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Abstract

Temperature, relative humidity water-cement ratio, cement contents, strength of concrete etc. and many other parameters, conduct a carbonation model and it is really costly and time consuming to generate a model which is conducted by more parameters. But for maximum structural arrangements, it is not possible to allocate ample resources and time to continue this process. That is why, it is highly required to make sure a less parameter based model or to identify the best one for all performance. This paper work is based on that idea to identify the best model for concrete carbonation, which enables the solution makers to adopt the best situation easily. Two carbonation models were selected for determining the best model between the two models and also the accuracy of each model was checked. Error distribution method was implicated for checking the models. In the end, it was found that the less number of parameters concerned, the more ease and accuracy would be achieved in predicting carbonation depth.

Keywords

Carbonation Depth, Diffusive Coefficient, Constant Parameters, Variable Parameters, Carbonation Depth-Time Relationship Curve, Error Distribution Curve

1. Introduction

Nowadays there is an increasing demand rising from the investors towards the researchers to predict the service life of concrete structures and performance of concrete at various times in the future for easy commercial understanding & application. One of the major concerns of modern structural concrete design methods is the durability design. The residual service life of existing concrete structures is largely determined by its deterioration over time. The deterioration rate of concrete structures depends not only on the construction processes employed and the composition of the materials used in the construction process, but also on the current as well as past environmental exposures [14], [15]. External reinforced concrete elements exposed to CO_2 will eventually have a lower pH, which will reactive the

reinforcement and initiate corrosion, thus causing failure of concrete. A carbonation model helps in determining the carbonation depth (hence predicting the service life) of a structure. An efficient carbonation model should not only be the best possible model on concrete carbonation which provides more accurate results in application, but also be the less parameter based carbonation model which requires less testing & data collection, hence saving time & money of the investors. Using the best prediction model is the most important part of the service life investigation of concrete structures. Relevant parameters of that model must be collected by less effort, since modeling service life of RC structures by considering all the parameters is a difficult task, as most of the parameters remain uncertain in nature. This paper seeks to find a model governed by lesser amounts of parameters to identify the best possible solution of the complex nature of environmental damage of concrete by

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carbonation. Apparently many more methods have been developed by researchers among which, picking one is really necessary for the better establishment of project, in which, all the recommended factors must be satisfied. Verma, S.K., Akhtar, S. & Bhadauria, S. S. (2014) made a probabilistic evaluation of failure (crack initiation & propagation) & estimated the residual life of RC structures [20]. On the contrary, instead of using probability distribution functions & characteristic values for some of the parameters, Luković, M. &Ignjatović, I. (2012) showed that approximate mean values for majority of parameters can be used for establishing carbonation model for the local environmental conditions [8]. Badaoui, A., Badaoui, M. & Kharchi, F. (2013) established a relationship of carbonation depth with the probability density function, taking into account the effect of uncertainty of various parameters i.e. water-cement ratio, relative humidity & the pressure of the carbonic gas randomness on the carbonation depth [2]. Stewart, M. G. et al. & CSIRO Australia (2012) presented a model depicting probability of corrosion damage by predicting CO₂ concentration, temperature, relative humidity, hence mean carbonation depths in Oceania region upto 2100 AD [15]. Wang et al. (2013) presented a set of four-parameter empirical formulae to simulate time dependent carbonation depth of different types of concrete [22]. Arguments had been established there between investigated carbonation data & improved empirical formulae simulations [21], [22]. Carbonation in the concrete infrastructures in the context of the global climate change was analysed by Talukdar et al. (2012) to predict the carbonation depth in unloaded concrete specimens, taking into account the time-varying concentrations of CO2, temperature & humidity [17]. The applicability of the model presented there was verified after calibration using data from accelerated carbonation experiments (Talukdar et al. (2012) [16]. Qu W., Liang M. T. & Liang C. (2002) developed a formula for concrete carbonation by adopting mathematical modeling & applying prediction methods [11].

In this paper, the author established two different models for carbonation with several parameters under various conditions & got an endeavour to compare those & find an relatively efficient model which would give an accurate result of carbonation depth with ease efforts. This work, which concerns selecting an efficient less-parameter carbonation depth model, actually, was a part of a vast ageold commercial-cum-research project consisting of some other activities to fulfill a broader purpose of auditing the adverse effect of corrosion on existing structures in Chittagong city to sense the influence of gradually increasing temperature in coastal region of Bangladesh. The author was in a contractual routine visit of the plant, where he was responsible for the data collection of "PE205" phase work [3]. This phase work included the investigation of workability of Crown Cement, a product of NEB Prosperity Ltd.® (founded in 1963 AD) and the reinforcing steel bars, provided by BSRM (established in 1952 AD), where the samples were subjected to several constant rates of corrosion. All studied relevant field data before 2014 & 2015 AD were collected from previous employees, executive wings as well as record book of TK Engg. Group, which has been the main patron of this investigatory project work since 1978, later with collaboration of BA Consultancy®, Dhaka & Paradise Prestressed Cables®, Dhaka. All the concrete specimens, arrangements & derived field data were preserved in the laboratory of the research cell, financed by TK Engg. Group. The author was in a voluntary taskforce with BA Consultancy®, Dhaka & later, he presented this work of carbonation model in a business idea fare & won "RDF-Champion of a Cause" award for safe, scientific, tradefriendly propagation of an idea. This paper will be useful for the corrosion engineering learners who are interested in acquiring the knowledge of mechanisms by carbonation. Especially graduate students and science workers, who are affected with a sense of aversion and fear instead of enthusiasm while studying this phenomenon of carbonation, shall find it beneficial. The data provided in this paper are with the sole permission of the concerned farms and the author, on behalf of the concerning companies, declares no conflict of interest thereby.

