

# The Carbonation Model of Concrete Structures and Its Application

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**Abstract.** Carbonization is one of the main factors affecting the durability of concrete structures in atmospheric environment. According to the theory of reliability and the climate forecast data, using the concrete carbonation prediction model improved, the time-dependent reliability of concrete structures were researched, for three environmental classes of I environment in china Code for durability of concrete structures. The study results showed: (1) In this paper, the results of the improved concrete carbonation prediction model was in good agreement with those of other reference's concrete carbonation prediction models. (2) When the carbonation emission scenarios would make CO<sub>2</sub> concentration to be higher, then this would lead to the carbonation depth in concrete cover and cumulative failure probability to increase more. But the carbonation depth in concrete cover and cumulative failure probability would decrease more when environmental effect being more serious; for concrete carbonation development was delayed by raising the concrete minimum strength, increasing concrete cover depth, and decreasing concrete Maximum water cement ratio. (3) Improving the concrete strength and the concrete cover depth should be done in future concrete structures design to improve the concrete carbonation resistance and concrete structures durability.

## Introduction

Concrete carbonation is the main cause of the durability and service life for reinforced concrete (RC) structures in atmospheric environment. Carbonation of concrete is a complex physical and chemical process, which are affected by the working environment (such as temperature, relative humidity and CO<sub>2</sub> concentration, the load and so on) and concrete material properties (such as water cement ratio, cement content, compressive strength and the cover thickness). Now in the world on the concrete carbonization mechanism and its influencing factors have been investigated deeply. from different angles, the researchers have proposed some various carbonization prediction models, including the early theoretical model [1], experience model [2-4], based on theory and experiment of the practical model based on theory and experiment [5] and the stochastic model [6-10] ect. Due to the diversity of influencing factors, the complexity of the environmental conditions, material property discrete, and the uncertainty of other influence factors for concrete carbonation; there is no the practical calculation model which had the adequate theoretical basis and the comprehensive consideration of various affecting factors [11]. So then we still need to continue exploring in order to suggest a more scientific, reasonable and practical model of concrete carbonation.

With the rapid development of the global economy, the climate is changing, and the concentration of CO<sub>2</sub> is increasing continuously in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) fourth 2007 Climate Research Report has given: In the end of 2000, the global atmospheric CO<sub>2</sub> concentration increased to about 365ppm; and predicted that the atmospheric CO<sub>2</sub> concentration would exceed 1000ppm in the end of 2100 [12]. In recent years, the influence of concrete carbonization from climate change (such as CO<sub>2</sub> concentration, temperature, etc.) has been studied by [8-10, 13]. Yoon et al. studied the effect of atmospheric CO<sub>2</sub> concentration on concrete carbonation, and proposed the carbonation prediction model h based on the first law of Fick in 2007 [8]. Jian Xin Peng et al. proposed carbonation model considering the uncertainty of CO<sub>2</sub> concentration based on the Yoon carbonation model, then studied the influence on concrete carbonation form the high, medium

and low three carbon emission scenarios according to the fourth IPCC climate research report data in 2010 [9]. Stewart et al. improved the Yoon model, suggested the carbonation  $\text{CO}_2$  volume integral correction considering climate change, and researched the effect on Australian concrete carbonation, the durability form the increased  $\text{CO}_2$  concentration and the increased temperature on the basis of climate forecasting data in 2011 [10]. Xie Huibing et al. used Stewart's model method, and researched the carbonation depth and reliability index of RC structures designed by China concrete structure durability specification [14] with 100 years service life according to the carbon emissions prediction data of the IPCC Fourth Climate Research Report in 2015. These study results showed that the increasing  $\text{CO}_2$  concentration and the elevated temperature in the future climate would have the effects on RC carbonation, and this should not be ignored. Fick's first law is the theoretical foundation of carbonation model in the reference [8-10, 13]; and the model parameters are more, which are not easy to measure.

