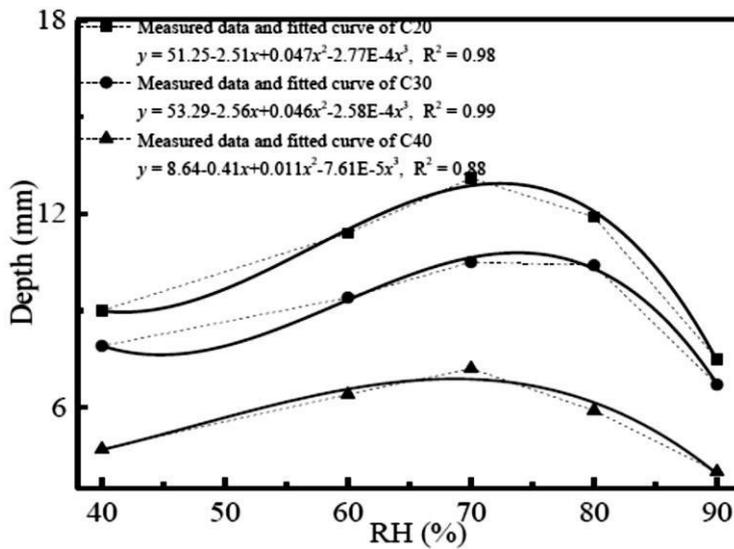
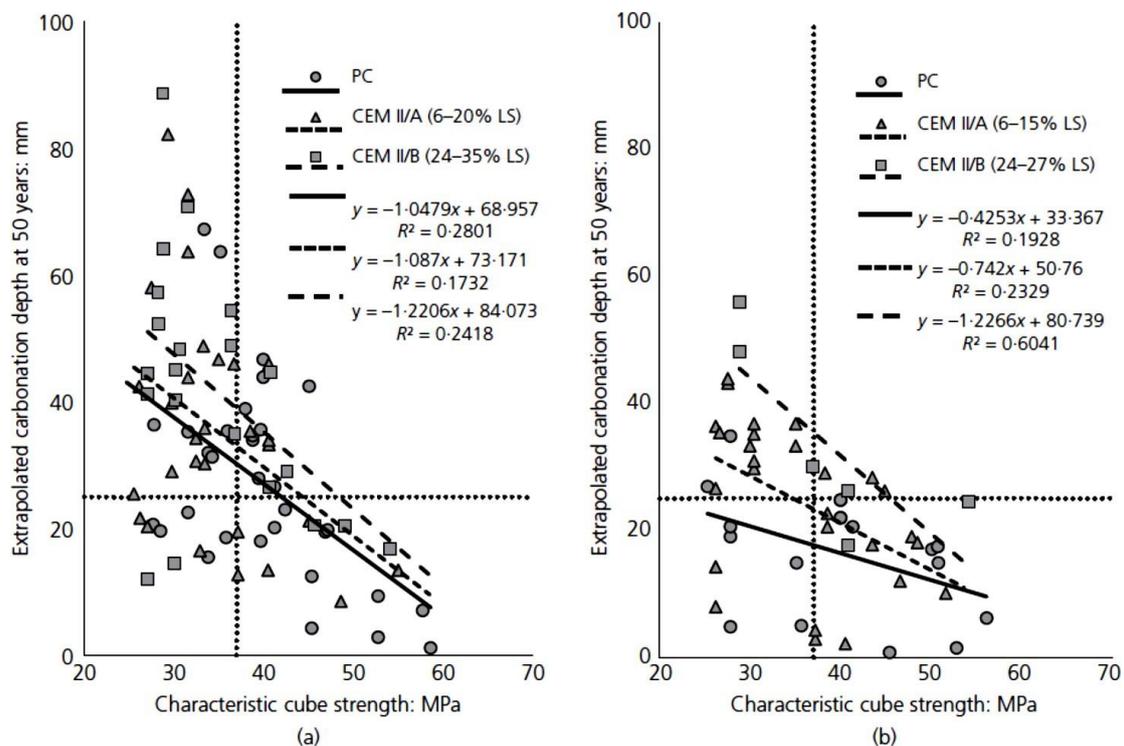


Fig. 3 Relation between RH and carbonation depth of concrete [9]

