Model verification, refinement, and testing on independent 10 - year carbonation field data

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ABSTRACT: An extensive range of data generated from a 10-year long-term experimental and field carbonation study was used in this work to test, validate and refine an independent existing model for carbonation prediction in reinforced concrete structures. These data are detailed in the CSIR, 1999 report. In the report, data was generated for twenty one (21) concretes mixtures of nominal strengths 25, 35, 50 MPa made using ordinary Portland cement (OPC) or rapid hardening Portland cement (RHC) with or without 15, 30, 50% fly ash (FA), each mix being subjected to five (5) different curing regimes prior to exposure of samples to the natural Pretoria weather. Strength and carbonation measurements of the field exposed specimens were determined at the ages of 3.5, 6 and 10 years, along with their compressive strengths. Also determined were compressive strengths at 1, 3, 7, 28, 90, 100 days, 3.5, 6, 10 years for specimens stored under laboratory conditions.

It should be underscored that the model origin was not in anyway related to these data. But when tested using laboratory data from the CSIR investigation, the model prediction of carbonation rates was remarkably accurate. The model also accounted for the cement or binder type quite well. However, when field strength data was used in the model, the prediction results diverged from measured carbonation rates. In analysing the strength data, it was found that long-term field data gave higher compressive strengths than the corresponding laboratory strengths. These observations can be attributed to the effect of carbonation on exposed samples, leading to relative strength increase. The model has been modified by the author in order to account for the carbonation effect on strength. The good performance by the model on independent data demonstrates its underlying robustness for use in service life prediction.

1 INTRODUCTION

Engineering models typically attempt to capture universal or fundamental concepts and by expressing these in some form of mathematical expressions, the process of determining the future behaviour of a system can be predicted. They are particularly important tools in predicting future performance, which information is usually of value to current knowledge. For example, it is greatly valuable to an owner who invests in physical infrastructure to determine the period of service that can be expected from the structure's physical life. One alternative way of predicting the asset performance would be to depend on past performance of structures in a similar environment.

Past performance experience and accelerated tests are useful in design and quality control. But for prediction of residual service life, little can be expected from these methods. Scientific understanding of the deterioration processes within the material system or structure allows the underlying fundamental principles of the mechanism to be captured and modelled mathematically.

This paper is concerned with carbonation modelling. In Africa, carbonation is perhaps a more widespread problem than chloride attack, the two mechanisms being responsible for corrosion of steel reinforcement in reinforced concrete (RC) structures. In the literature there are a plethora of carbonation models that have been proposed by various researchers (Parrot, 1987). But it is often the case that models that have been developed basing on particular data fail when treated to another data set of different origin.

2 A PLAUSIBLE CARBONATION MODEL

In this paper, a carbonation model which the author of this article considers to be plausible, was subjected to testing and verification (RILEM, 1996):

$$\mu(D) = K_c\sqrt{t} \quad \text{and} \quad K_c = C_{env}C_{air}a(f_{ck} + 8)^b$$

Where: μ(D) = mean carbonation depth (mm), K_c = coefficient of carbonation rate (mm/yr$^{0.5}$), t = time of exposure (years), C_{env} = environmental coefficient, C_{air} = air content coefficient, f_{ck} = characteristic cube compressive strength, f_{cu} = Mean cube compressive strength, a,b = constants dependant on binder type

Previous work (Ekolu, 2010) in which the model was applied to bridges and RC buildings in Johannesburg showed meaningful model predictions and a strong potential for good performance. In this paper, the model is tested and verified against independent, extensive field data of a long-term carbonation study conducted over a period of 10 years and reported in CSIR, 1999.

3 EXPERIMENTAL

The compressive strength and carbonation investigation (CSIR, 1999) conducted from 1988 to 1999 was done using concretes made with OPC, RHC cements. The OPC and RHC cements had 7 day strengths of 41 and 53 MPa respectively, and both cements had 77 MPa at 28 days. The cements are equivalent to CEM I 52.5 and CEM I 52.5R cement classifications of EN 197-1. Fly ash was blended with OPC in proportions of 0 to 50%FA while RHC mixes contained 0 to 25%FA. Three concrete strength grades of 25, 35 and 50 MPa were made according to mix parameters shown in Table 1. Altogether 21 (twenty-one) mixtures were prepared in 62 batches, all of slumps of 50 to 70 mm. Concrete cubes of 100 mm were cast for compressive strength and carbonation testing at various ages. The specimen were prepared and stored under the different exposure conditions of:

- Five (5) varied laboratory curing and storage conditions for compressive strength
- Pretoria weather field exposure for compressive strength and carbonation

Table 2 gives a detailed description of the curing and storage conditions employed, designated (a) to (e). No accelerated carbonation studies were conducted in the laboratory.

