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Predicting depth of carbonation of concrete for varying climatic conditions

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ABSTRACT

Corrosion of reinforcing steel is the result of poor durability performance of reinforced concrete structures. Carbonation of concrete caused by the diffusion of carbon dioxide into the concrete is one of the major factors responsible for reinforcing steel corrosion. A carbonation model which predicts the rate and extent of carbonation is useful not only in the design phase by facilitating the right choice of materials, but also in helping to assess the rate and extent of carbonation of existing structures. Most of the currently available carbonation models predict the depth of carbonation based on constant humidity conditions. The influence of varying climatic conditions (i.e., drying and wetting cycles) is not taken into consideration in predicting depth of carbonation. However, current approaches may be conservative or non-conservative, depending on the different climatic conditions which influence the rate of carbonation. The main aim of this study was to develop or modify a carbonation model to as to accommodate varying climatic conditions. The carbonation model developed is validated based on experimental data from specimens prepared with different concrete mixes exposed to natural carbonation.

Keywords: Carbonation model, drying and wetting cycles, Oxygen Permeability Index (OPI) test

1. INTRODUCTION

Carbonation-induced corrosion is one of the main causes of deterioration of reinforced concrete (RC) elements or structures. Carbonation-induced corrosion occurs mainly due to the diffusion of carbon dioxide (CO_2) from the atmosphere into the capillary pores of concrete, where it reacts with the products of cement hydration resulting in the reduction of pH of the pore solution from between 12.5 - 13.5 to a value of about 8.3. This reduction in the alkalinity destabilises the protective oxide layer and renders the steel susceptible to corrosion (Steffens et al., 2002; Neville, 2007).

To address the issue of carbonation of concrete, various empirical, analytical and numerical models have been developed to predict the depth of carbonation with time. (Parrott, 1987; Papadakis et al., 1989; Steffens et al., 2002) In South Africa, an empirical model based on correlation between permeability and measured carbonation depths in concretes with different binders was developed (Yam, 2004). The advantage to such an approach is that the permeability coefficient is an output of the Oxygen Permeability Index (OPI) test, which is a Durability Index (DI) test developed in South Africa for performance-based durability design. The OPI test provides an engineering measure of the resistance of cover concrete towards gaseous transport for varying constituent materials properties, and accounts for construction practices (Beushausen and Alexander, 2009).

However, the empirical carbonation model referred to above does not consider the influence of chemistry or the aggressiveness of the environment. A more fundamental carbonation model based on a permeability coefficient from the OPI test as the key material variable, and taking into account the effect of material and relative humidity (RH) on diffusion and carbonation, was developed by Salvoldi (2015) using accelerated carbonation test data. Though the model incorporates the impact of ambient relative humidity and carbonatable material, the influence of varying climatic condition is not taken into account, and hence the model underestimates the carbonation resistance of concrete exposed to rain (drying-wetting cycles). This paper discusses an improved carbonation model, which is being developed by adopting the modelling framework by Salvoldi (2015), and incorporating the effect of drying-wetting cycles. Thereafter the model is 'validated' using experimental results of carbonation tests conducted on concretes subjected to varying climatic conditions and for concretes with different binders.

2. EXPERIMENTAL PROGRAMME, TEST RESULTS AND DISCUSSION

Table 1 summarizes the details of the concrete mix constituents and proportions along with the oxygen permeability coefficient (k), and the depth of carbonation after 1000 days of exposure. Six different concrete mixes with 0.45 and 0.55 water: binder ratios (w/b) using a combination of cement (CEM I 52.5 N), fly ash (at 30% replacement) and granulated blast furnace slag (GGBS) (at 50% replacement) were used in the current study. The slump of the concrete was in the range of 90-120 mm. In order to achieve a wide range of microstructure, the concrete specimens were exposed to three different curing conditions.

- Curing –A: Water bath maintained at a temperature of 23 - 25°C till 28 days after casting
- Curing –B: 1 day in moulds, then inside lab at 20-22°C and 60-70% RH, till 28 days after casting
- Curing –C: 1 day in moulds, 6 days covered by plastic, then in air inside lab at 20-22°C and 60-70% RH, till 28 days after casting

Table 1. Concrete mix proportions, Permeability Coefficient and Carbonation Depth

Mix Designation	**CEM I 52.5N**	**FA (30%)**	**GGBS (50%)**	**Crusher Sand**	**Dune sand**	**13mm Granite**	**w/b**	**Permeability coefficient (k) from OPI test**			**Carbonation Depth @1000 days of Exposure**					
											Sheltered (WS)			**Exposed (WE)**		
								Curing-A	Curing-B	Curing-C	Curing-A	Curing-B	Curing-C	Curing-A	Curing-B	Curing-C
	(kg/m^3)							**(m/s)**			**(mm)**			**(mm)**		
0.45 PC	377	0	0	512	341	1000	0.45	4.23E-11	5.47E-11	7.28E-11	0.0	3.5	0.5	0.0	2.6	0.0
0.45 FA	264	113	0					3.59E-11	1.13E-10	8.34E-11	3.4	8.7	5.8	2.7	4.3	3.4
0.45 GS	189	0	189					1.31E-11	1.19E-10	8.90E-11	2.1	8.1	5.4	0.0	4.7	4.1
0.55 PC	309	0	0	553	368	1000	0.55	4.89E-11	1.01E-10	9.31E-11	0.0	6.4	4.6	0.0	3.6	4.0
0.55 FA	216	93	0					5.84E-11	2.87E-10	3.13E-10	7.6	11.0	9.7	5.6	8.1	6.9
0.55 GS	155	0	155					1.88E-11	2.91E-10	1.17E-10	7.2	12.8	11.1	4.2	9.6	8.8