### Concrete Quality and Compressive Strength

Concrete quality is one of the most important factors influencing carbonation. There are two major factors, namely the density of the hardened cement pastes and the curing method applied to the concrete, and the latter affecting the density of the layers near to the surface decisively. Many research [9-13] proved that carbonation depth is affected with concrete compressive strengths. The similar results are obtained by Khalil and Anwar [14] who studied carbonation of ternary cementitious concrete systems containing fly ash and silica fume and they found that the carbonation process is inversely proportional to the concrete strength regardless of its cementitious content. Effect of concrete compressive strength as an indicator of the quality of concrete on carbonation rate has studied by Sharobim and Tazawa [15]. A link between the compressive strength of concrete and its carbonation performance has been noted by Venkat et al., [13]. Fig. 4 shows the relation between depth of carbonation and compressive strength of different types of cement after 50-60 years of exposure indoor and outdoor. The depth of carbonation was found to be closely proportional to the compressive strength at the time of carbonation.



**Fig. 4** The relation between carbonation depth and characteristic compressive strength after 50 years of exposure; (a) outdoor & (b) indoor [13]

### Influence of W/C Ratio

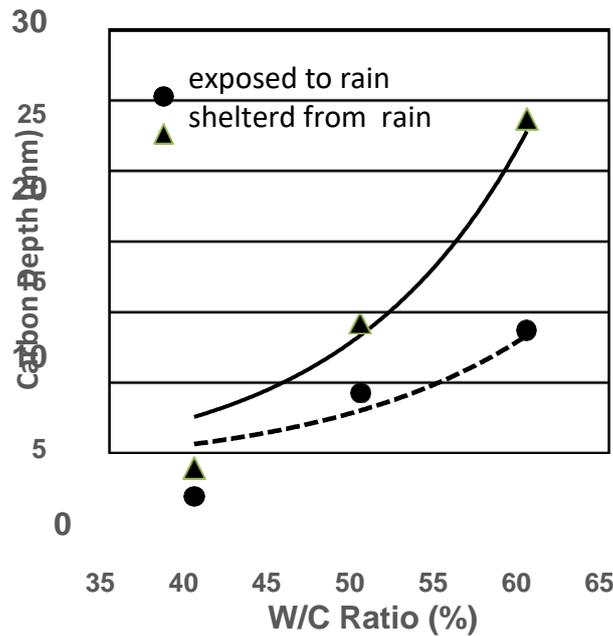
The effect of W/C ratio on carbonation has received much attention in many publications [12-14]. Sharobim and Tazawa [15] said that the water-cement ratio was an even more critical factor in the carbonation context than the cement content. In many studies the importance of curing is emphasized, showing that curing regimes became more onerous with increasing water-cement ratio. The significance of impact of w/b and early curing time on depth of carbonation was confirmed by Czarnecki et al. [16]. In all tested concretes, regardless of the type of cement, an increase of w/b and a decrease of early curing time leads to a higher value of depth of carbonation. Comparison of depths of carbonation for different W/C ratios have been presented by number of authors [6, 17-22] and those obtained by Sharobim [12], these are tabulated in Table (1). The experimental results show that for OPC when W/C ratio is increased from 0.35 to

0.5, carbonation depth is increased by 100% however when W/C ratio is increased to 0.6, carbonation depth is increased by 218%.

**Table (1)** Comparative effect of water-cement ration carbonation[12].

Source	Water-Cement Ratio	Relative Carbonation Values
Gille [17]	0.50, 0.65, 0.78, 0.82, 1.29	1: 0.5, 1.3, 1.4, 3.8
Hamada [6]	0.50, 0.65, 0.75	1: 2, 5
Kasai [18]	0.50, 0.65	1: 2.5
Matthews[19]	0.55, 0.85	1: 2
Mayer [20]	0.50, 0.80	1: 2
Nischer [21]	0.40, 0.50, 0.70	1: 2, 4
Waiz [22]	0.45, 0.60, 0.80	1: 2.5, 5
Sharobim [12]	0.35, 0.40, 0.50, 0.60, 0.70	1: 1.7, 2.0, 5.4, 9.6

The effect of water-cement ratio of concrete exposed to rain or sheltered from rain for 10 years are presented by Sharobim [15] and shown in Fig. 5. As discussed before, W/C ratio has great effect on carbonation, and carbonation depths can be eliminated by reducing the W/C ratio. It can be noticed from this figure that exposure to rain can reduce the carbonation depth, because ingress of CO<sub>2</sub> into saturated concrete will be reduced. The rate of carbonation was found to be increasing with increase in w/c ratio. Concrete having lower w/c ratios were found to be more carbonation resistant even with smaller curing periods. Adler k.k, [23], carried out similar study and he found that the rate of carbonation in sheltered concrete is higher than on exposed, frequently rain soaked concrete after 10 years of exposure.