2. Procedures

2.1. Working Methodology



Fig. 1. Overall Methodology of the Project.

The diagram above is the overall projection of the total activities, where two Carbonation models were selected for determining the best model between the two models and also for checking the accuracy of the models. By this methodology, it creates an opportunity to make a decision concerning which model would be preferable and also the prediction of the performance of each model became possible. Here for the sake of simplicity of expression, the two models were named as Model-1 and Model-2. And error distribution method was implicated for checking the models.

2.2. Experimental Procedure

There are two types of cements are manufactured in Bangladesh. Cement type I (CEM-I) & cement type II (CEM-II). Cement type I is OPC (Ordinary Portland Cement) with no SCM (Supplementary Cementious Material) such as fly ash, slag, silica fume etc. Cement type II is PCC (Portland Composite Cement) where SCM or pozzolona is added by replacing the clinker. It is noteworthy that 95% of clinker is required to produce OPC, whereas only 65~80% of clinker is required to produce PCC. In areas of durability problem such as sulphate or chloride attack, PCC performs with more compatibility. Before 2003 AD, OPC was a monopoly in the application of concrete construction in Bangladesh. Since 2003 AD, PCC had been commenced in the usage commercially following European Standard Methods (ESM) [18]. For the experimental procedure, Bashundhara Portland Composite Cement (a product of Bashundhara Group) was used to prepare concrete specimens. It's specification & composition was according to the ASTM C-595. Slag, fly-ash & limestone (SCM) was average 30% [18]. Specific gravity of the cement was 2.916(\pm 0.01). Fineness was about 3650 cm²/g i.e. 365 m²/kg. Amount of cement content (which is the main source of emission in concrete) was 360 kg per unit cubic metre concrete volume.

Tests were conducted with a view to measuring the carbonation depth precisely under several following conditions: for model 1, when only one parameter was considered (in four conditions) & for model 2, when several parameters were taken into account. Again for model 2, four different conditions were adopted: (a) when all parameters (temperature, relative humidity and CO₂ concentration) were kept constant, (b) when only temperature was kept variable, (c) when only relative humidity was kept variable, and (d) when only CO₂ concentration was kept variable. Hence, to generate these data, eight different sets of specimens were prepared. All those specimens were virgin, uncontaminated. At first all concrete specimens (9.85 inch \times 4.70 inch or, 250 mm \times 120 mm) were shaped by using moulds& allowed to cure in a water sink by 28 days, then expelled from the sink & allowed to come to an equilibrium with an average laboratory condition (25°C, 65% RH) over a further period of 28 days more. Next, the specimens were kept in the carbonation chambers having drilled holes. Arrangements for controlling parameters were kept in four different carbonation chambers, in which different set of specimens were subjected to a constant rate of carbonation process throughout the test period. In order to have a physical measurement of the extent of carbonation, freshly exposed surface of the concrete specimens were sprayed with 1% phenolphthalein solution at an interval of 28 days (4 weeks or 0.0767 years, since 1 year includes 52.14 weeks), which was made through dissolving 1g of phenolphthalein in 90cc of ethyl alcohol. The solution was made upto 100 cc by adding distilled water. At the beginning of procedure, the dust was expelled from the hole of each chamber using an air brushcomb. The depths of the uncolored layer (carbonated layer) from the external surface were recorded to the nearest digit (mm) at least 10 positions with the help of slide calipers & the average was taken. The carbonated areas remained unchanged in color (pH > 9), whereas the areas left uncarbonated became alkaline (pH< 9), hence got changed into purple. Hence a neat differentiation between unaffected

& affected areas was possible.

2.3. Computational Procedure for Model 1

2.3.1. Formulae for Model 1 Where Merely One Parameter (Moisture Content) Is Dominant

Tour sets of experimental arrangements were made, which were used to assess the carbonation data for model 1, where the moisture content was the only parameter considered.

From [5], [7] & [19], when w/c< 0.6, formula for model carbonation depth (x_c)

$$x_c$$
 (cm) = R₁ × \sqrt{t} (years) × $\sqrt{[(0.639 \times w/c) - 0.244]}$ (1)

Here, w/c = 0.4 & coefficient of cement type, $R_1 = 1.0$ for Ordinary Portland cement. [5]

Therefore, we get, x_c (cm) = $0.1077\sqrt{t}$ (2)

When w/c < 0.6, formula for model carbonation depth,

$$x_c \text{ (cm)} = R_1 \times \sqrt{t} \times \sqrt{[(0.639 \times \text{w/c}) - 0.244]}$$
 (3)

Here, w/c = 0.5 & coefficient of cement type, R_1 = 1.0 for Ordinary Portland cement.