The oxygen permeability index (OPI) test is a performance-based durability index test used to measure the gas permeability coefficient of concrete, which can be correlated to the carbonation resistance. The test was done on concrete samples at the age of 28 days after casting as per (UCT, 2010). The test results (permeability coefficients, k) are given in Table 1, and reflect the microstructure of the concrete. It can be observed from the test results that with increase in w/b, the permeability of the concrete mixes increases which is due to the increase in pore connectivity resulting in poor microstructure. Similar trends were observed by Salvoldi et al. (2015). The influence of curing is also reflected in the OPI test results as it can be seen that samples with Curing-B, which is the poor curing condition, show higher permeability.

In order to understand the carbonation mechanism of concrete with different microstructures and exposure conditions, concrete prism of dimensions 100x100x200 mm were cast and exposed to the environment for natural carbonation. The specimens were coated with epoxy after curing, except two opposite faces perpendicular to the casting direction. The specimens were then exposed to the natural environment without any preconditioning. To accommodate and understand the variation in climatic condition on concrete carbonation, two different exposure conditions were adopted for the same site (Johannesburg (-26.192209, 28.029418)). The first set of samples was sheltered from rain and the other set was exposed such that it could be wetted by rain.

The carbonation depth was measured using the phenolphthalein test (using a 1% solution of Phenolphthalein). The measurements were taken at regular intervals and the data at the initial stages were used for the model development. The model developed is validated using the depth of carbonation at 1000 days of exposure, as tabulated in Table-1. The carbonation depth at 1000 days of exposure correlates well with the permeability coefficient, and increases with poor curing (Curing-B). Also, the carbonation depth was observed to be higher with increase in w/b and with the addition of supplementary cementitious materials (fly ash and slag), which agrees with the Salvoldi et al. (2015).

3. CARBONATION MODEL DEVELOPMENT

The basic mechanism of carbonation is the diffusion of atmospheric CO_2 through the pore system in concrete. Thus, most carbonation models are based on Fick's laws of diffusion. Assuming the diffusion coefficient and the amount of carbonatable material are considered constant throughout the concrete matrix; and the carbonation depth is given by a reaction front separating the carbonated and non-carbonated concrete, Kropp (1995) related the carbonation depth with time as follows:

$$X = \sqrt{2D \, {}^{c}\!/_{a}} \times \sqrt{t} \tag{1}$$

Where X is the depth of carbonation (mm); 'c' is the environmental carbon dioxide concentration (mol/m^3); 'a' is the amount of carbonatable material in the concrete matrix (mol/m^3), D is the effective diffusion coefficient (mm^2/day) and t is the time of exposure in days.

Most carbonation models correlate the diffusion coefficient with porosity (Papadakis et al., 1991; Thiery et al., (2007). However, this is not always the best approach since the porosity is not the true representation of the transport phenomena. As discussed in the previous section, the OPI test, which is a performance-based durability index test, was used in this work to measure the permeability coefficient, which shows good correlation with depth of carbonation. The correlation between durability and permeability coefficient is well established by other researchers (Nilsson and Luping, 1995).

However, since the OPI test is done on dry samples, the permeability coefficient obtained will not represent the moisture condition, and hence a humidity factor needs to be incorporated. Adopting the framework of Gopinath et al. (2014) and Salvoldi et al. (2015), and based on the data from the OPI test and natural carbonation at early ages, the effective diffusion coefficient D can be correlated with the permeability coefficient (k) as follows.

$$D = m k^{n} H_{s} \tag{2}$$

$$H_{s} = 23.32\left(1-\left[RH/100\right]\right)^{2}\left(RH/100\right)^{2.6} \tag{3}$$

Where, m=295 and n= 0.68 are empirical factors which were calibrated, based on OPI test data and natural carbonation test results at early ages. ‘Hs’ is the humidity factor which is a function of relative humidity as given in equation (3); RH is the relative humidity in percentage (%), and k is the oxygen permeability coefficient in (m/s).