Based on the Niu Ditao's concrete carbonation model [6], this paper propose a improved concrete carbonation model, which consider the dependent time and the uncertainty of  $\text{CO}_2$  concentration. Then according to the carbon emissions prediction data of the IPCC Fourth Climate Research Report, the effect from  $\text{CO}_2$  concentration changing are researched on the carbonation and durability of RC structures in China.

### Carbonation Prediction Model

The Niu Ditao's concrete carbonation model [6] is easy to get the parameters, considers the random of the parameter variables in the process of calculation, then the calculated results are in good agreement with the measured values. But the  $\text{CO}_2$  concentration in the model is constant, which can not be changed with the time and the uncertainty of the  $\text{CO}_2$  concentration in the atmosphere. So one carbonation model is improved in this paper, and it is presented as follow:

$$x_{c(t)} = 2.56K_{mc}k_j \sqrt{K_{CO_2} \frac{C_{CO_2(t)}}{C_{CO_2(0)}}} k_p k_s \sqrt[4]{T} (1 - RH) RH \left( \frac{57.94}{f_{cu}} m_c - 0.76 \right) \sqrt{t} \quad (1)$$

Where  $x_{c(t)}$  is the concrete carbonation depth at time  $t$ , /mm;  $t$  is the concrete time  $t$ , /year;  $K_{mc}$  is the uncertainty of calculation model, a random variable with mean= 0.996 and standard deviation=0.355;  $C_{CO_2(t)}$  is the time-varying mean function of  $\text{CO}_2$  concentration( form Fig.1 ), the unit needs to be converted to volume concentration, namely:  $\times 10^{-6}$ ;  $K_{CO_2}$  is the  $\text{CO}_2$  concentration uncertainty, a random variable with mean = 1.0, standard deviation (according to Fig.1);  $C_{CO_2(0)}$  is that the average concentration of  $\text{CO}_2$  at the beginning of carbonization, and the unit is the volume concentration; Other parameters are the same with those in references [6].

### Comparison between Carbonation Prediction Models

In order to verify the effectiveness of the improved model proposed in this paper, one RC member is calculated. For the RC member, cover thickness mean is 20mm, its variation coefficient of is 0.1; Water cement ratio is 0.5; Concrete strength grade is C30,  $f_{cu}$  mean =30Mpa, its variation coefficient is 0.12; Ambient temperature  $T=20^\circ\text{C}$ , relative humidity  $RH=75\%$ ;  $k_j=1$ ,  $k_p=1$ ,  $k_s=1.2$ ,  $C_{CO_2(0)}$  is measured in Fig.1 in 2015:  $390 \times 10^{-6}$ .

**Comparison of Calculation results of the models between in this paper in Literatures [8-10].** As shown in Fig.2, the calculation results of the improved concrete carbonation model are presented in this paper. The results are in good agreement with those of the models in the literatures [8] - [10].

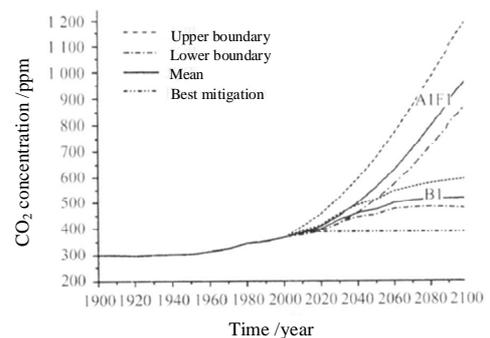
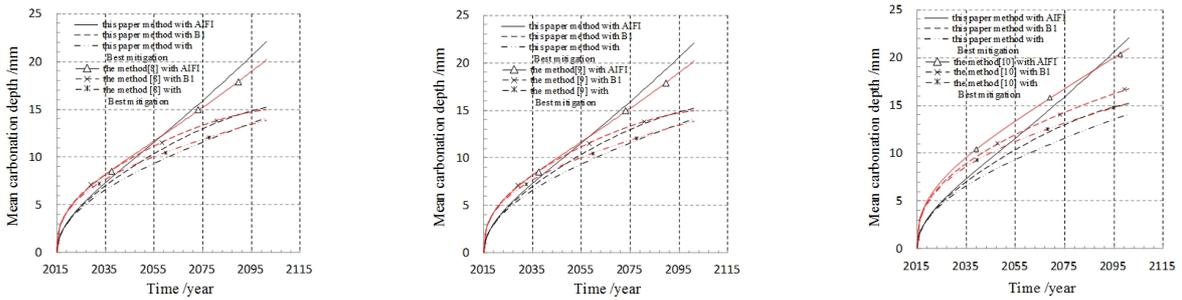


