Carbonation induced deterioration of concrete structures

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Premature deterioration of reinforced concerete structures is becoming a major problem for engineers and researchers. Several researchers considered carbonation as one of major deterioration mechanisms accelerating steel corrosion in reinforced concrete structures. Carbonation reduces the pH of concrete surrounding the reinforcement and increases the probability of corrosion in embedded steel bars. In the present research, a carbonation model similar to Fick's first law of diffusion, has been developed through in-situ testing performed on various concrete structures located in Bhopal City. Coefficient of carbonation 'K' has been obtained as 5.5168, which lies within the expected range observed from literature. The data obtained from field testing has been analyzed based on various parameters such as age, concrete cover and compressive strength and their effect over carbonation ingress has been evaluated.

INTRODUCTION

In the last century reinforced concrete (RC) has been very widely used in civil engineering as it is one of the most economical and durable construction materials. However, even the most durable concrete structure can develop cracks and deteriorate when exposed to hazardous conditions, carbonation being one of them. Hence, monitoring condition and diagnosing deterioration is of prime importance for scheduling remedial actions and ensuring that RC structures remain in good working condition

The majority of concrete deterioration is related to corrosion of reinforcement due to carbonation or chloride induced depassivation of steel bars (Basheer et al., 1996) [1]. The carbonation of concrete is a complex physiochemical process (Papadis et al., 1991) [2]. In urban areas, where environmental pollution results in a considerable concentration of carbon dioxide, carbonation induced reinforcement corrosion takes place. In the case of carbonation, chemical reaction between carbon dioxide from air and the hydration products of cement in concrete causes a reduction in the alkalinity of concrete and consequently reduces its ability to protect the steel from corrosion. It has been found that higher temperature and humidity enhances the rate of carbonation (Maslehuddin,1996) [3].

The rate of carbonation is highest in the range of relative humidity of 50 to 70% (Neville, 2003) [4].The global warming phenomenon due to the increase in temperature and CO_2 concentration has been regarded as one of the most critical problems in the 21st century (Yoon et al., 2007) [5].

OBJECTIVES AND SCOPE OF PRESENT STUDY

Degradation in performance of RC structures due to carbonation of concrete is a major problem. To prevent premature deterioration of concrete structures, design and maintenance guidelines have been issued by a number of organisations including American Concrete Institute (ACI) and the Japanese Society of Civil Engineers (JSCE) [6,7]. Therefore, deep researches for the evaluation of deterioration due to carbonation has been required. A research has been conducted on various concrete structures located in Bhopal City (India) with the following objectives –

1. To propose a carbonation model for Indian semitropical regions like Bhopal
2. To study the effect of compressive strength on variation of carbonation depth with age

RECENT CARBONATION STUDIES

Several researchers performed studies on carbonation, worldwide, some recent studies are presented here. Liang et al. (2013) examined the predicted carbonation life of an existing concrete viaduct/bridge in the atmospheric environment based on probability and reliability indices [8]. The results showed that both the structures were serviceable and reliable comparing the initiation time calculated using Fick's second law and other methods.

Neves et al. (2013) investigated the relationship between natural and accelerated concrete carbonation resistance in real structures and their non-carbonated inner part which had been subjected to accelerated carbonation resistance testing [9]. Different factors, according to exposure classes, were determined by linear regression analysis to correlate accelerated and natural carbonation coefficients. The use of these factors together with Fick's first law enables the long term prediction of carbonation depth in structures based on accelerated carbonation.

Uddin et al. (2013) determined the carbonation coefficient 'K = 3.75' for different structural elements by testing seventy structures in Dhaka City [10]. The age of structures was varied from 1 to 79 years. More carbonation depth was found in outdoor exposure condition compared to the indoor exposure condition.

Monteiro et al. (2012) investigated around 47 samples from existing concrete structures of age up to 99 years and found the value of carbonation coefficient K = 3.76 mm/year$^{1/2}$ based on Fick's first law, for moderately humid exposure condition [11].

Takla et al. (2011) evaluated the progress of carbonation depth with respect to time. Carbonation depth has been measured using phenolphthalein spray and recorded a quasi-linear relationship between carbonation depth and time [12].