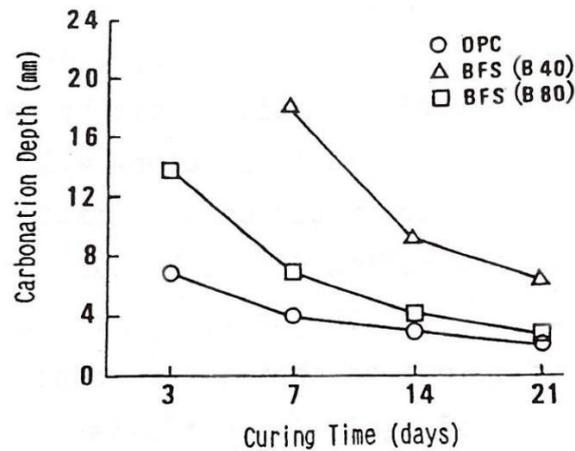


**Fig. 5** The relation between carbonation depth and W/C ratio of concrete exposed to rain or sheltered from rain for 10 years [15].

**Influence of Curing Time**

The curing of concrete is one of the most important factors affecting the quality of concrete. The influence of initial curing time on depth of carbonation was studied by many researchers [12-16]. Experimental study was carried out by Sharobim [12] and the results are shown in Fig. 6. It was found that a reduction of more than 70% in carbonation depth for mortar specimens cured in

water for 7 days compared with those cured for 3 days. More reduction in depth of carbonation was obtained for those cured for 14 and 21 days. It is possible to deduct that the depth of carbonation can be reduced by increasing curing time mainly due to the development of dense structure. Also, the effect of curing time is more significant on those specimens which made from BFS than those made from OPC. This possibly related to the promotion of long-term reactions associated with blended cement. The effect of curing time on carbonation depth is clearer for blended cement and that contains blast furnace slag than that of Ordinary Portland Cement. Therefore, carbonation depth can be eliminated with increasing the curing time specially for concrete contains blended cement. Similar results were obtained by Khalil and Anwar. [14].



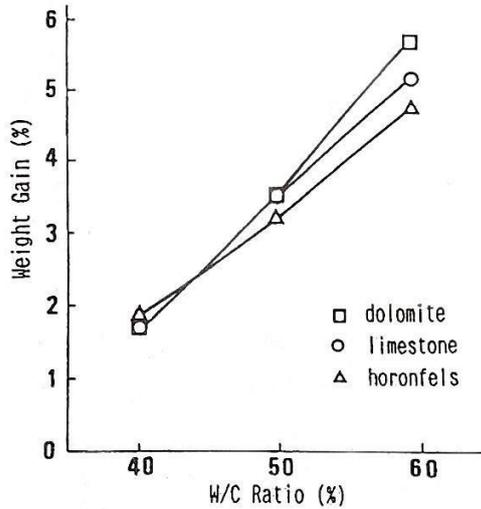
**Fig. 6** The effect of curing time on carbonation depth for different cement type [12]