4 STRENGTH DATA

The main variables dealt with by the model are environmental and material system factors:

- Varied exposure conditions: The model applies to field conditions and provides the coefficients, C_{env} = 1 /0.5 for use with concretes *sheltered* /*unsheltered* from rain.
- Binder type: In the present form, the model accounts for the strength effects of OPC cement and extenders by coefficients a, b given for OPC (a = 1800, b = -1.7) and 28%FA (a = 360, b = -1.2). The effects of using RHC and different proportions of FA are not defined in the model account.

In this analysis, the strength results for laboratory-stored specimen were compared to those for specimen exposed under field conditions at the ages of 3.5, 6 and 10 years as shown in Figures 1 and 2 respectively. There are some interesting observations notable from these strength patterns.

(1) In all the ages, the strengths of RHC behaved exactly the same as OPC cements without any peculiarities. The FA mixes also behaved consistently as plain OPC and RHPC cements. Considering the longer ages used in the CSIR, 1999 investigation, it can be expected that the RHC and OPC concrete should behave similarly.

Table 1 Concrete mixtures used in the investigation

	25 MPa concretes		35 MPa concretes		50 MPa concretes	
	OPC	RHC	OPC	RHC	OPC	RHC
Fly ash (%)	0, 15, 30, 50	0, 15, 25	0, 15, 30, 50	0, 15, 25	0, 15, 30	0, 15, 25
Binder content (kg/m^3)	245, 256, 260, 244	247, 240, 261	314, 321, 341, 322	283, 286, 285, 314	390, 400, 420	365,355, 490
Water /binder ratio	0.78, 0.73, 0.65, 0.69	0.79, 0.77, 0.69	0.59, 0.56, 0.51, 0.53	0.69, 0.64, 0.60, 0.59	0.49, 0.49, 0.51	0.54, 0.51, 0.46

Table 2 Curing, storage and exposure conditions

Condition	Description of the laboratory curing and controlled storage conditions	Exposure to Pretoria weather: average annual temperature of 10 to 25°C, 65 to 75% RH, and 780 mm precipitation only during the five summer months
	Compressive strength tests done at 1, 3, 7, 28, 90, 100 days, 3.5, 6, 10 years	Compressive strength and carbonation tests done at 3.5 and 6 years
a	Continuous storage in a fog room at 23°C	Storage in a fog room for 28 days then exposed
b	24 hour storage in 80%RH /50°C room, then 27 days in 50%RH /10°C room followed by storage in 50%RH/23°C room until testing	24 hour storage in 80%RH /50°C room, then 27 days in 50%RH/10°C room and then exposed
c	Storage in 50%RH/23°C room until testing	Storage in 50%RH/23°C room for 28 days then exposed
d	Steam cured at 60°C for 24 hours then stored in 50%RH/23°C room until testing	Steam cured at 60°C for 24 hours then stored in 50%RH/23°C room for 27 days and then exposed
e	Oven-dry cured at 40°C for 24 hours then stored in 50%RH/23°C room until testing	Oven-dry cured at 40°C for 24 hours then stored in 50%RH/23°C room for 27 days and then exposed

Typically, RHC is expected to influence the early strengths of up to 7 days while the long-term strength behaviour will be similar to that of OPC. The specimens were exposed to field conditions after 28 days of laboratory curing and treatments, meaning that the early-age influence of RHC had been surpassed by the time of exposure.

(2) The strengths of field exposed specimens were higher but only for concretes of 20 to 50 MPa. For strengths exceeding 50 MPa, the field and laboratory strengths were similar, falling along the line of equality. The observed higher strengths in field exposed samples are attributed mainly to carbonation of the specimens. Carbonation is known to increase the strength and permeability properties of concretes as reported variously in the literature (Claisse et al, Chi et al. 2002, Kim et al. 2009). Under carbonation, it is clear that high strength concretes (HSCs) behave differently from normal strength concretes (NSCs), with the mechanism showing no significant influence on strengths of HSC.