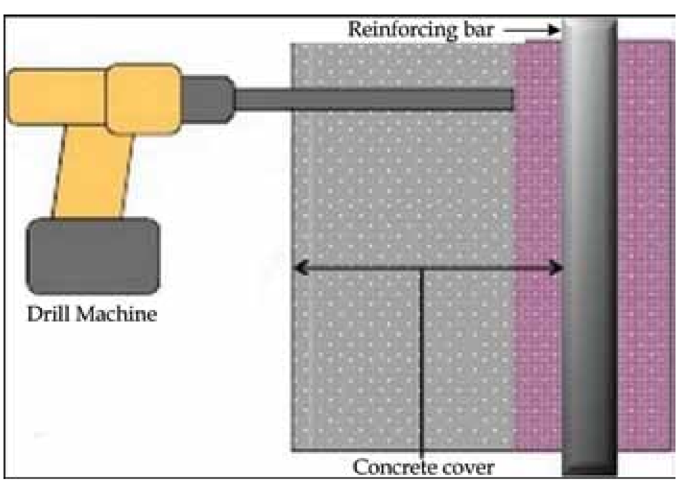

Figure 1. Method of concrete drill

Ann et al. (2010) considered Fick's first law to evaluate carbonation depth and performed study to evaluate service life for different values of coefficient of carbonation [13].

Marques and Costa (2010) conducted an experimental work to evaluate the performance of different concrete composition and developed performance based methodologies regarding carbonation induced corrosion [14].

Al-Khaiat et al. (2004) performed a long term investigation of concrete structures exposed to natural weather conditions in Kuwait [15]. Fifty four different concrete mixes were exposed to hot and arid weather. The results showed that the W/C ratio is one of the main factors affecting carbonation. The values of 'K' ranged from 2.1 to 7.8 as the W/C ratio increased from 0.45 to 0.8.

As per above literature survey, carbonation phenomena is one of the major causes responsible for reducing the alkalinity of concrete which leads to deterioration of RC structures. The carbonation mechanism purely depends on environmental factors such as humidity, greenhouse gas emission and high concentration of gases such as nitrogen, sulphur and carbon dioxide due to air pollution.

FIELD SURVEY – METHODOLOGY AND DATA

Carbonation induced corrosion is a major concern for durability of reinforced concrete structures globally. The City of Bhopal is one of the fastest growing cities of India, observed a very fast growth of urban population in recent times. As a result, CO_2 concentration in the air has increased in and around Bhopal. In the subtropical regions of India CO_2 concentration is increasing due to vehicular traffic and setup of various small and large scale industries.

In order to develop a carbonation model and to evaluate the effect of compressive strength on the rate of carbonation ingress, various non-destructive tests have been performed on almost twenty five concrete structures of different age ranging from 1 to 60 years. The methodology adopted for collecting the field data involves selection of structures, evaluation of carbonation depth and compressive strength as described below –

1. Selection of Structures
2. Evaluation of carbonation depth
3. Evaluation of compressive strength

Table 1. Data obtained from field survey conducted on structures

S. No.	Age (years)	Concrete Cover (mm)	Carbonation Depth (mm)	Compressive Strength (N/mm^2)
1.	1	30	3	17
2.	2	30	8	13
3.	3	40	10	14
4.	4	30	12	25
5.	4	35	15	20
6.	7	35	18	14
7.	10	33	22	12
8.	10	40	26	24
9.	13	32	26	22
10.	14	35	28	40
11.	15	40	28	18
12.	16	40	25	24
13.	17	50	28	17
14.	18	35	28	14
15.	20	30	26	20
16.	24	32	28	28
17.	25	45	30	25
18.	28	32	30	18
19.	32	42	34	12
20.	34	40	34	10
21.	39	36	36	10
22.	40	40	40	24
23.	44	42	40	13
24.	54	42	42	19
25.	59	42	42	16

The carbonation depth and thickness of concrete cover has been measured during the field survey. Carbonation depth has been measured based on drilling method, shown in Figure 1.

Field survey and Data

Data obtained through in-situ survey such as concrete cover (mm), Carbonation depth (mm), compressive strength (N/mm^2) and age (years) of the identified structures are presented in Table 1.

The data obtained are categorised in different groups based on various parameters such as age, compressive strength, concrete cover and carbonation depth, as listed below. The number of structures classified in different categories are listed in Table 2.

Structures having age below 25 years are classified as new while structures having age of 25 years or more are classified as old.