### Influence of Type of aggregates

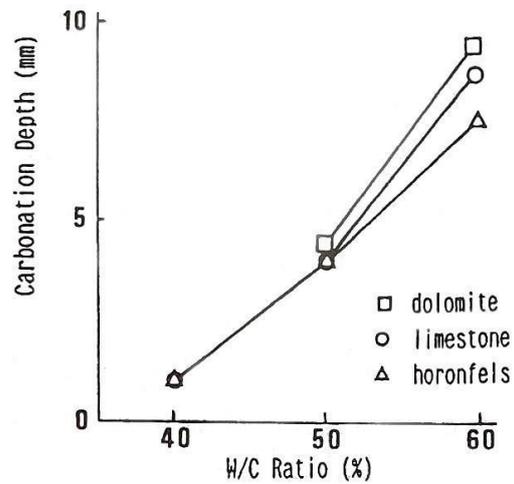
The influence of three types of crushed aggregates including limestone, hornfels and dolomite on carbonation of mortar specimens were investigated [24]. The influence of type of aggregate on the relation between w/c ratio and weight gain after accelerating carbonation depth is shown in Fig.7. The weight gain of mortar samples made from dolomite are higher than those made from limestone or hornfels. The influence of type of aggregate on the relation between w/c ratio and depth of carbonation are shown in Fig. 8. At w/c ratio equal 40 & 50%, it was found that there is no difference between carbonation depth of mortars prepared from hornfels and limestone, but at w/c ratio equal 60% limestone mortar showed greater carbonation depth than hornfels mortar. Moreover, dolomite mortar showed the greatest carbonation depths at w/c ratio 50% and 60%. Mortars made from limestone had greater carbonation depths than those made from hornfels may be due to the reaction of calcium compound existing in limestone with water and carbon dioxide.

### Effect of Type and Content of Cement

Well hydrated ordinary Portland cements have a calcium hydroxide content varying from 15 to 30 % by weight of unhydrated cement. Other types of cements have various amounts of hydroxide bound to siliceous materials and hence their basicity would be different. This includes Portland blast furnace and Portland pozzolanic cements. An experimental result obtained by Sharobim [12] using an accelerated carbonation test on mortar samples, shows that the carbonation depths of mortar contained blast furnace slag and silica fume were higher than that of OPC at the same mix proportion (same cementitious material), same water and same sand contents and curing time.



**Fig. 7** Effect of type of aggregates on depth weight gain of mortar specimens [24]



**Fig. 8** Effect of type of aggregates on of carbonation of mortar specimens [24]

Table (2) shows the rate of carbonation of different kinds of cements including four types of BFSC and Portland pozzualanic cement. The rate of carbonation BFSC was between 1.6 and 6 times of that of OPC depending on type BFS. The depth of carbonation of pozzolanic cement (20 % silica fume) was twice that of OPC at 7 days curing time. On the other hand, the depths of carbonation of mortar made from HESPC were smaller than those made from OPC. The rate of carbonation was decreased with the time and their values of specimens which were made from HESPC were about 25 to 35 % of those made from OPC with the same mix proportion. High early strength cement is characterized by increased fineness or a higher C3S content. Thus, the hydration of HESPC is quicker, the porosity is smaller and compressive strength is higher than those of OPC. Also, it may be noted that the production of larger amount of calcium hydroxide through hydration of C3S and, to lesser extent, be C2S, so that the higher concentration of calcium hydroxide would be expected through the hydration of HESPC than that of OPC.

**Table (2)** The rate of carbonation of mortar made from different kind of cement [12]

Type of Cement	Carbonation depth (mm)	Rate of Carbonation (mm/day)	Ratio to that of OPC
OPC	4.0	1.3	1.0
HESPC	1.2	0.4	0.3
40% B25	24.0	8.0	6.0
40% B40	14.0	4.7	3.5
40% B50	13.4	4.5	3.3
40% B80	6.4	2.1	1.6
20% SilicaFume	8.0	2.7	2.0

In these experiments, it was found that the carbonation depths of mortar made from slag or silica fume were higher than those made from OPC as shown in Fig. 9, since a calcium hydroxide is also consumed by the reaction of silica fume or slag. This figure shows the relation between carbonation depth and reacted Ca(OH)<sub>2</sub> which was calculated from the weight gain of specimens after carbonation test. Mortars contain OPC has the lower carbonation depths. However, replacement 40% of OPC by Blast Furnace Slag (B55) has the higher carbonation depths.

