DETERMINAREA IN-SITU A ADÂNCIMII DE CARBONATARE A BETONULUI STRUCTURILOR EXISTENTE
DETERMINATION OF CARBONATION DEPTH THROUGH IN-SITU TESTING OF CONCRETE STRUCTURES

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In the last few decades, failure of concrete structures awakened researchers to focus on durability influencing parameters along with compressive strength. Factors like environmental or exposure conditions are found to be governing the service life of reinforced concrete (RC) structures significantly. One of the major processes influencing condition of steel bars is carbonation of concrete surrounding steel bars in RC structures. Hence, considerable researches on the carbonation of concrete in laboratory and field are carried out around the world. Present article reviewed several previous carbonation studies conducted by researchers and by utilizing the results of a field survey determines coefficient of carbonation 'K' for concrete structures located in the City of Bhopal, India and for other semitropical regions.

Keywords: *concrete, carbonation, model, reinforcement, corrosion*

1. Introduction

Deterioration of concrete, caused by several physical and chemical attacks, result in degradation of performance with time. According to Binda and Molina (1990) [1] along with compressive strength, service life of structures is governed by exposure conditions. Experimental and field results are necessary to develop realistic deterioration models for assessing performance of existing concrete structures. Using material properties from field data instead of assumed value is a better approach.

Deterioration of RC structures due to corrosion initiated by carbonation is a major problem especially in urban regions with increased concentration of carbon dioxide, released from vehicles and industries in atmosphere (Sisomphon and franke 2007) [2]. Carbonation induced corrosion of RC structures is the most common deterioration process (Monteiro et al. 2012) [3]. Carbon dioxide from atmosphere reacts with hydrated cement paste products and reduces the pH of concrete pore solution, which in end initiates corrosion of rebars embedded in concrete structures. Corrosion of reinforcement leads to the formation of cracks on concrete cover and decreases the residual life of RC structures.

2. Carbonation process

Corrosion affects the RC elements in many ways such as cross section loss of reinforcement, reduction in strength, cracking and spalling of concrete cover etc. During hydration of cement a highly alkaline solution having pH value greater than 12.5 is formed in concrete and due to this alkaline environment reinforcing steel forms a very thin oxide passive film which protects the steel from corrosion. This protective film is destroyed by penetration of chloride ions or when pH value is reduced below 9 due to carbonation.

Carbonation can lead to corrosion causing loss in area of steel, reduction in load carrying capacity of structure and variation in mechanical properties of concrete. According to Mullauer et al. (2012) [4] carbonation of concrete results in change of porosity and pore size distribution and affects transport of various elements.

Service life of structures affected from carbonation induced corrosion has been defined by Tesfamariam and Martin-Perez (2008) [5] as the time for the carbonation front to reach reinforcing steel depth. End of service life for corrosion affected structures is characterized by Bhargava et al. (2006) [6] as the loss of protective

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action provided by cover concrete to reinforcement against the contact with the corrosion inducing agents such as carbon dioxide. According to Saetta (2005) [7] service life of the structure is identified as the time it takes for the front of carbonation to reach the reinforcement. Service life of a structure can be improved by using low water/cement ratio and by proving adequate curing and cover (Al-khaiat and Fattuhi 2002) [8].

Initially carbonation of concrete starts at the exposed concrete surface and then progress towards rebars, this carbonation process is based on the diffusion of carbon dioxide in concrete (Pade and Guimaraes, 2007) [9]. Progress of carbonation depth (x) with respect to age of concrete (y) is defined by most of the researchers using square-root relationship based on Fick's first law of diffusion $x = K\sqrt{y}$, where 'K' is the coefficient of carbonation. Value of 'K' depends on several factors such as exposure conditions, quality of concrete and variation in surrounding environment.

During carbonation process atmospheric carbon dioxide penetrates the concrete and reacts with hydroxides $Ca(OH)_2$ to form carbonates $CaCO_3$, and reduces the alkalinity (pH) of concrete. In the first reaction carbon dioxide and water in pores react to form carbonic acid H_2CO_3.

$$CO_2+H_2O \rightarrow H_2CO_3 \quad (1)$$

Then carbonic acid reacts with hydroxides to form carbonates

$$H_2CO_3+Ca(OH)_2 \rightarrow CaCO_3+2H_2O \quad (2)$$

With these reactions pH of carbonated concrete drops beneath 9. This reduction in pH destroys passive protective film and initiates corrosion.