Table 2. Classification of structures based on various parameters

Parameter	Range	Classification	No. of structures
Age (years)	<25	New	17
	≥25	Old	8
Compressive strength (N/mm^2)	<20	Low	17
	≥20	High	8
Concrete Cover (mm)	<30	Insufficient	Nil
	≥30	Sufficient	25
Carbonation depth (mm)	<30	Safe	16
	≥30	Critical	9

Compressive strength below 20 N/mm^2 has been considered as low while compressive strength of 20 N/mm^2 or more has been considered as high.

Concrete cover below 30 mm has been considered as insufficient while concrete cover of 30 mm or more has been considered as sufficient to withstand the effect of carbonation ingress up to a certain age.

Structures having carbonation depth below 30 mm are considered to be safe while structures having carbonation depth of 30 mm or more have been considered as safe.

DEVELOPMENT OF CARBONATION MODEL

A graph between the square root of age and carbonation depth of RC structures has been plotted and fitted linearly in Figure 2. Equation (1) is obtained as a linear relationship between carbonation depth and square root of age.

$$Cd = 5.5168 \sqrt{t} + 2.9501 \quad ...(1)$$

Where Cd is the carbonation depth in mm, and t is the age in years.

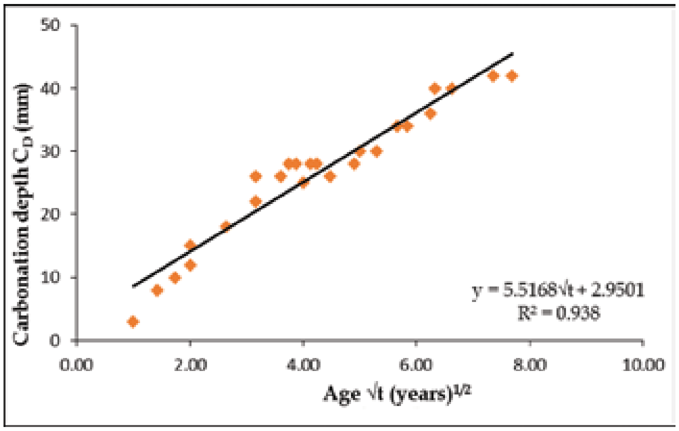

Figure 2. Relation between age and carbonation depth

The equation (1) obtained above is a linear equation and its general form is y = mx + c, where 'c' is an empirical constant. The value of **'c' 2.9501,** is negligible when compared with measured carbonation depths, hence, it can be neglected. Thereafter, eqn. (1) becomes similar to Fick's first law Cd = K √t as shown in equation (2).

Cd = 5.5168 √**t** ...(2)

Hence, by comparing the above eqn. with Fick's law, value of coefficient of carbonation obtained is **K = 5.5168.**

VALIDATION OF RESULTS

The value of carbonation coefficient (K = 5.5168) obtained above is very close to the values found on the basis of available reported work by other researchers.

Ann et al. (2010) [13] proposed a table for evaluating the value of K. The mean value of K obtained from this table, for the conditions similar to present one, is found to be 5.79 $mm/year^{1/2}$.

Sulapha et al. (2003)[16] proposed a relationship based on compressive strength of concrete for evaluating coefficient of carbonation 'K' by performing accelerated carbonation test; given in equation (3) below.

K = – 0.0831 S + 7.5127 ...(3)

Where K is the carbonation coefficient $mm/week^{1/2}$ and S is the compressive strength (N/mm^2). The average compressive strength of concrete in the present study is 20 N/mm^2. On substituting this value of compressive strength in the above equation, the coefficient of carbonation 'K' has been found as 5.9 $mm/week^{1/2}$.

Ho and Harrison (1989) [17] performed accelerated carbonation tests to obtain value of 'K'. It has 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 field conditions. Hence, for real field conditions value of 'K' obtained by Sulapha et al. (2003) [16] is 5.9 $mm/year^{1/2}$.

Table 3. Classification of structures on the basis of compressive strength

S. No.	Compressive Strength (N/mm^2)	Structures	Classification
1.	≤ 20	17	CS_1
2.	> 20	8	CS_2

Effect of compressive strength

To evaluate the effect of compressive strength over carbonation depth the structures have been grouped into two categories, as given in Table 3.

1. Structures with compressive strength less than or equal to 20 N/mm^2
2. Structures with compressive strength more than 20 N/mm^2

All the structures surveyed in the present study are having concrete cover more than 30 mm. So, the structures with carbonation depth less than 30 mm are safer in comparison with structures having carbonation depth equal to or more than 30 mm. Based on above observation concrete structures are classified in two categories i.e. safe and critical. The classification is presented in Table 4.