Fig.1 The  $\text{CO}_2$  concentration time-dependent prediction data of three carbonation emission [12]



(a) The comparison between this paper and literature [8]      (b) The comparison between this paper and literature [9]      (c) The comparison between this paper and literature [10]

Fig.2 The comparison of the calculation results between concrete carbonation models

**Comparison of Calculation results of the models between in this paper in Literatures [6].** As shown in Fig.3, the carbonation depths of literature [6] model are the same with AIFI, B1 and Best mitigation carbon emission. The reason is the constant coefficient  $CO_2$  in literature [6] model; and the time variability of  $CO_2$  concentration can't be reflected with future climate changing. In the early carbonation time when  $CO_2$  concentration variation is not obvious, the calculation result of this paper model is in agreement with that of literature [6] model. In the mid and late carbonation time with  $CO_2$  concentration changing more and more, this paper model calculation result could reflect the effect on carbonization from  $CO_2$  concentration variation.

### Carbonation Reliability Analysis

**Carbonation Cumulative Failure Probability.** Commonly for RC structures in the atmosphere, the concrete carbonation depth is considered as the load effect  $S$ , the concrete cover thickness as structure resistance  $R$ . So the function is as following in the normal use limit state:

$$Z = R - S = C - x_{c(t)} \quad (2)$$

Where  $Z$  is the time-varying function;  $C$  is the concrete cover thickness, /mm;  $x_{c(t)}$  is calculated by Eq. (1).

**Calculating Carbonation Cumulative Failure Probability.** The carbonation cumulative failure probability would be calculated By Eq. (1) and Eq. (3). Due to the random and variability of parameter-s, such as the protective layer thickness, concrete strength,  $k_{CO_2}$  and  $k_{mc}$ , Monte-Carlo method (MC method) is adopted, sampling number  $n=10^5$ .

### Engineering Applications

**The Durability Code of Concrete Structures in China.** The durability design code of concrete structures [14] was promulgated in 2008, and the design code of concrete structures [15] was promulgated in 2010. The two codes had the durability design specification of concrete structures. In literature [14], Environment I refers to the deterioration caused by concrete carbonation and the structure durability reducing. Environment I is divided into three grade: I-A (minor environmental effects), I-B (mild environmental effects), I-C (moderate environmental effects); and the special technical requirements are seen in table 1 about service life, the minimum strength and maximum water cement ratio an

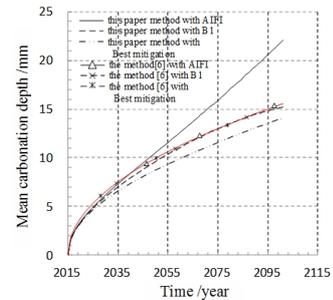


Fig.3 The calculation result comparison between this paper and reference [6]

d the minimum cover thickness. In this paper, the technical requirements of RC durability design are calculated according to literature [14].

**Random Variables and Other Parameters.** In this paper, the statistical parameters,  $K_{mc}$ ,  $f_{cu}$ ,  $K_{CO_2}$  and  $c$  are the random variables, as shown in table 2. The other parameters are:  $T=20\text{ }^\circ\text{C}$ ,  $RH=75\%$ ,  $k_j=1$ ,  $k_p=1$ ,  $k_s=1.2$ ,  $C_{CO_2(0)}$  is measured in Fig.1 in 2015:  $390 \times 10^{-6}$ .