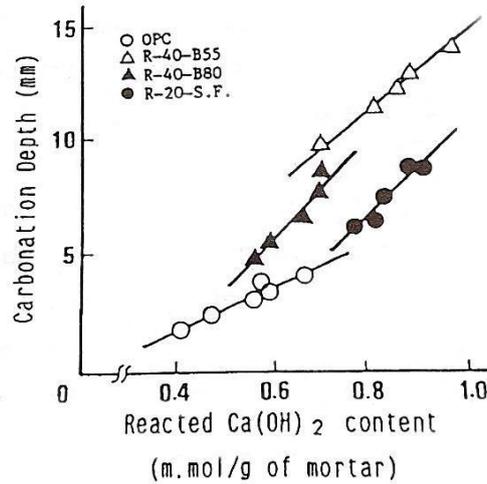


Fig. 9 Effect of type of cement on the relation between reacted Ca(OH)<sub>2</sub> content and depth of carbonation [12]

**Effect of Cracks**

Japanese Concrete Institute (JCI) research committee on concrete cracking mentioned that even if all cover concrete is not carbonated the presence wide crack can develop the carbonation around reinforcing steel [25]. The author [26] studied the relation between the carbonation depth at the crack position of cement mortar made from different type of cement. The results are presented in Figs.10 and 11, where the relation between carbonation depth and crack width is shown in Fig.10, and relation between depth of carbonation and crack depth is shown in Fig.11. The mean values of carbonation depths are between 30 mm and 80 mm depending on the crack widths. There is a remarkable increase with increasing the crack width up to 0.15 mm, but at crack width more than 0.15 mm, the effect of crack width on carbonation depth is somewhat decreased. But there is no change in these values with different kinds of mortars (i.e. there is no effect of type of cement or curing time on the relation between crack width and carbonation depth). Indeed, the carbonation of mortar at the crack is not dependent upon mortar quality, but it is mostly depending on crack widths and crack depths.

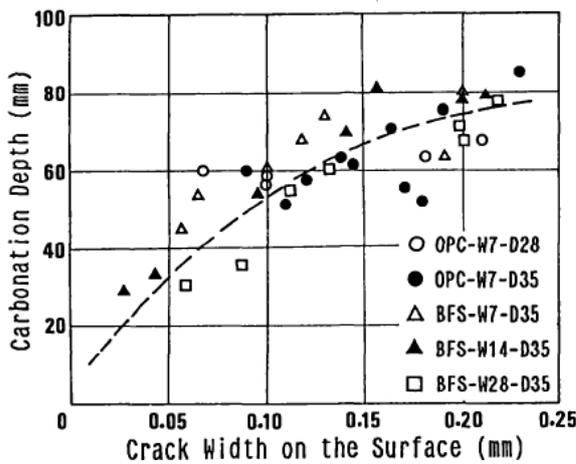


Fig. 10 The relation between crack width depth and carbonation depth [26]

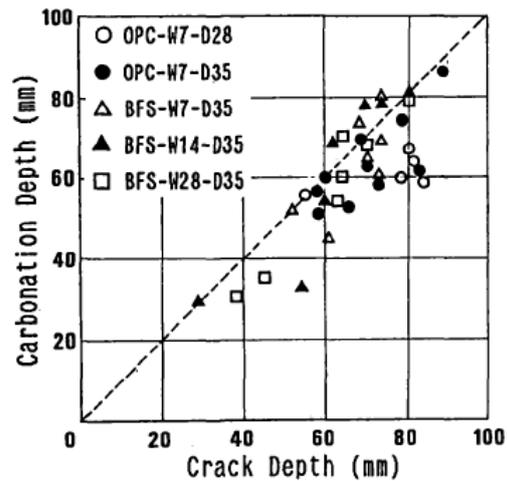


Fig. 11 The relation between crack and carbonation depth [26]

### Carbonation of Concrete Contains Chloride Ions

After 10 years of exposure of concrete contain chloride ions in their mixes, the chloride content at different distances from surfaced was measured [15]. The chloride concentrations in concrete made with W/C ratio 0.40 and 0.65 are shown in Fig. 12. It was found that the maximum values of chloride ions were located at depths of 2 and 3 cm for concrete with W/C ratio 0.40 and 0.65 respectively. However, the chloride concentration on the surface was decreased due to moving of chloride ions to inside the specimens. The reason was that the carbonation pushes the chloride ions to inside where the chloride concentration in the carbonated zone was decreased and chloride concentration in non-carbonated part was increased. Some cases of this observation have been reported by Kobayashi and Kawai [27].