Therefore, we get,
$$x_c$$
 (cm) = $0.275\sqrt{t}$ (4)

From [5], [7] & [19], when $w/c \ge 0.6$, formula for model carbonation depth

$$x_c$$
 (cm) = R₂× \sqrt{t} (years)× $\sqrt{[(w/c - 0.25)^2 \div (0.345 + w/c)]}$ (5)

Here, w/c = 0.6 & coefficient of cement type, R_2 = 1.0 for Ordinary Portland cement. [5]

Therefore, we get,
$$x_c$$
 (cm) = $0.36\sqrt{t}$ (6)

When $w/c \ge 0.6$, formula for model carbonation depth,

$$x_c \text{ (cm)} = \text{R}_2 \times \sqrt{\text{t}} \times \sqrt{[((w/c - 0.25)^2 \div (0.345 + w/c)]}$$
(7)

Here, w/c = 0.7 & coefficient of cement type, $R_2 = 1.0$ for Ordinary Portland cement.

Therefore, we get, x_c (cm) = 0.44 \sqrt{t} (8)

2.3.2. Error Distribution Curve for Model 1 at w/c = 0.4

Data for carbonation depth-time relationship & error distribution for model 1 at w/c = 0.4 are available in table 1. Figure 2 & figure 3 are representing respectively graph for carbonation depth-time relationship at w/c = 0.4 for model 1 and error distribution curve for model 1 at w/c = 0.4.

Table 1. Data table for carbonation depth-time relationship & error distribution for model 1 at w/c = 0.4.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of <u>exposure days</u> 365	Formula carbonation depth, A = 10 × 0.1077√t (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	0	0	0
October 8, 2014	1	0.0767	0.2983	0.25	19.3200
November 5, 2014	2	0.1534	0.4219	0.35	20.5430

Date of data collection	Total number of exposure months [1 month= 4 weeks]	$Exposure Time, t(years)total number of= \frac{exposure \ days}{365}$	Formula carbonation depth, A = 10 × 0.1077√t (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
December 3, 2014	3	0.2300	0.5165	0.44	17.3860
December 31, 2014	4	0.3100	0.5996	0.51	17.5682
January 28, 2015	5	0.3836	0.6670	0.57	17.0175
February 25, 2015	6	0.4603	0.7307	0.62	17.8548
March 25, 2015	7	0.5370	0.7892	0.68	16.0588
April 22, 2015	8	0.6137	0.8437	0.73	15.5753
May 20, 2015	9	0.6904	0.8949	0.77	16.2208
June 17, 2015	10	0.7671	0.9433	0.80	17.9125
July 15, 2015	11	0.8438	0.9893	0.85	16.1529
August 12, 2015	12	0.9205	1.0333	0.88	17.4204
September 9, 2015	13	0.9973	1.0755	0.93	15.6452
October 7, 2015	14	1.0740	1.1160	0.97	15.0515



Fig. 2. Graph for carbonation depth-time relationship at w/c=0.4 for model 1.



Fig. 3. Error distribution curve for model 1 at w/c=0.4.

The error distribution curve is almost within the range of $15\sim20\%$. That means the amount of error remains almost constant as the exposure time increases gradually, which is within the range of $15\sim20\%$. Mathematically, model 1 at w/c = 0.4 shows a moderate relative error having an average of 17.1234%.

2.3.3. Error Distribution Curve for Model 1 at w/c = 0.5

Data for carbonation depth-time relationship & error distribution for model 1 at w/c = 0.5 are available in table 2. Figure 4 & figure 5 are representing respectively graph for carbonation depth-time relationship at w/c = 0.5 for model 1 and error distribution curve for model 1 at w/c = 0.5.

Table 2. Data table for carbonation depth-time relationship & error distribution for model 1 at $w/c = 0.5$.									
Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of = <u>exposure days</u> 365	formula carbonation depth, A = 10 ×0.275√t (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100				
September 10, 2014	0	0	0	0	0				
October 8, 2014	1	0.0767	0.7616	0.66	15.394				
November 5, 2014	2	0.1534	1.0771	0.94	14.585				
December 3, 2014	3	0.2300	1.3188	1.15	14.678				
December 31, 2014	4	0.3100	1.5311	1.33	15.120				
January 28, 2015	5	0.3836	1.7032	1.47	15.864				
February 25, 2015	6	0.4603	1.8657	1.62	15.167				
March 25, 2015	7	0.5370	2.0152	1.76	14.500				
April 22, 2015	8	0.6137	2.1543	1.90	13.384				
May 20, 2015	9	0.6904	2.2850	2.00	14.250				
June 17, 2015	10	0.7671	2.4086	2.09	15.244				
July 15, 2015	11	0.8438	2.5260	2.17	16.406				
August 12, 2015	12	0.9205	2.6384	2.30	14.713				
September 9, 2015	13	0.9973	2.7463	2.38	15.391				
October 7, 2015	14	1.0740	2.8499	2.49	14.454				



Fig. 4. Graph for carbonation depth-time relationship at w/c=0.5 for model 1.

The error distribution curve is almost within the range of $13\sim17\%$. That means the amount of error remains almost predictable within the range of $13\sim17\%$, which is comparatively lower than that of previous case (w/c = 0.4). Mathematically, model 1 at w/c = 0.5 shows a moderate relative error having an average of 14.939%.



Fig. 5. Error distribution curve for model 1 at w/c = 0.5.