**Calculation Result Analysis.** In order to the effects on carbonation of reinforced concrete structure from different carbon emission scenarios, A1fI, B1, and Best mitigation emission scenarios are calculated from 2015 to 2100 year. The 2015-year level carbon emissions is assumed as the standard carbonation. The carbonization of A1fI, B1 and Best mitigation emissions were compared with the standard carbonation; then the carbonation reliability are analyzed, according to Environment I [14].

**Mean Carbonation Depth Corresponding to Different Carbon Emission.** Fig.4 shows the average carbonation depth of three different carbon emission scenarios, A1fI, B1, and Best mitigation emissions for 100 year service life, corresponding to the three grades of Environment I class. From the Fig.4, (1) for A1fI, B1 and Best mitigation carbon emissions, the average carbonation depth is: A1fI > B1 > Best mitigation. The reason is that  $CO_2$  concentration is more high to cause average carbonation depth more large; and the corresponding  $CO_2$  concentration forecast data is A1fI > B1 > Best mitigation for the three carbon emissions. (2) The effective technical measures, for example raising minimum concrete strength and increasing minimum concrete cover thickness, and reducing maximum water cement ratio, the concrete carbonation depth could be decreased with the environment grade increasing.

Table 1 Concrete durability specification<sup>[14]</sup>

Grade	minimum concrete strength	maximum water cement ratio	minimum cover thickness /mm	service life /year
I-A	C30	0.55	20	100
I-B	C35	0.50	30	100
I-C	C40	0.45	40	100

Table 2 Random variable parameters

random variables	mean	standard deviation	probability distribution	references
$f_{cu}/\text{MPa}$	$f_{cuk}+5.7$	5.700	Normal	[16]
$c/\text{mm}$	$c$	5.000	Normal	[14]
$K_{CO_2}$	1.0	Fig.1	Normal	[9]
$K_{mc}$	0.996	0.355	Normal	[6]

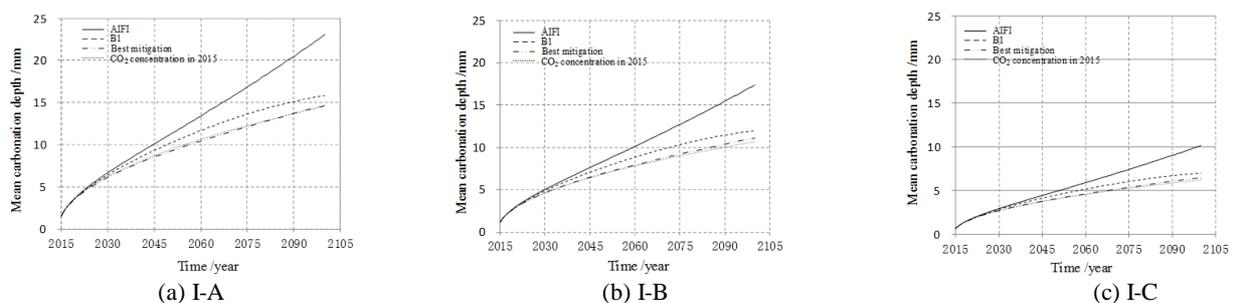


Fig.4 The mean carbonation depth of I environment with different carbonation emission for 100-year designed service life

Table 3 is the comparison of average carbonation depth between three carbon emission scenarios and the standard carbonation level. As shown in Table 3, (1) when  $t=50$  years, the average carbonation depth of A1fI is about 130% of the standard carbonation level; the average carbonation depth of B1 is about 110% of the standard carbonation level; and the average carbonation depth of Best mitigation is the same as that of the standard carbonation level, for its  $CO_2$  concentration is close to that of the standard carbonation level. (2) When  $t=86$  years the average carbonation depth of A1fI is about 160% of the standard carbonation level; the average carbonation depth of B1 is about 120% of the standard carbonation level; and the average carbonation depth of Best mitigation is the same as that of the standard carbonation level.