3. Other carbonation studies

The relationship between carbonation depth (Cd) and age of concrete (t) has been described by several models proposed by different researchers, of which the most popular is Fick's first law of diffusion shown in eqn. (3)

$$\mathbf{Cd = K \sqrt{t}} \quad (3)$$

where **K** is coefficient of carbonation. This coefficient of carbonation depends on several factors influencing the carbonation process. Researchers have evaluated and proposed different values of 'K' for structures in different exposure conditions. A model based on Fick's first law similar to eqn. (3) has been proposed by Monteiro et al. (2012) [3], considered the value of K as the concrete durability coefficient as it include effects of all durability and performance related variables. From the regression analysis of carbonation depth and age of structure value of carbonation coefficient has been evaluated as **K**=3.76. Association between K and compressive strength has been investigated and it has been found that they are having inverse relationship.

Takla et al. (2011) [10] performed carbonation process in a climatic chamber with an aim to evaluate carbonation progress with time. Carbonation depth has been measured using phenolphthalein spray and recorded a quasi-linear relationship between carbonation depth (mm) and time (day) as shown in eqn. (4). Square-root relationship was not obtained as it is for atmospheric carbonation and it may takes many years to observe the variation for real structures. It has been concluded that due to decrease in porosity of cement and due to formation of calcite carbonation produces a positive effect on mechanical strength of concrete.

$$\textbf{Carbonation depth} = \mathbf{0.3334} x\ \textbf{(time)} \quad (4)$$

An experimental work has been carried out by Marques and Costa (2010) [11] to evaluate performance of different concrete composition, moreover developed performance based methodologies regarding carbonation induced corrosion. They preferred relation shown in equation (5) for evaluating carbonation depth (x) based on coefficient of diffusion for CO_2 (D), amount of CO_2 that origins the carbonation (a), difference between external CO_2 and at the carbonation front (ΔC) and time (t) in years

$$\boldsymbol{x} = \sqrt{(\mathbf{2}\frac{\boldsymbol{D}}{\boldsymbol{a}}\Delta\boldsymbol{Ct})} \quad (5)$$

Ann et al. (2010) [12] considered Fick's first law similar to eqn. (3) for evaluating carbonation depthFrom results it has been concluded that for 'K'< 3 the concrete was almost free from carbonation, and from given table mean value of '**K**' for cracked concrete bridges is evaluated as 5.79.

McPolin et al. (2009) [13] performed accelerated carbonation test to investigate carbonation in mortars also presented different techniques for evaluating degree of carbonation and change in pH value of concrete.

A Study to understand the deterioration of concrete by carbonation has been performed by Parameswaran et al. (2008) [14]. Investigated effects of carbonation on initiation and propagation time of corrosion and used eqn. (3) to obtain carbonation depth against age of structure. Coefficient of carbonation 'K' has been obtained by considering factors such as characteristic strength of the concrete, environmental coefficient, air content coefficient etc. as given in equation (6). Where $\mathbf{C}_{env}$ = environmental coefficient, $\mathbf{C}_{air}$ = air content coefficient and a, b are constants depends upon type of cement used

$$\mathbf{K}=\mathbf{C}_{env}\mathbf{C}_{air}\mathbf{a}(\mathbf{f}_{ck}+8)\mathbf{b} \quad (6)$$

For a sheltered, air entrained and Portland cement concrete with approximate compressive strength of 20MPa (these conditions are almost similar to conditions of the structures surveyed in Bhopal with average compressive strength of about 20MPa), value of '**K**' obtained from above relationship is 4.37.

Tesfamariam and Martin-Perez (2008) [5] proposed a relationship to evaluate the carbonation depth (x) with respect to age of concrete (t) as shown in eqn. (7)

$$\mathbf{x = K\ t^{1/m}} \qquad (7)$$

where K is carbonation coefficient and m is a constant. Carbonation coefficient has also been evaluated by considering effects of moisture content, concrete quality, surface inclination, carbonation profile and environmental carbon dioxide concentration. Form a table presented by authors for evaluating value of 'K' for different conditions, 'K' for sheltered urban area and medium quality concrete (similar conditions) is found to be 5, with m=2. So eqn. (7) becomes similar to Fick's law with **K**=5.