2.3.4. Error Distribution Curve for Model 1 at w/c= 0.6

Data for carbonation depth-time relationship & error distribution for model 1 at w/c = 0.6 are available in table 3. Figure 6 & figure 7 are representing respectively graph for carbonation depth-time relationship at w/c = 0.6 for model 1 and error distribution curve for model 1 at w/c = 0.6.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of $= \frac{exposure \ days}{365}$	formula carbonation depth, A = 10 × 0.36√t (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	0	0	0
October 8, 2014	1	0.0767	0.9970	0.90	10.778
November 5, 2014	2	0.1534	1.4099	1.29	9.294
December 3, 2014	3	0.2300	1.7265	1.56	10.673
December 31, 2014	4	0.3100	2.0044	1.83	9.530
January 28, 2015	5	0.3836	2.2297	2.04	9.299
February 25, 2015	6	0.4603	2.4424	2.25	8.551
March 25, 2015	7	0.5370	2.6381	2.40	9.921
April 22, 2015	8	0.6137	2.8202	2.61	8.054
May 20, 2015	9	0.6904	2.9913	2.75	8.775
June 17, 2015	10	0.7671	3.1530	2.88	9.479
July 15, 2015	11	0.8438	3.3069	2.99	10.599
August 12, 2015	12	0.9205	3.4539	3.15	9.648
September 9, 2015	13	0.9973	3.5951	3.28	9.607
October 7, 2015	14	1.0740	3.7308	3.39	10.053

 Table 3. Data table for carbonation-depth time relationship & error distribution for model 1 at w/c=0.6.



Fig. 6. Graph for carbonation depth-time relationship at w/c=0.6 for model 1.

The error distribution curve is almost within the range of $8 \sim 11\%$. That means the amount of error exists within the range of $8 \sim 11\%$, which is comparatively lower than that of previous cases (w/c = 0.4 & 0.5) both; however whimsicality of the curve is easily manifested. If an error distribution curve is plotted with help of probabilistic approach (where data is to be manipulated upto exposure time of 20 years), the curve becomes almost a straight line and parallel to the x-axis (i.e. gradual increase in exposure time) [3]. Mathematically,

model 1 at w/c = 0.6 shows a lesser relative error having an average of 9.59%.



Fig. 7. Error distribution curve for model 1 at w/c = 0.6.

2.3.5. Error Distribution Curve for Model 1 at w/c = 0.7

Data for carbonation depth-time relationship & error distribution for model 1 at w/c = 0.7 are available in table 4. Figure 8 & figure 9 are representing respectively graph for carbonation depth-time relationship at w/c = 0.7 for model 1 and error distribution curve for model 1 at w/c = 0.7.

Table 4. Data table f	or carbonation-depth	time relationship & err	ror distribution for model	t at w/c = 0.7.
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Date of data collection	Total number of exposure months [1 month= 4 weeks]	$\frac{\text{Exposure Time, t(years)}}{{}_{act}} = \frac{exposure days}{365}$	formula carbonation depth, A = $10 \times 0.44 \sqrt{t}$ (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	0	0	0
October 8, 2014	1	0.0767	1.2186	1.15	5.965
November 5, 2014	2	0.1534	1.7233	1.60	7.706
December 3, 2014	3	0.2300	2.1102	1.96	7.663
December 31, 2014	4	0.3100	2.4498	2.30	6.513
January 28, 2015	5	0.3836	2.7252	2.57	6.039
February 25, 2015	6	0.4603	2.9852	2.80	6.614
March 25, 2015	7	0.5370	3.2243	3.00	7.477
April 22, 2015	8	0.6137	3.4469	3.20	7.716
May 20, 2015	9	0.6904	3.6560	3.42	6.900
June 17, 2015	10	0.7671	3.8537	3.63	6.163
July 15, 2015	11	0.8438	4.0418	3.75	7.781
August 12, 2015	12	0.9205	4.2215	3.97	6.335
September 9, 2015	13	0.9973	4.3941	4.09	7.435
October 7, 2015	14	1.0740	4.5599	4.25	7.292



Fig. 8. Graph for carbonation depth-time relationship at w/c = 0.7 for model 1.



Fig. 9. Error distribution curve for model 1 at w/c = 0.7.

The error distribution curve is almost by the range of 6~8%. That means the amount of error remains almost predictable by the range of 6~8%, which is the lowest amongst that of all previous cases (w/c = 0.4, 0.5 & 0.6). However a high degree of whimsicality is evident here (zigzag). It was found that if an error distribution curve is plotted with help of a probabilistic approach (where data is to be manipulated upto exposure time of 35 years), the curve becomes almost a straight line and parallel to the x-axis (i.e. gradual increase in exposure time) [3]. Mathematically, model 1 at w/c = 0.7 shows the least relative error having an average of 6.97%.

2.4. Computational Procedure for Model 2

2.4.1. Formulae for Model 2 Where More Than One Parameter Are Under Consideration

From [10] & [13], we can write formula for effective diffusive coefficient of CO_2 at 20°C temperature,

$$D (mm) = 6.1 \times 10^{-6} \times A^3 \times (1 - RH)^{2.2}$$
(9)

where,
$$A = \left(\frac{M}{N}\right)$$
 (10)

$$M = \frac{[W - 0.267(C + kP)]}{1000}$$
(11)

$$N = \left[\frac{C + kP}{\rho_c}\right] + \left(\frac{W}{\rho_w}\right)$$
(12)

Relative Humidity, RH = 65% = 0.65

Water content in concrete, $W = 180 \text{ kgm}^{-3}$

Cement content in concrete, C=360kgm⁻³

That makes required w/c content = 0.5.