(3) For the lab-stored specimens, the long-term strength increase depended very much on the storage condition of specimens:- the condition (a) of continuous moist storage in a fog room, and conditions (b)-(e) of storage under 50%RH/23^{o}C (50/23). Under storage condition (a), both the cement type and the extender content in the mix play key influence, with plain OPC showing greater strength increase of +7 to +17 MPa compared to about +3.5 to +11 MPa for plain RHC concrete.

(4) The strength increase in FA mixes was higher with rise in the proportion of extender incorporated, as seen in Table 3. Under 50/23 storage, the influence of the binder type diminishes and all the mixes show more or less a similar level of strength gains in the range of +5 to +9 MPa. Clearly, the strength gains beyond 28 days were higher and widely scattered for specimens stored under condition (a), with values sporadically ranging from +12.8 to +40.5 MPa, unlike specimen stored under 50/23 whose results were closely varied from +1 to +15 MPa. Accordingly, the results from moist storage condition (a) cannot be relied upon due to their wide scatter. But consistency exists for 50/23 storage such that a global average increase of +7 to +8 MPa (over their 28 day strength results) can suitably be used for long-term ages, regardless of the binder type. This data analysis and deduction validates the model which also recommends use of the characteristic strength value (f_{ck}) plus 8 MPa.

Table 3 Mean strength increase beyond the age of 28 days, combined for all mixtures and conditions

Binder		3.5, 6, and 10 - year mean strength increase over 28-day value (MPa)	
		Condition (a)	Condition (b)-(e):
OPC	100OPC	+12.8	+8.0
	15FA	+19.3	+8.8
	30FA	+28.3	+7.1
	50FA	+37.6	+5.5
RHC	100RHC	+6.2	+5.0
	15FA	+11.0	+6.2
	25FA	+17.7	+6.9

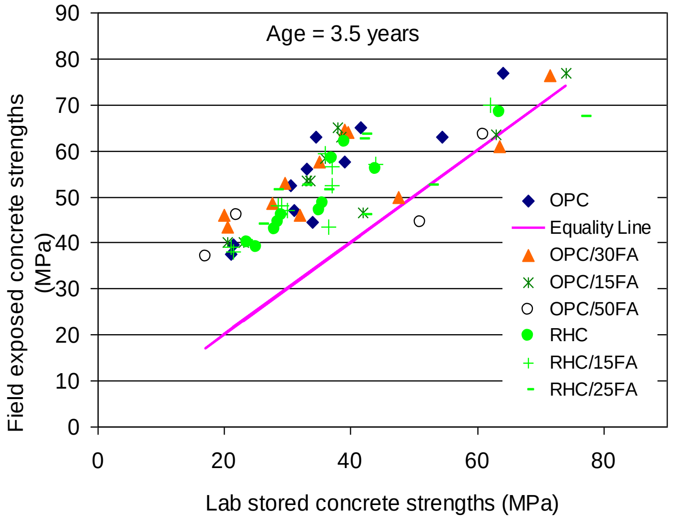

Figure 1 Comparison of 3.5-year strengths for laboratory-stored and field exposed concretes

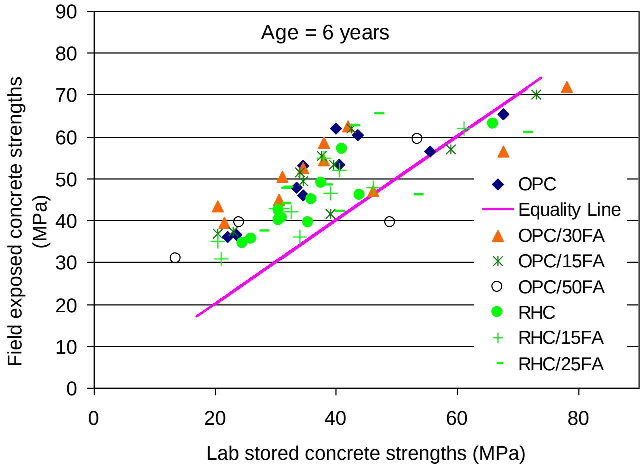

Figure 2 Comparison of 6-year compressive strengths for laboratory-stored and field exposed concretes