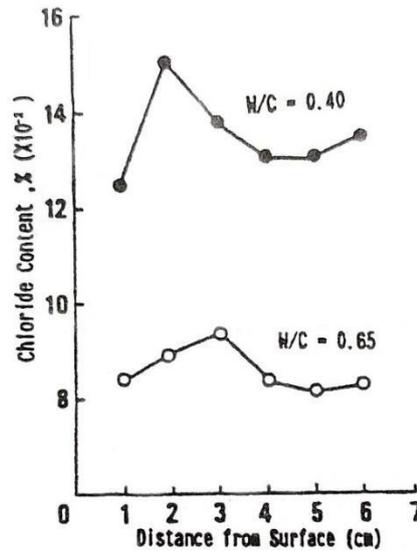


Fig. 12 Chloride Concentration in Concrete after 10 years exposure [15]

### CRBONATION PREVENTION

Carbonation cannot be avoided because CO<sub>2</sub> exists in the atmosphere, the penetration path of this harmful gas inside the concrete is the porosity of the cover concrete. However, as discussed before, carbonation can be controlled by improving the quality of concrete and increasing of its compressive strength through reducing W/C ratio and increasing the curing time. The effect of using admixtures, protective coating and anti-carbonation coating will be discussed in the following paragraphs.

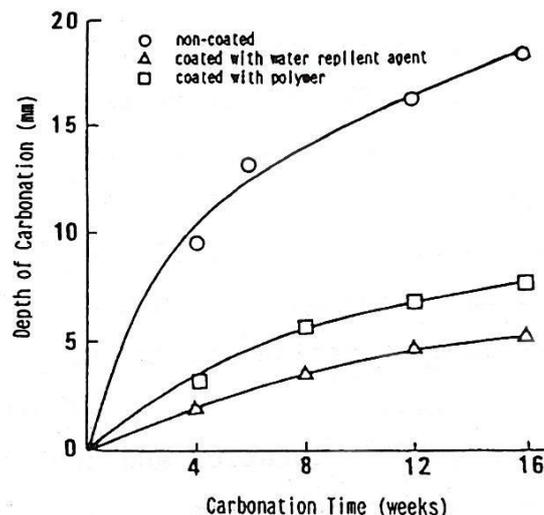
#### Use of Admixture

It is well known that using of any kind of High Range Water Reducing Admixtures (HWRA) will reduce the water cement ratio and subsequently increase the compressive strength of concrete. This will have great effect on increasing the carbonation resistance of concrete as discussed before. Jie Cui [28] study the effect of two types of concrete admixtures: naphthalene series water reducer (FDN) and polycarboxylate water reducer (CPA). He found that Polycarboxylate water reducer was better than naphthalene series water reducer on improving the ability of anti-carbonation of concrete. The effect of CPA on the morphology of cement hydration products made the concrete structure more compact and the mechanical properties, especially the compressive strength was greatly improved, the permeability of CO<sub>2</sub> was decreased, and the depth of carbonation was reduced accordingly. The third generation of high-performance polycarboxylate water reduce CPA represents the development direction of concrete admixture, is multi-functional concrete admixture combined large water reduction can improve the ability of concrete carbonation resistance, frost resistance, chloride ion erosion resistance and steel protective in different degree.

### Use of Protective Coatings

Preventing and slowing down carbonation in concrete is a simple method by reducing the ingress of CO<sub>2</sub> and moisture into concrete. Protective coatings of the concrete surface against aggressive environments are constantly evolving. Given their diversity, the effectiveness of the latter becomes an important criterion for making the right among of a large, commercialized variety, therefore, in recent years, several researchers [23, 29, 30, 31] have started research in this area and have proposed solutions to protect the surface exterior of concrete with coatings, such as organic, inorganic, mortars and paints against environmental aggressions. Among these aggressions, comes first the concrete carbonation, which is a natural phenomenon which compromises the durability of reinforced concrete structures by causing the corrosion of the reinforcements. Two types of surface coatings were tested by Sharobim [12]. The first is water repellent agent, while the second is acrylic polymer type. The results show that these coatings are absorbed in the outer skin of specimens and can slow down the rate of carbonation by acting as diffusion barrier for carbon dioxide to penetrate. Fig.13 shows the influence of type of coating on the relation between carbonation depth and carbonation time during accelerated test. The depth of carbonation of coated specimens was less than that of non-coated specimens by 30% to 60% depending on type of coating and exposure time. Also, it was found that water repellent agent had better results on carbonation control than polymer coatings. In another study, he investigated six types of surface coatings [29], he found that tar pitch, and pitch extended epoxy resin coatings completely stop the diffusion of CO<sub>2</sub> gas and no carbonation areas are observed after 20 weeks of exposure to an accelerated test with 5% CO<sub>2</sub>. However, cementitious waterproofing coatings cannot be retarding the carbonation of concrete.