Efficiency factor of supplementary cementious material, k

= 1 for indoor storage. [4]

Concrete density, $\rho_c = 2400 \text{kgm}^{-3}$

Density of water, $\rho_w = 1000 \text{kgm}^{-3}$

Amount of SCM, $P = 30 \text{ kgm}^{-3}$

According to the carbonation depth model recommended by Duracrete (1998), Yoon et al. (2007) and others [4, 5, 9, 23], here a formula was established to work out formula carbonation depth, x_c .

$$x_c \text{ (mm)} = I \times J \times K$$
 (13)

where,
$$I = \sqrt{(2 \times k_1 \times k_2 \times k_3 \times \Delta c)}$$
 (14)

 k_1 = coefficient of concrete humidity = 1.0

 k_2 = coefficient of time of early curing = 1.0

 k_3 = coefficient of concrete bleeding = 1.0

 Δc = difference of CO₂ concentration on the surface of concrete & inside the concrete = c_0 , concentration of CO₂ in the air = 0.685×10^{-3} kgm⁻³ [5], [12]

From [4], [5] & [23], we write,
$$J = \sqrt{(\frac{D1 \times t}{a})}$$
 (15)

$$D_1 = \text{diffusion coefficient at 65\% RH \& 25^{\circ}\text{C} (mm^2/\text{year}) = D \\ \times f(T)$$
(16)

where D = effective diffusion coefficient of CO_2 at 20°C &65% RH and

f(T) = effective diffusive coefficient factor due to temperature increase above 20°C.

t = time of exposure (year)

a = amount of CO₂ for concrete full carbonation, kg/m³=

$$0.75 \times C \times [CaO] \times \alpha_{H} \times (M_{CO_2} \div M_{CaO})$$
 (17)

Cement content in concrete, $C= 360 \text{kg/m}^3$ [CaO] = CaO content in the cement composition = 65% = 0.65

$$\left(\text{for}\frac{\text{w}}{\text{c}} \sim 0.5\right)$$
 we write, α_{H} = degree of hydration of cement =
 $1 - e^{-3.385 \text{w/c}} = 0.816$ (18)

 M_{CO_2} = molar masses of CO_2 = 44.0 M_{CaO} =molar masses of CaO = 56.1 Therefore, a = 112.32 kg/m³

$$\mathbf{K} = \left(\frac{t_o}{t}\right)^n \tag{19}$$

 t_0 = one climatic year (a reference period of September 10, 2014 AD)

t = time of exposure (year) = t - September 10, 2014

n = coefficient of influence of changes in external conditions, for laboratory conditions, n = 0. That makes K = 1.

From [6], [14] & [16], we established formula for effective diffusive coefficient factor at t°C (T K) & 65% RH,

$$f(T) = \mathbf{e}^{\left[\left(\frac{E}{R}\right)\left(\frac{1}{293} - \frac{1}{273 + T}\right)\right]}$$
(20)

Here, E = activation energy = 40 kJ/mol.K

 $R = 8.314 \times 10^{-3} \text{ kJ/mol.K}$

T = absolute temperature (K) = $(273+t^{\circ}C)$ K

Value for carbonation depth for model 2 after an exposure of 28 days, when all parameters were kept constant, was worked out following.

Using (9), where M = 0.07587, N= 0.3425, we get D at 20°C & 65% = $6.583 \times 10^{-9} \text{m}^2/\text{sec.} = 6.583 \times 10^{-9} \times 1000 \times (365.25 \times 24 \times 3600) \text{ mm}^2/\text{year} = 0.208 \times 10^6 \text{mm}^2/\text{year}.$

Using (20), effective diffusive coefficient factor at 25°C & 65% RH, f(298) = 1.317.

Therefore, effective diffusion coefficient at 25°C & 65% RH, $D_1 = D \times f(T) = (1.317 \times 0.208 \times 10^6) \text{ mm}^2/\text{year} = 0.2740 \times 10^6 \text{ mm}^2/\text{year}.$

Using (13), where I = 0.037, J = 13.6787 & K = 1, we get, $x_c = 0.50611* \text{ mm} \sim 0.506 \text{ mm}.$

2.4.2. Error Distribution Curve for Model 2, All Parameters Remaining Constant

Constant temperature (25°C), relative humidity (65%) & CO_2 concentration (1%) were kept. Using eqn. 01 & 02, values of D & x_c are determined.

$$x_{c} \text{ (mm)} = \mathbf{I} \times \mathbf{J} \times \mathbf{K}$$

= 0.037 × $\sqrt{\left(\frac{0.2740 \times 10^{-6} \times t}{112.32}\right)} \times 1.00$
= 1.8275 \sqrt{t} (21)

Data for carbonation depth-time relationship & error

distribution for model 2, when all parameters remain constant, are available in table 5. Figure 10 and figure 11 are representing respectively a graph depicting comparison of experimental results vs. formulae prediction (control), uncontaminated concrete & the error distribution curve for Model-2, all parameters remain constant.