Peter et al. (2008) [15] extended a previously developed mathematical model of carbonation by including additional carbonation and hydration reactions. Numerical simulation of an accelerated carbonation test has been used to investigate influence of each reaction on carbonation depth.

According to Pade and Guimaraes (2007) [9] depth of carbonation (d) as a function of time (t) can be described by the relationship $d= K\ t^{0.5}$, however, in case of outdoor exposed conditions and higher strength concrete square-root relationship may not fit and exponent seems to be less than 0.5. Hence, there is low increase in carbonation depth with time. A table is also presented to obtain the value of 'K' on the basis of exposure conditions and compressive strength, for sheltered structures of compressive strength approximately 20MPa value of carbonation coefficient obtained from this table is **K**=6.

Sisomphon and Franke (2007) [2] used eqn. (8) to determine value of 'K'

$$\mathbf{K} = \sqrt{\frac{\mathbf{2DC1}}{\mathbf{C0}}} \qquad (8)$$

where D is diffusion coefficient, C1 is environmental carbon dioxide concentration and C0 represents carbon dioxide required to react with alkali phases in a unit volume of phases.

An analytical technique for predicting carbonation in early aged cracked concrete has been developed by Song et al. (2006) [16], for determining CO_2 diffusion of sound and cracked concrete. Thereafter, numerical results were compared with experimental data. McGrath (2005) [17] performed accelerated carbonation test for evaluating carbonation rate of concrete specimens with different protective coatings. Carbonation depth has been measured through phenolphthalein solution.

Atis (2004) [18] performed different field and accelerated condition tests to evaluate compressive strength, carbonation depth and porosity of concrete mixtures of fly ash and Portland cement. It has been concluded from results that the carbonation depth decreases with the increase in compressive strength.

Accelerated carbonation test has been conducted by Sulapha et al. (2003) [19] on concrete incorporating different admixtures. Coefficient of carbonation has been correlated with corresponding compressive strength and found that, coefficient of carbonation and compressive strength indicates carbonation rate of concrete. A linear relationship has been obtained between coefficient of carbonation (K) and corresponding compressive strength (S), as shown in eqn. (9)

$$\mathbf{K= -0.0831\ S + 7.5127} \qquad (9)$$

Al-khaiat and Fattuhi (2002) [8] performed a carbonation investigation on naturally exposed concrete and reported carbonation measurements up to a maximum age of 600 days. Results indicated that surface coating, water/cement ratio, curing period and season in which concrete made and exposed influence the carbonation significantly. Ho and Harrison (1989) [20] determined the variation of carbonation depth for coated and uncoated concrete. Found that carbonation depth at a given time depends upon the coefficient of carbonation, which depends on exposure conditions and quality of concrete. For untreated concrete carbonation depth (X) is evaluated through eqn. (10)

$$\boldsymbol{X} = \sqrt{(\boldsymbol{2Dt})} \qquad (10)$$

where D= carbonation coefficient. Through accelerated carbonation test obtained value of carbonation coefficient as 24.5 mm^2/ week, it has also been reported that value of 'K' obtained after one week by performing accelerated carbonation test is approximately equals to the value obtained after one year exposure in normal atmosphere. Hence, value of D is 24.5 is m^2/ year, therefore, eqn. (9) becomes similar to eqn. (3) with **K**=7.

4. Field Survey

In the present study carbonation depth of almost hundred structures of age 3 to 62 years including residential buildings, commercial buildings and bridges located around the city of Bhopal (India) has been measured using rainbow indicator test. To obtain consistent results average of three readings on a structure has been considered. Bhopal is situated in semi-tropical region of India. Where, in summer highest temperature is around 45^0C and in winter lowest