In Figures 3 and 4, variation of carbonation depth with age of structures for CS_1 and CS_2 groups have been presented

Table 4. Classification of structures on the basis of carbonation depth

S. No.	Category	Carbonation depth (mm)	Structures	Classification
1.	Safe	< 30	16	CS_3
2.	Critical	≥ 30	9	CS_4

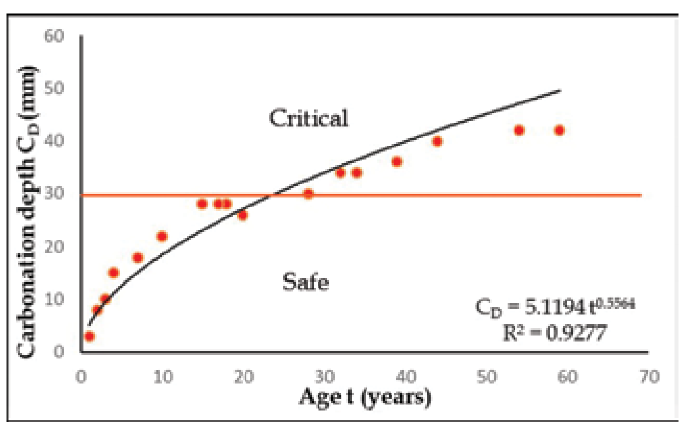

Figure 3 – Variation of carbonation depth with age for CS_1 category

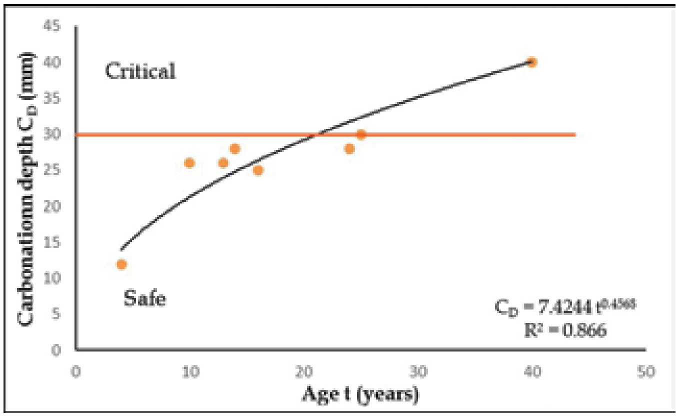

Figure 4 – Variation of carbonation depth with age for CS_2 category

From Figure 3, it has been observed that more number of structures after the age of 30 years falls under critical category for C_{S1} group. Thereafter, it has been observed from Figure 4, that less number of structures lie under critical category for C_{S2} group in comparison with Cs_1 group, even after 30 years of age.

Hence from above observations, it has been concluded that concrete structures with compressive strength more than 20 N/mm^2 are less prone to carbonation than structures with compressive strength less than or equal to 20 N/mm^2.

DISCUSSIONS

1. The data obtained from field testing has been analyzed based on various criteria. A carbonation model has been developed and the effect of age, concrete cover and compressive strength over carbonation ingress has been evaluated
2. Carbonation model Cd = 5.5168√t similar to Fick's first law of diffusion Cd = K√t has been developed
3. Coefficient of carbonation 'K' has been obtained as 5.5168, which lies within the expected range, as observed from literature
4. It has been observed that the carbonation depth of structures reaches 40 mm to 45 mm in about 40 to 50 years. Therefore, in order to enhance the durability and to safeguard the structures against carbonation for that many years, it is necessary to provide a clear cover of at least 40 mm
5. The improved knowledge will enable designers to properly rehabilitate and maintain the concrete structures

9. CONCLUSIONS

From the present study, carbonation has been found to be a major factor responsible for the deterioration of RC structures located in semitropical regions of India like Bhopal. It has been observed that the rate of carbonation ingress is governed by various factors such as age, concrete cover and compressive strength. Steps should be taken to safeguard the structures from the getting deteriorated due to effect of carbonation. Various conclusions drawn are discussed here.

1. Carbonation is dominant in semitropical regions of India due to higher concentration of CO_2 in the atmosphere
2. Developed model can be used to estimate the carbonation depth of concrete structures at a particular age
3. Compressive strength of concrete affects the rate of carbonation to a great extent for structures
4. Provisions of sufficient concrete cover shall protect the concrete structures in a better way

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