Table 5. Data table for carbonation depth-time relationship & error distribution for model 2, all parameters remaining constant.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of $= \frac{exposure days}{365}$	Formula carbonation depth, A = 1.8275√t (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	0	0	0
October 8, 2014	1	0.0767	0.5061*	0.40	26.525
November 5, 2014	2	0.1534	0.7158	0.56	27.821
December 3, 2014	3	0.2300	0.8764	0.68	28.882
December 31, 2014	4	0.3100	1.0175	0.79	28.797
January 28, 2015	5	0.3836	1.1319	0.89	27.180
February 25, 2015	6	0.4603	1.2399	0.98	26.520
March 25, 2015	7	0.5370	1.3392	1.05	27.543
April 22, 2015	8	0.6137	1.4316	1.13	26.690
May 20, 2015	9	0.6904	1.5185	1.20	26.542
June 17, 2015	10	0.7671	1.6006	1.26	26.984
July 15, 2015	11	0.8438	1.6787	1.32	27.174
August 12, 2015	12	0.9205	1.7534	1.38	27.058
September 9, 2015	13	0.9973	1.8250	1.44	26.736
October 7, 2015	14	1.0740	1.8939	1.50	26.260



Fig. 10. Comparison of experimental results vs. formulae prediction (control), uncontaminated concrete.



Fig. 11. Error distribution curve for Model-2, all parameters remaining constant.

The error distribution curve is within the range of 25~30%.

That means the amount of error is stable within the range of $25\sim30\%$. Mathematically, model 2 gives a moderate relative error having an average of 27.194%, when all parameters remain constant.

2.4.3. Error Distribution Curve for Model 2, Temperature Remaining Variable and Rest Two Parameters Remaining Constant

Error distribution curve was derived, where temperature was allowed to vary in the range of 25°C to 39°C, while other two parameters, relative humidity (65%) and CO₂ concentration (1%), were kept constant. Using eqn. 01 & 02, values of D & x_c are determined.

$$x_{c} \text{ (mm)} = \mathbf{I} \times \mathbf{J} \times \mathbf{K}$$

= 0.037 × $\sqrt{\left(\frac{\mathbf{D}1 \times \mathbf{t}}{112.32}\right)} \times 1.00$
= 3.491 × 10⁻³ $\sqrt{(\mathbf{D}1 \times \mathbf{t})}$ (22)

Data for formula carbonation depth for variable temperature, while rest two parameters remain constant, are available in table 6. Table 7 provides data for carbonation depth-time relationship & error distribution for model 2, when temperature remains variable and rest two parameters remain constant. Figure 12 represents a graph showing comparison of experimental results vs. model prediction (variable temperature), uncontaminated concrete. On the other hand, figure 13 displays the error distribution curve for Model-2, temperature remaining variable and rest two parameters remaining constant.

Table 6. Data table for formula carbonation depth for variable temperature, while rest two parameters remaining constant.									
Date of data collection	Exposure Time, t (years) total number of $= \frac{exposure days}{365}$	$T^{\circ}C =$ 25+ $\frac{14}{1.074}t$	TK = (273+T°C) K	effective diffusive coefficient factor at T K & 65% RH	effective diffusive coefficient,D ₁ ×10 ⁶ mm ² /year	Formula carbonation depth= 3.491 × $10^{-3}\sqrt{(D_1 \times t)}$ (mm)			
September 10, 2014	0	25	298	1.317	0.2740	0			
October 8, 2014	0.0767	26	299	1.390	0.2891	0.520			
November 5, 2014	0.1534	27	300	1.467	0.3051	0.755			
December 3, 2014	0.2300	28	301	1.547	0.3220	0.950			
December 31, 2014	0.3100	29	302	1.631	0.3392	1.131			
January 28, 2015	0.3836	30	303	1.719	0.3576	1.293			
February 25, 2015	0.4603	31	304	1.812	0.3769	1.454			
March 25, 2015	0.5370	32	305	1.908	0.3969	1.612			
April 22, 2015	0.6137	33	306	2.010	0.4181	1.768			
May 20, 2015	0.6904	34	307	2.114	0.4397	1.923			
June 17, 2015	0.7671	35	308	2.225	0.4628	2.080			
July 15, 2015	0.8438	36	309	2.340	0.4867	2.237			
August 12, 2015	0.9205	37	310	2.461	0.5120	2.297			
September 9, 2015	0.9973	38	311	2.587	0.5381	2.557			
October 7, 2015	1.0740	39	312	2.718	0.5653	2.720			

Table 7. Data table for carbonation depth-time relationship & error distribution for model 2, temperature remaining variable and rest two parameters remaining constant.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of $= \frac{exposure \ days}{365}$	Formula carbonation depth, A = 3. 18 × $10^{-3}\sqrt{D_1 \times t}$ (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	0	0	0
October 8, 2014	1	0.0767	0.520	0.35	48.571
November 5, 2014	2	0.1534	0.755	0.51	48.039
December 3, 2014	3	0.2300	0.950	0.65	46.154
December 31, 2014	4	0.3100	1.131	0.77	46.883
January 28, 2015	5	0.3836	1.293	0.88	46.932
February 25, 2015	6	0.4603	1.454	0.99	46.869
March 25, 2015	7	0.5370	1.612	1.11	45.225
April 22, 2015	8	0.6137	1.768	1.20	47.333
May 20, 2015	9	0.6904	1.923	1.32	45.682
June 17, 2015	10	0.7671	2.080	1.42	46.479
July 15, 2015	11	0.8438	2.237	1.52	47.171
August 12, 2015	12	0.9205	2.297	1.57	46.306
September 9, 2015	13	0.9973	2.557	1.73	47.803
October 7, 2015	14	1.0740	2.720	1.86	46.237



50 40 30 50 70 10 0 0 5 10 15 time (4 weeks)

Fig. 12. Comparison of experimental results vs. formulae prediction (variable temperature), uncontaminated concrete.