Table 1

Details of surveyed structures

S. No.	Parameters	Classification	No. of structures
1	Age (years)	< 20 (new)	30
		21-40 (average)	41
		>20 (old)	27
2	Compressive strength (MPa)	<15 (low)	44
		16-25 (medium)	37
		>25 (good)	17
3	Concrete Cover (mm)	< 20 (small)	16
		21-30 (adequate)	35
		>30 (large)	47
4	Carbonation depth (mm)	< 20 (low)	25
		21-30 (alarming)	29
		>30 (dangerous)	44
5	Carbonation depth(cd) as percentage of concrete cover (cc) ***[cd/cc] x 100=***	< 50% (safe)	26
		>50% to 100% (dangerous)	71
		More than 100% (disastrous)	1

temperature is around 10^0C, average annual rain fall is about 110cm. Structures surveyed are having average compressive strength about 20MPa and most of the surveyed parts are sheltered. Details of the structures surveyed are provided in Table 1. Surveyed structures are classified in different categories according to their age, measured compressive strength, concrete cover and carbonation depth.

Carbonation starts at concrete surface and advances gradually towards reinforcement, when carbonation reaches near rebar it initiates the corrosion of reinforcement. Hence, if carbonation depth is more than 50% of concrete cover than it indicates that corrosion will initiate very soon. Therefore, structures are also classified considering carbonation depth as percentage of concrete cover. It has been observed that most of the structures are having carbonation depth more than 50% of concrete cover.

Figure 1, presents the variation of carbonation depth as percentage of concrete cover with age of the structures. It has been observed from figure 1, that structures with age less than 20 years are having carbonation depth less than 50% of concrete cover and with the increase in age of the structures percentage of carbonation depth increases and it reaches towards 100% for the structures of more than 40 years. Hence, it has been concluded that structures with age less than 20 years, even with low concrete cover, are almost safe from carbonation.

5. Proposed carbonation model and comparison with other models

Cd versus **√t** data obtained through field tests are fitted using Excel curve fitting tools as shown in Figure 2. The relationship obtained is **Cd = 5.733√t - 2.813**, which is similar to eqn. (11)

$$C_d = K\sqrt{t} + a \qquad (11)$$

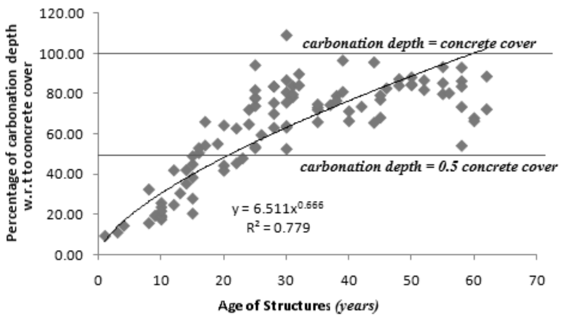

Fig. 1 - Variation of Ingress of carbonation with the age of structures.

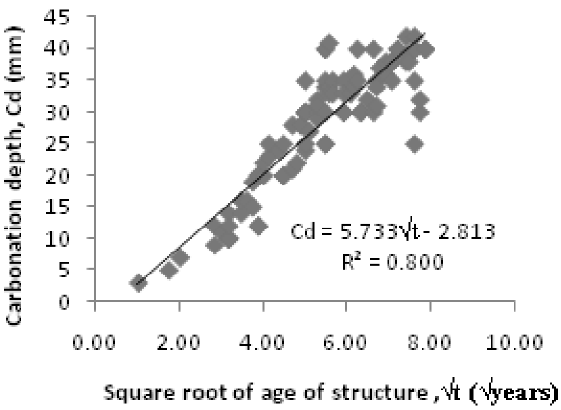

Fig. 2 - Carbonation depth plotted against square root of age of the structure.

where **a**= empirical constant (mm), value of **a** obtained is negligible when compared with Cd, therefore, it can be neglected. Hence, eqn. (8) becomes similar to Fick's first law Cd = K √t. Thereafter, neglecting empirical constant 'a', value of carbonation coefficient is obtained as **5.73**, so proposed model similar to Fick's first law is presented by eqn. (12)

$$C_d = 5.73\sqrt{t} \qquad (12)$$

Table 2

Values of ‘K’ proposed by researchers

Relation No.	Evaluated value of coefficient of carbonation ‘K’ (mm / √year)	Proposed by
R1	3.76	Monteiro et al. (2012) [3]
R2	5.79	Ann et al. (2010) [12]
R3	4.37	Parameswaran et al. (2008) [14]
R4	5.0	Tesfamariam and Martin-Perez (2008) [5]
R5	6.0	Pade and Guimaraes (2007) [9]
R6	7.0	Ho and Harrison (1989) [20]
R7	5.73	Present model

Different values of ‘K’ proposed by other researchers obtained in previous section are shown in Table 2.