5 CARBONATION DATA AND MODEL PREDICTIONS

Model carbonation rate predictions were conducted basing on different sets of strength results:

(1) 28-day strength prior to field exposure (f_{c28})

(2) f_{c28} + 8 MPa

(3) Strengths of carbonated exposed specimens measured corresponding to the age of field carbonation testing (f_{cbn})

(4) Strengths of 50/23 lab-stored specimens measured corresponding to the age of field carbonation testing ($f_{c50/23}$)

No 10 – year carbonation data was available, hence model predictions have been limited to 3.5 and 6 year data.

5.1 Prediction of carbonation rates basing on f_{c28} and f_{c28} + 8 MPa

Figure 3 gives the relations between model prediction of the carbonation rates basing on f_{c28}, and the actual rates recorded for the 3.5 year data. It can be seen that the model predictions are correspondingly higher and fail to agree with measured rates. Similar behaviour was found for the 6-year carbonation results. It is evident that applying 28-day results in this manner for purposes of model predictions will result in overestimation of carbonation rates. When the model predictions were based on f_{c28} + 8 MPa, the predicted carbonation rates corrected and fell along the line of equality with the actual rates measured in the field, as shown in Figure 4. Again, the 6-year results also behaved in the same manner as the 3.5-year results.

5.2 Prediction of carbonation rates basing on f_{cbn}

It was found that by using the strengths of carbonated specimens determined at the same age along with carbonation depth testing, the predicted carbonation rates were lower than the actual measured rates from field exposure. These observations can be seen in Figure 5 for 3.5 year specimens. The lower predicted carbonation rates are a result of higher strengths in the 20 to 50 MPa concretes affected by carbonation of field exposed specimens, as discussed in Section 4. It is however interesting to note that the data points below the carbonation rate of 2 mm/yr$^{0.5}$, line along the line of equality. These are the high strength concretes whose strengths are not affected by field carbonation (see Section 4). These interesting deductions were also observed in the 6 –year results.

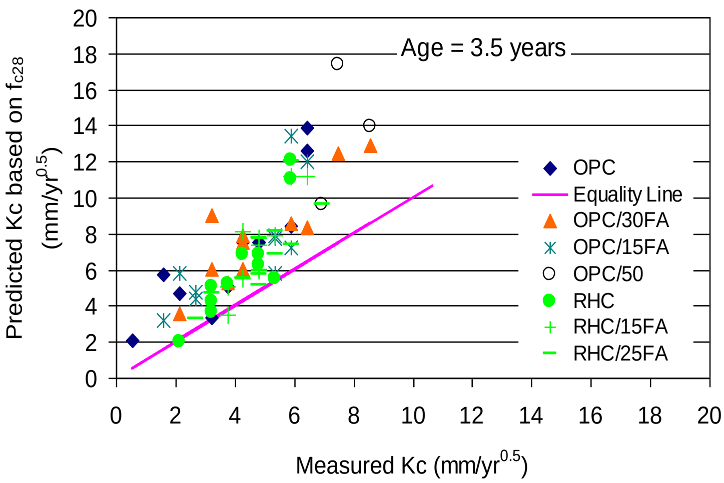

Figure 3 A plot of 3.5-year actual and predicted carbonation rates based on 28-day strength. Note that the data points lie above the equality line.

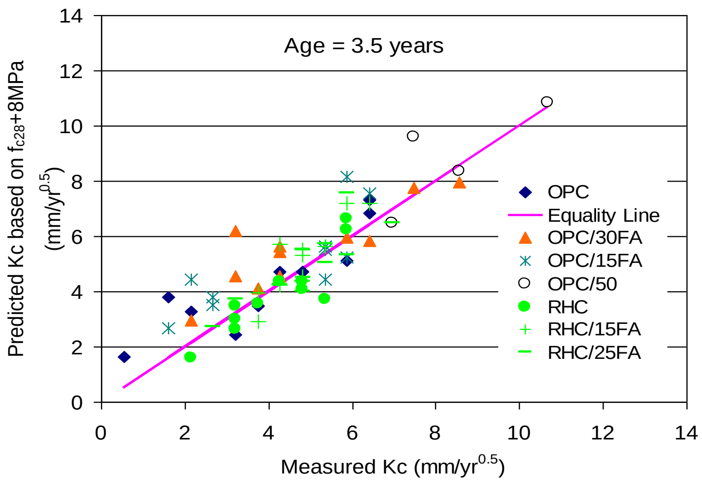

Figure 4 A plot of 3.5-year actual and predicted carbonation rates based on 28-day+8 MPa strength. Note that the data points lie along the equality line.