Fig. 13. Error distribution curve for Model-2, temperature remaining variable and rest two parameters remaining constant.



 x_{c}

The error distribution curve is within the range of $40 \sim 50\%$. The amount of error is stable within the range of $46 \sim 48\%$. Mathematically, model 2 gives a comparatively higher relative error having an average of 46.835%, when only temperature remains variable and rest two parameters remain constant.

2.4.4. Error Distribution Curve for Model 2, Relative Humidity Remaining Variable and Rest Two Parameters Remaining Constant

Error distribution curve was derived, where relative humidity was allowed to vary from 60% to 81%, while two other parameters, temperature (25°C) and CO₂ concentration (1%), were kept constant. Using eqn. (9) & (13), values of D & x_c are determined.

At 20°C, D =
$$2.093 \times 10^6 \times (1 - \text{RH})^{2.2} \text{ mm}^2/\text{year}$$

Effective diffusive coefficient factor at $25^{\circ}C = 1.317$

Therefore, at 25°C,
$$D_1 = 1.317 \times 2.093 \times 10^6 \times (1 - RH)^{2.2} \text{ mm}^2/\text{vear} = 2.76 \times 10^6 \times (1 - RH)^{2.2} \text{ mm}^2/\text{vear}$$

$$(mm) = 1 \times J \times K$$

= 0.037 × 156.76\sqrt{[(1 - RH)^{2.2} \times t] \times 1.00}
= 5.80\sqrt{[(1 - RH)^{2.2} \times t]} (23)

Table 8 represents data for model carbonation depth, carbonation depth-time relationship & error distribution for model 2, relative humidity remaining variable and rest two parameters remaining constant. Figure 14 represents a graph for the comparison of experimental results vs. formula prediction (variable relative humidity), uncontaminated concrete. On the contrary, figure 15 depicts the error distribution curve for model 2, relative humidity remaining variable and rest two parameters remaining constant.

 Table 8. Data table for carbonation depth-time relationship & error distribution for model 2, relative humidity remaining variable and rest two parameters remaining constant.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t(years) total number of $= \frac{exposure days}{365}$	Relative Humidity, RH = $60+\frac{21t}{1.0740}t$	effective diffusive coefficient,D ₁ ×10 ⁶ mm ² /year	Formula carbonation depth, A = $5.80\sqrt{(1 - RH)^{2.2} \times t}$ (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	60.0	0.3677	0	0	0
October 8, 2014	1	0.0767	61.5	0.3374	0.556	0.37	50.270
November 5, 2014	2	0.1534	63.0	0.3092	0.765	0.51	50.000
December 3, 2014	3	0.2300	64.5	0.2823	0.885	0.59	50.000
December 31, 2014	4	0.3100	66.0	0.2570	0.984	0.60	49.091
January 28, 2015	5	0.3836	67.5	0.2324	1.047	0.70	49.571
February 25, 2015	6	0.4603	69.0	0.2095	1.095	0.72	52.083
March 25, 2015	7	0.5370	70.5	0.1878	1.111	0.73	52.192
April 22, 2015	8	0.6137	72.0	0.1675	1.120	0.73	53.425
May 20, 2015	9	0.6904	73.5	0.1483	1.118	0.74	51.081
June 17, 2015	10	0.7671	75.0	0.1305	1.106	0.74	49.459
July 15, 2015	11	0.8438	76.5	0.1139	1.083	0.74	46.351
August 12, 2015	12	0.9205	78.0	0.0985	1.052	0.74	42.162
September 9, 2015	13	0.9973	79.5	0.0843	1.013	0.74	36.892
October 7, 2015	14	1.0740	81.0	0.0714	0.967	0.75	28.933



Fig. 14. Comparison of experimental results vs. formulae prediction (variable relative humidity), uncontaminated concrete.

Fig. 15. Error distribution curve for model 2, relative humidity remaining variable and rest two parameters remaining constant.

Due to the presence of the expression $(1 - RH)^{2.2}$, the dependent output recedes after reaching a maximum value.

Here the formula depth of carbonation commences from 0, increases, & after reaching a maximum value of 1.019 for a certain value of the relative humidity 72%, it started declining. Against the formula carbonation depth values, it was observed that after increasing, the experimental values of carbonation depth reach a certain value & then it stopped increasing for a certain value of relative humidity 70.5% [after that actually the increases were infinitesimally tiny]. Hence the latter portion of the error distribution curve became parabolic. But in the former portion, the amount of relative error was within the range of 50~55% with an average of 51.26375%, which is quite larger than those of previous conditions.