Carbonation depths obtained from these values of ‘K’ have been compared with proposed model in Figure 3 and it has been observed that all the models are showing similar pattern in the variation of carbonation depth with age of structure.

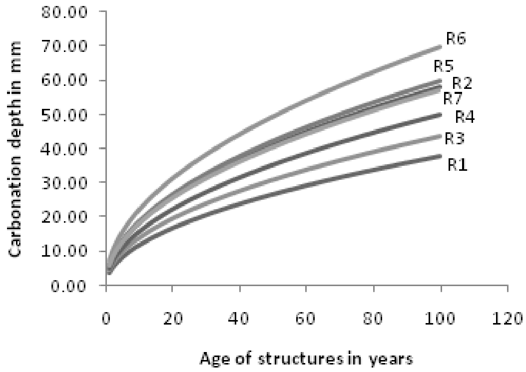

Fig. 3 - Carbonation depths obtained from relations R1 to R7.

6.Effect of carbonation depth on the probability of corrosion

Half cell potential has been widely used as indicator of probability of the corrosion of embedded steel bars in RC components of the structures. Value of potential difference measured by half cell indicates the percentage of corrosion probability and decrease in the value of half cell indicated the higher probability of corrosion. As per ASTM C876 for Ag/ AgCl half cell, if value of half cell potential is more than -119 mV then probability of corrosion is only 10%, if value is between -119 and -269 mV then probability of corrosion is 50%, and if value is less than -269 mV then probability of corrosion is 90%.

Here, in-situ values of carbonation depth and half-cell potential values of all surveyed structures are plotted in fig. 4, to evaluate effect of carbonation depth on the half cell potential. It has been observed that increase in carbonation increases the probability of corrosion. If carbonation depth is more than 25mm than probability of corrosion is more than 90%, when carbonation depth is equal or more than concrete cover it initiates the corrosion. Hence, it has been recommended to keep concrete cover more than 25mm for low probability of early corrosion initiation.

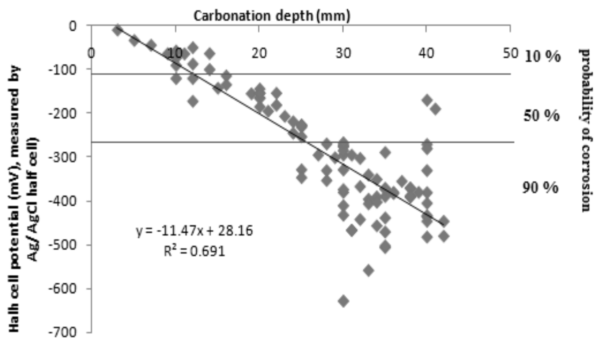

Fig. 4 - Effect of carbonation depth on the probability of corrosion.

7. Discussion and Conclusions

Several recent carbonation studies performed by different researchers have been reviewed and it has been observed that most of the researchers used Fick’s first law of diffusion $Cd = K\sqrt{t}$ for modeling carbonation process.

Data obtained from field survey conducted around Bhopal (India) using rainbow indicator, half cell potential and rebound hammer have been used in present study. Value of carbonation coefficient ‘K’ for concrete structures located in the City of Bhopal, India has been determined as 5.733, therefore, proposed carbonation model is $\mathbf{Cd = 5.733\sqrt{t}}$. Carbonation depths evaluated for all the surveyed structures from proposed model are compared with other models and it has been found that they follow similar pattern and results are comparable.

Increase in carbonation depth increases the probability of corrosion. And it has been observed that a minimum concrete cover of 25 mm has been required for low probability of early corrosion initiation.

Also effect of compressive strength on the carbonation depth has been investigated and it has been observed that they are having inverse relationship with each other. Model presented in eqn. (12) may be used by engineers in future to predict carbonation depth of concrete in places similar to Bhopal city.

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