Substituting equations (2) and (3) in equation (1), the carbonation depth X is given by:

$$X = \sqrt{1.2\times10^{4}\times\left(k\times10^{11}\right)\times\left(1-\left[RH/100\right]\right)^{2}\times\left(RH/100\right)^{2.6}\left(c/a\right)}\times\sqrt{t} \tag{4}$$

4. MODEL VALIDATION

Figure 1(a) shows carbonation data measured in this study against the predicted values using equation (4), of samples sheltered from rain, and samples exposed to rain, in a locality in Johannesburg, South Africa. Figure 1(a) indicates that the carbonation model gave a good representation (based on the line of equality) of the carbonation depth of samples sheltered from rain, and hence can be used in both design and repair of concrete structures to predict the rate of carbonation. However, Figure 1(b) shows that the model was not able to predict accurately the carbonation depth of samples exposed to rain. This implies that the model is not able to reflect the influence of rain, and overestimates the depth of carbonation for samples exposed to rain or moisture. Hence it is necessary to consider the effect of drying and wetting cycles as addressed previously by other researchers (Bakker, 1993; Thiery et al., 2012).

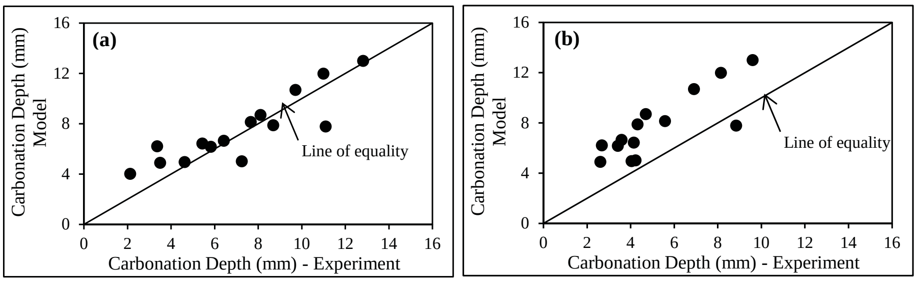

Figure 1. Depth of carbonation: Prediction model vs. experimental results for (a) samples sheltered from rain (b) samples exposed to rain. (Line on graph is a line of equality)

Figure 2(a) gives the schematic representation of the influence of drying and wetting cycles on the rate of carbonation (based on Bakker (1993) and Thiery et al. (2012)). It can be observed that drying and wetting cycles reduce the rate of carbonation, attributed to an increase in moisture in the pores because of rain or other sources of moisture, thereby reducing the diffusion of carbon dioxide into the concrete. Thus, carbonation only resumes when the moisture reduces to a certain critical level during the drying period (Neville, 2007). As a result, the power series constant in equation (1) deviates from 0.5, taking a lower value. Similar variations in the power series constants were observed by Alexander et al. (2007), based on the carbonation depth measured on reinforced concrete bridges at different localities in South Africa. Based on the experimental results from the current study, the carbonation model is modified as follows:

$$X = \sqrt{1.2\times10^{4}\times\left(k\times10^{11}\right)\times\left(1-\left[RH/100\right]\right)^{2}\times\left(RH/100\right)^{2.6}\left(c/a\right)\times\left(t^{0.45}\right)} \tag{5}$$

Figure 2(b) represents the correlation between the experimental carbonation data at 1000 days of samples exposed to rain, and the results from the modified carbonation model given in equation (5). It can be seen that the modified carbonation model is able to predict realistic depths of carbonation of samples exposed to rain.

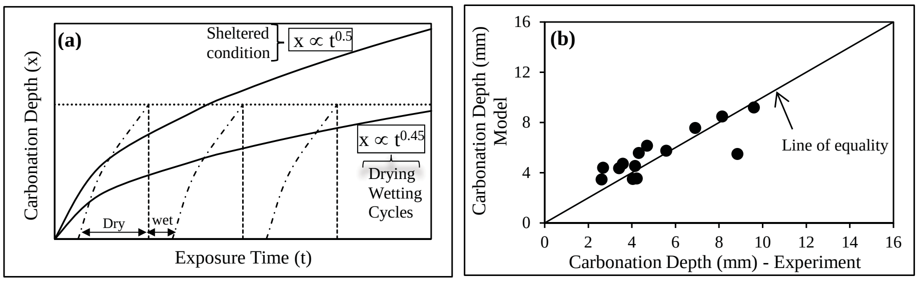

Figure 2: (a) Influence of drying and wetting cycles on the rate of carbonation (based on Bakker (1993); Thiery et al. (2012)) (b) Depth of carbonation: Modified Prediction model vs. experimental results for samples exposed to rain. (Line on graph is a line of equality)

Based on these preliminary results and analyses, a comprehensive carbonation model which can account for varying climatic condition is being developed in this work. The method described above to modify the carbonation model is regarded as elementary, and a more fundamental and scientific approach will be developed as part of the goals of the ongoing research.

5. CONCLUSIONS

- The OPI test reflects relevant concrete material properties regarding durability, and test values show good correlation with carbonation depth. Hence it can be used as a property variable in the carbonation model.
- A carbonation model with permeability coefficient determined from the OPI test as the key variable was developed, which gives a good estimation of the carbonation depth of samples sheltered from rain. However, the model was not able to incorporate varying climatic conditions (drying and wetting cycles) and hence overestimates the carbonation depth for samples exposed to rain.
- The carbonation model developed was modified based on the experimental results by adopting a power series constant lower than 0.5. The modified carbonation model, regarded as only elementary at this stage, incorporates the influence of moisture in the environment and is able to predict the carbonation depth of concrete exposed to rain with fair accuracy.

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