2.4.5. Error Distribution Curve for Model 2, CO_2 Concentration Remaining Variable and Rest Two Parameters Remaining Constant

Error distribution curve was derived, where CO_2 concentration was allowed to vary (1% ~ 15%), while two

other parameters, temperature (25°C) and relative humidity (65%), were kept constant. Using eqn. (9) & (13), values of D & x_c are determined.

$$x_c = I \times J \times K = 1.414 \sqrt{c_0} \times 49.391 \sqrt{t}$$

= 69.84 $\sqrt{(c_0 t)}$ (24)

Table 9 represents data table for formula carbonation depth, carbonation depth-time relationship & error distribution for model 2, when CO_2 concentration was remaining variable and rest two parameters remaining constant. Figure 16 represents a graph for comparing experimental results with model prediction (variable CO_2 concentration), uncontaminated concrete. Figure 17 shows the error distribution curve for model 2, CO_2 concentration remaining variable and rest two parameters remaining remaining constant.

Table 9. Data table for carbonation depth-time relationship & error distribution for model 2, when CO₂ concentration was remaining variable and rest two parameters remaining constant.

Date of data collection	Total number of exposure months [1 month= 4 weeks]	Exposure Time, t (years)= total number of <u>exposure days</u> 365	Percentage increase in CO ₂ concentration $(\%) = 1 + \frac{14t}{1.0740}$	concentration of CO ₂ , c ₀ (10 ⁻³ kgm ⁻³	Formula carbonation depth, A = $69.84\sqrt{(c_0 t)}$ (mm)	Laboratory carbonation depth, B (mm)	Simulated error (%) = (A-B ÷ B) × 100
September 10, 2014	0	0	1	0.690	0	0	0
October 8, 2014	1	0.0767	2	0.704	0.5132	0.37	38.703
November 5, 2014	2	0.1534	3	0.711	0.7294	0.53	37.623
December 3, 2014	3	0.2300	4	0.718	0.8975	0.65	38.077
December 31, 2014	4	0.3100	5	0.725	1.0470	0.76	37.763
January 28, 2015	5	0.3836	6	0.731	1.1695	0.85	37.588
February 25, 2015	6	0.4603	7	0.738	1.2872	0.93	38.405
March 25, 2015	7	0.5370	8	0.745	1.3969	1.01	38.317
April 22, 2015	8	0.6137	9	0.752	1.5003	1.09	37.615
May 20, 2015	9	0.6904	10	0.759	1.5987	1.16	37.819
June 17, 2015	10	0.7671	11	0.766	1.6930	1.23	37.642
July 15, 2015	11	0.8438	12	0.773	1.7837	1.29	38.271
August 12, 2015	12	0.9205	13	0.780	1.8714	1.35	38.622
September 9, 2015	13	0.9973	14	0.787	1.9566	1.42	37.789
October 7, 2015	14	1.0740	15	0.794	2.0395	1.48	37.804



Fig. 16. Comparison of experimental results vs. formulae prediction (variable CO_2 concentration), uncontaminated concrete.

The error distribution curve is within the range of 35~40%. The amount of error is stable within this range.

Mathematically, model 2 gives a comparatively lesser relative error having an average of 37.999%, when only CO₂ concentration remains variable and rest two parameters remain constant.



Fig. 17. Error distribution curve for model 2, CO_2 concentration remaining variable and rest two parameters remaining constant.

3. Conclusion

From the carbonation depth-time relationship curves & error distribution curves of both models under several conditions, it is evident that Model-1 gives less relative error and fewer differences between experimental data from laboratory and data predicted through formulae. Hence, Model-1 ensures to be a comparatively more viable & accurate selection and offers comfort & saves the time & economy thereby. That means, the less parameters are involved, the more accuracy can be enabled in prediction of the carbonation depth, and hence the durability, i.e. service life of reinforced concrete structures.

Dissimilarities between the data obtained from using carbonation depth formulae and the data obtained from experimental procedures are maybe due to generalization of formulae conditions, as those formulae proposed by previous researchers are just analytical propositions or logical assumptions or mere mathematical interpretations regarding respective local (not global, it seems) environments. That is why carbonation phenomena in Bangladesh, especially in temperate zone like Rajshahi division and coastal areas like Chittagong division, needs further study and surveys and hence concerns renovated formulations. Moreover there may be mistakes in data entry or errors in measuring experimental data from laboratory. To get a more precise analysis, the author is currently involved in making another study concerning a statistical methodology for checking the accuracy of each model (model-1 & model-2) by implementing a probabilistic approach.

As this research work is a mere part of an on-going commercial project with broader vision; the incumbent worker(s) would continue the work in future according to the concept interest of investors. Here data with 28 days-interval was simulated, instead the incumbent would work with 1-year interval, which would give a vastly broader scope to analyse & formulate the traits of carbonation in the concerned districts of Bangladesh with a greater accuracy. There are works also going on for carbonation behavior analyses in case of chlorine contaminated concrete by the same research consultancy group coworkers. The author is now in another task of assessing the affect of carbonation over RCC bridges in several rural subdistricts of Bangladesh, which concerns meteorological data collection and establishment of corrosion properties (i.e. carbonation depth etc.) with natural parameters on a monthly basis. All these collected data would be re-approached in a statistical manner for prediction of corrosion mechanisms involving some other parameters i.e. compressive and tensile strength of concrete, concrete admixtures etc. There is a plan for the investigation of the affect of corrosion phenomena over prestressed concrete properties in coastal regions of Bangladesh. Then these works will be combined and manipulated for a wider outcome and formulation.

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