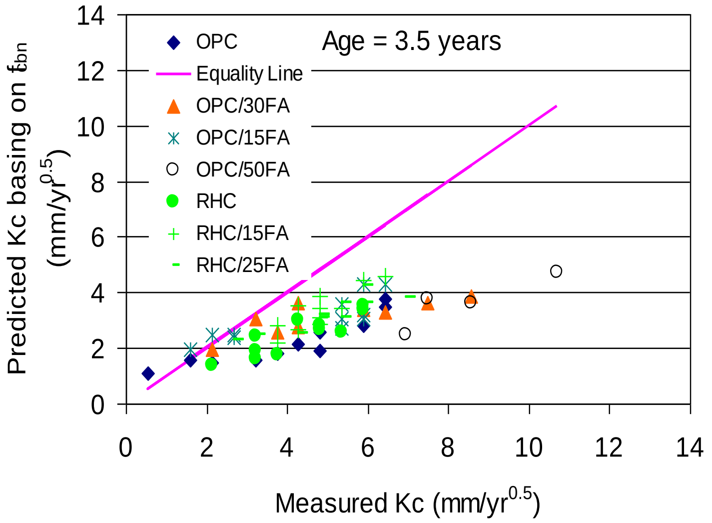

Figure 5 A plot of 3.5-year actual and predicted carbonation rates based on the strength of carbonated field concretes, f_{cbn}. Notice that the predicted rates fall below the equality line.

In order to correct the predicted rates to allow for the strength effect of carbonation in the model, a shift factor was introduced by the author, in form of an inverse to the exponent of strength parameter. The shift factor applies only to NSCs of 20 to 50 MPa and is not required for HSCs of strength > 50 MPa. When the shift factor, s = 1.11 was applied to the data, the predicted carbonation rates now fall along the line of equality as seen Figure 6.

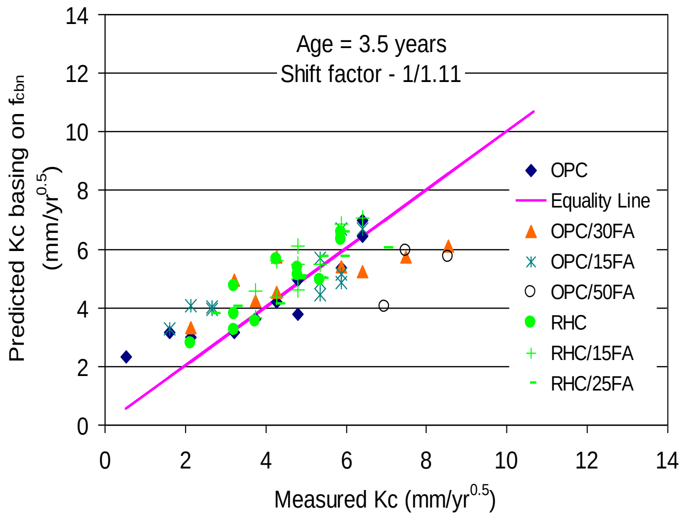

Figure 6 A plot of 3.5-year actual and corrected predicted carbonation rates based on strength of carbonated field concretes, f_{cbn}. Notice that the predicted rates now fall along the line of equality.