Zafeiropoulou et al. [30] study nine organic coating systems regarding their protection level against corrosion by chloride ions and carbonation. They found that the PVA copolymer paint presented low resistance against water and CO<sub>2</sub> penetration. Acrylic paints and especially Acr2 exhibited satisfying protection level against chloride ions corrosion. Their behavior against carbonation was the best among all coatings. Adler K.K [23] said that concrete can be protected against carbonation either by protective coatings such as high quality emulsion paints or polymer modified cementitious slurries. The permeability to carbon dioxide, as measured in the laboratory, correlates very well with the field test. The carbonation rate of concrete can also be reduced by



**Fig. 13** The influence of type of coating on relation between depth and time of carbonation [12]

the incorporation of suitable film forming thermoplastic polymers in the mortar, provided that the porosity of the mortar is not too high. The results indicate further that the curve of carbonation shows little progression with increasing exposure time, and the rate of carbonation in sheltered concrete is higher than on exposed frequently rain soaked concrete.

### Use of Anti-Carbonation Coatings

Nowadays a large number of products for concrete protection are available on the market and the efficacy of these materials still needs more research. Carnerio, A et. al. [31], in their study aimed to evaluate the efficiency of certain surface treatments (such as polyurethane coating, hydrophobic agents and cementitious crystalline) applied on concrete under chloride ions and carbon dioxide exposure. The results indicated that polyurethane coating is efficient against the ingress of aggressive agents. An increase in cement consumption also provided significant reduction in the penetration depths among untreated samples. Zafeiropoulou et al. [32], examined the behavior of three major categories of organic coatings which are applied on the surface of concrete structures and specifically conventional, high performance and nanotechnology paint systems. The comparison is achieved in the means of anticorrosion properties under the presence of chloride ions and carbonation resistance. The evaluation methods included electrochemical measurements in order to assess corrosion properties and the determination of steel's mass loss after the end of the experimental procedure. Carbonation depth was measured using phenolphthalein as indicator after accelerated and physical exposure, and they found that high performance coatings did not carbonate after 15 months of exposure whereas conventional coatings and Nano-coatings were carbonated 1 mm or 2 mm. Pantazopoulou et al. [33] conclude that Polyurethane and epoxy coatings present very low water-vapor transmission rate and liquid water permeability. The two acrylic emulsions present fairly good behavior towards moisture. Finally, the nanotechnology coating presents an improved behavior compared to all other coatings systems regarding water-vapor transmission rate and liquid water permeability. Epoxy and polyurethane coatings provide the best protection against carbonation, as well as aqueous dispersions which offer a satisfying level of protection, whereas the nanotechnology coating provides a low and negligible protection rate. Different types of surface coatings were tested by Marcos da Silva [34] as shown in Table (3). The tested coatings act as a CO<sub>2</sub> diffusion barrier, but they can also act as a barrier to water vapor. The presence of a coating besides reducing the CO<sub>2</sub> ingress, it can also affect the specimen moisture.

**Table (3)** Characteristics of the tested surface coatings [34]

Coatings	Sikagard® 660 ES (S660)	Sikagard® 670 W (S670)	Sikagard® 680-ES Betoncolor (S680)	Dyrup Dyrurway ref. 5780 (Dyrup)
Base	Solvent acrylic resin dispersion	Solvent acrylic resin dispersion	Solvent acrylic resin dispersion	Aqueous acrylic resin dispersion
CO <sub>2</sub> diffusion resistance	120 μm ~ 290 m μ(CO <sub>2</sub> ) = 24,2 . 10 <sup>5</sup>	187 μm ~ 88 m μ(CO <sub>2</sub> ) = 4,7 . 10 <sup>5</sup>	130 μm = 420 m μ(CO <sub>2</sub> ) = 32,3 . 10 <sup>5</sup>	-
Water vapor diffusion resistance	120 μm ~ 2,8 m μ (H <sub>2</sub> O) = 23333	s <sub>p</sub> (H <sub>2</sub> O) = 0,75 m μ (H <sub>2</sub> O) = 4200	130 μm = 2,2 m μ (H <sub>2</sub> O) = 16923	-
Liquid water permeability	W = 0,003 kg/(m <sup>2</sup> .h <sup>1/2</sup> )	Impemeable to rain	Resistant to weather conditions	-