Table 3 The mean carbonation depth comparison

Grade	t /year	mean carbonation depth /mm							service life /year
		AIFI	B1	Best	Base	AIFI/Base	B1/Base	Best/Base	
I-A	50	14.32	12.22	10.91	11.10	1.290	1.101	0.983	100
I-B	50	10.80	9.27	8.25	8.13	1.328	1.140	1.015	100
I-C	50	6.28	5.39	4.79	4.73	1.326	1.138	1.013	100
I-A	86	23.07	15.84	14.69	14.60	1.580	1.085	1.006	100
I-B	86	17.38	11.96	11.07	10.63	1.635	1.125	1.041	100
I-C	86	10.13	6.95	6.44	6.18	1.639	1.124	1.042	100

**Carbonation Cumulative Failure Probability Corresponding to Different Carbon Emission.**

Fig.5 shows the carbonation cumulative failure probability of three different carbon emission scenarios, A1fI, B1, and Best mitigation emissions for 100 year service life, corresponding to the three grades of Environment I class. According to the Fig.5, (1) for A1fI, B1 and Best mitigation carbon emissions, the carbonation cumulative failure probability is: A1fI>B1>Best mitigation. This shows that the greater the CO<sub>2</sub> concentration is, the greater the carbonation cumulative failure probability is, the more obvious the influence on the durability of RC structures is with time increasing. (2) The carbonation cumulative failure probability of decrease when environmental grade raises. For some effective technical measures are used, such as increasing concrete minimum strength, concrete minimum cover thickness, and reducing maximum water cement ratio, then the concrete carbonation process is decreased.

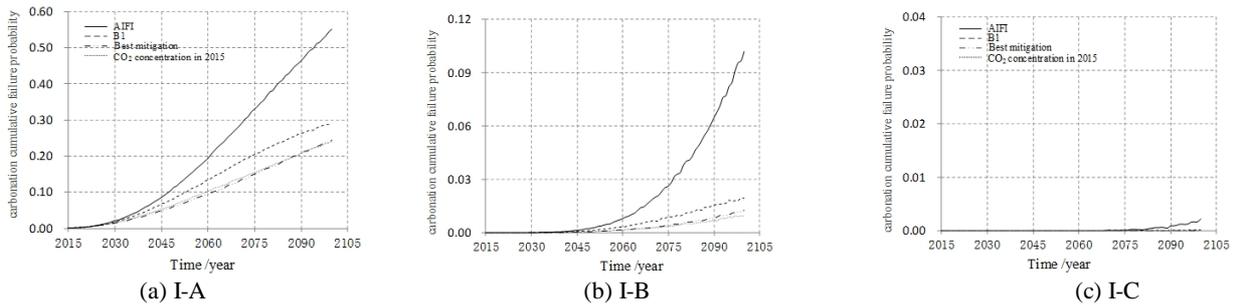


Fig.5 The carbonation cumulative failure probability of I environment with different carbonation emission for 100-year designed service life

**Conclusions**

(i) In this paper, the improved carbonation model is proposed. The comparison of calculation results are done by using the improved model method; and they are in good agreement with those of existing model methods.

(ii) For Environment I [14], A1fI and B1 carbon emission scenarios would cause carbonation depth and carbonization cumulative failure probability to increase; best mitigation of carbon emissions situation is basically not caused by carbonization depth, cumulative failure probability increases; but Best mitigation carbon emission scenario wouldn't lead to the increase of the carbonation depth and the cumulative failure probability. Corresponding to the three carbon emissions, the carbonation depth and cumulative failure probability decreases with the increasing environmental grade, by increasing concrete minimum strength, minimum concrete cover thickness and reducing maximum water cement ratio, and the development of concrete carbonation is delayed.

(iii) According to the global future climate forecast report, the CO<sub>2</sub> concentration in the atmosphere would increase, and the durability of RC structures might be affected. In order to ensure the durability of RC structures and improve the concrete resistance carbonization, concrete strength and concrete cover thickness should be increased.

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