5.3 *Prediction of carbonation rates basing on $f_{c50/23}$*

It was discussed in Section 4 that the moist storage in a fog room (or water immersion), activates the influences of the different binder types to the extent that results deviate widely from field behaviour. Therefore all results obtained from moist storage (i.e. condition (a)) were eliminated from this analysis and only those from conditions (b) to (e) were used. The use of $f_{c50/23}$ required application of shift factor, s = 0.95 to correctly predict field carbonation rates. From the foregone model verifications, adjustments to the model are deemed necessary for performance improvement. The model now takes a proposed new form written as:

$$k_c = c_{env} c_{air} a\ (f_c)^{b/s}$$

Where, f_c = f_{ctx}+8 or f_{cbn} such that:

f_{ctx} = mean cube compressive strength at initial time of field exposure

f_{cbn} = mean cube compressive strength of field carbonated concrete at any given age

1/s = strength shift factor for carbonation, given in Table 4

Table 4 Strength shift factor for carbonation

Cube strength (fc) used in model	Concrete strength (MPa)		
	<20	20 to 50	>50
f_{ctx}+8	n/a*	1.00	1.00
f_{cbn}	n/a	1.11	1.00

* Note: the model is not applicable (na) to concretes of strengths < 20 MPa

6 MODEL TESTING

Basing on the proposed new form, model tests were carried out to predict carbonation depths in all the concrete mixes and then relate these to the actual measured carbonation. The model tests were conducted for carbonation depth predictions basing on compressive strengths of f_{ctx}+8 MPa and f_{cbn}. The model tests based on f_{ctx} +8 MPa were generally accurate for both 3.5 year and 6 year carbonation predictions. Few points showed overestimated predictions for mixtures containing the high FA contents of 50%. These mixtures had 28 day strengths of 10 to 20 MPa and should not be applied to the model. It is evident that the model is not applicable for concretes of strength range < 20 MPa.

Similarly, the f_{cbn}- based model tests gave accurate predictions for both of the 3.5 year and 6 year carbonation depths. Here also, the few elevated data points of model predictions belonged to the high fly ash concrete of 50%FA. Such concretes of low strength should not be used with the model, as already discussed. The other important features are the lower carbonation depths that the model appears to overestimate. These data points belong to the high strength concretes except that the same shift factor of s = 1.11 was applied alike to all the data points.

When the low strength concretes were discarded from the data and a shift factor s = 1.00 was applied to high strength concretes, it can be seen in Figure 7 that the model predicts field carbonation depths much more accurately, with both the measured and predicted carbonation depths lying within the same range of carbonation depth and the extreme points from field measurements being possible outliers.

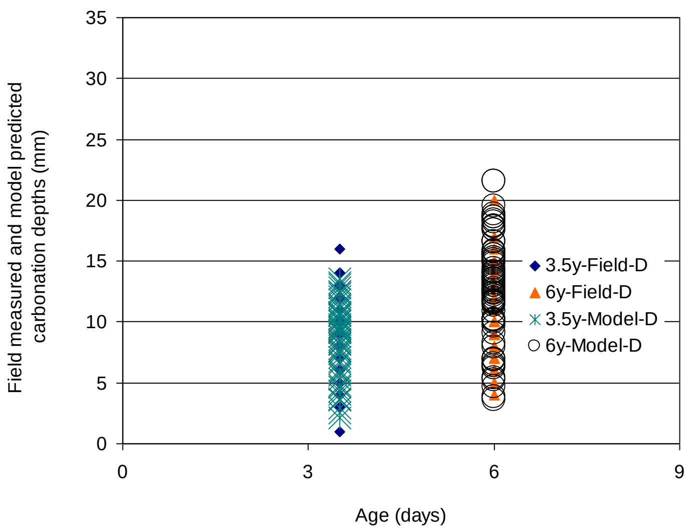

Figure 7 Model tests basing on f_{cbn} after correcting for low strength and high strength concretes

7 CONCLUSIONS

Verification and testing has been conducted on a carbonation model using extensive range of field data generated over 10 years of experimental study. Data analyses and verification showed that the model fully accounts for the effects of using various binder types including extenders incorporated under normal proportions. It was found that carbonation increases the strength of normal strength concretes in the range of 20 to 50 MPa but does not significantly influence high strength concretes of greater than 50 MPa. The model in its original form does not provide an adjustment to account for the strength-effect of carbonation. A new form of the model has been proposed which introduces a shift factor to account for the influence of carbonation on strength.

A strong correlation was found between predicted and field, rates and carbonation depths. The model demonstrates robustness for good performance in service life applications. Further research is being undertaken on the limitations identified.

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