Suresh C. Pattanaik, [35] study different protective coating and found that most of these coating fills surface pores and bridges fine cracks & form a barrier to the movement of carbon dioxide. It is measured by carbon dioxide diffusion, which is defined as ability of the coating to resist the ingress of carbon dioxide and to stop the carbonation of the concrete. He concludes that anti-carbonation coating helps to provide a protective barrier to the concrete structures not only for carbonation but also to prevent the ingress of chlorides and moistures. Acrylic, silicone enhanced, epoxy and polyurethane are most suitable for such coatings. Considering extreme environment all the RC structures should be protected with an aliphatic acrylic coating to increase their service lives. Ahmed Merch, [36] in his recently paper (2020) review of published

works on the effectiveness of anti-carbonation coatings for the protection of reinforced concrete structures against concrete carbonation and made classification for these coatings according to the type and the selection criteria of these coatings.

## TREATMENT OF CARBONATED RC STRUCTURES

Carbonation causes concrete acidification that brings in the loss of the steel rebar's passive layer, which in turn will allow initiation of an active corrosion process. A nondestructive technique to revert this condition is the electrochemical realkalization (ER) that consists in applying a direct current between the steel bars and an external auxiliary electrode placed on concrete surface with the aim of restoring the alkalinity loss. During treatment, the electrolyte, which is sodium carbonate solution, is transported into the carbonated concrete as symbolized by the penetrating front. Lopez et al. [37] studied the use of a conductive mortar as anode in the electrochemical realkalization of concrete. Carbonated reinforced concrete specimens with a water/cement ratio of 0.65 were evaluated. ER was applied by 5 days period with a current density of 2 A/m<sup>2</sup> and using as anode a layer of modified mortar (add 25% graphite powder by cement weight) saturated with a 1M Na<sub>2</sub>CO<sub>3</sub> solution. The pH in the concrete was determined by the phenolphthalein test and potentiometric titration. After the ER treatment the pH value of the carbonated concrete samples had increased from 8 to 11.95. The long-term effects of electrochemical realkalization on carbonated reinforced concrete with a W/C ratio of 0.65 were studied by ZHU et al. [38]. They concluded that the effects of realkalization have disappeared after seven years, and the long-term effects of this technique were unsatisfactory. The protection provided by the realkalization treatment was temporary, and a simple sodium carbonate solution or alkaline solution was not sufficiently effective to spontaneously form a stable passivation film on the rebars.

## CONCLUSIONS

From reviews of the different factors affecting the carbonation of concrete and how to protect RC structures from carbonation, the following conclusions can be drawn.

1. Although carbonation cannot be avoided because CO<sub>2</sub> exists in the atmosphere, good quality of concrete can control the carbonation process and eliminate the carbonation depth.
2. Good concrete practice including selection of suitable cement type, use of low W/C ratio with using HRWRA, and increase the curing time are the main factors controlling the carbonation.
3. Presence of cracks at concrete cover can develop the carbonation around reinforcing steel and cause corrosion. Therefore, the use of elastomeric protective coatings which can bridge the cracks will be useful to prevent concrete from carbonation and steel bars from corrosion.
4. Preventing and slowing down carbonation in concrete is a simple method by reducing the ingress of CO<sub>2</sub> and moisture into concrete, by using a protective or anti-carbonation coating for concrete.
5. There are many types of anti-carbonation coatings in the market. It is important to choose the right type. Anti-carbonation coating helps to provide a protective barrier to the concrete structures not only for carbonation but also to prevent the ingress of chlorides and moistures. Acrylic, silicone enhanced, epoxy and polyurethane are most suitable for such coatings
6. Anti-carbonation coatings shall be used for both new and existing structures especially tunnels and garages. Such product can ensure that RC structures remain visually attractive throughout their lifespan and avoid costly and disruptive repair and maintenance work.
7. Carbonated RC existing structures can be treated by realkalization method, and then concrete surface shall be protected with anti-carbonation coating.

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