APPLICATION OF A NEW NATURAL CARBONATION PREDICTION (NCP) MODEL TO EVALUATION OF DURABILITY DESIGN FACTORS - STRENGTH, COVER, AND CEMENT TYPE

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Abstract

In this paper, durability design parameters that are typically specified in structural design codes, were evaluated for their impacts on service lifespan. These parameters comprising concrete strength, cover depth, and cement type, were used as input variables into the new natural carbonation prediction (NCP) model. The resulting changes on the predicted lifespans were then evaluated. It was found that 10 MPa increment in concrete strength increases the structures lifespan geometrically 2.5 to 5.0 times. Similarly, 10 mm increment in cover extends the service lifespan 2.0 to 2.5 times. Also CEM II concretes with 10 MPa higher strength over that of CEM I concretes, gave the same carbonation resistance as the latter. Understanding of the impacts of durability design parameters aided by practical service life models, contributes towards a rational approach for service life design of concrete structures.

Keywords: Service lifespan, natural carbonation, prediction model, probabilistic, durability.

1. Introduction

Carbonation is a deterioration mechanism which occurs when the CO_2 that is prevailing in the atmosphere, penetrates into the concrete cover, coming into contact with steel reinforcement and leading to its corrosion. It is one of the two causes of steel reinforcement corrosion in concrete structures, the other mechanism being chloride attack. It should be underscored that steel corrosion is the most widespread durability problem in concrete structures. Both mechanisms are climate-driven attack processes. In South Africa and most other tropical or subtropical regions, carbonation is a much bigger problem responsible for a majority of the reinforcement corrosion problems observed in concrete structures.

Scientific understanding of the deterioration processes occurring within the material system allows the underlying fundamental principles of the mechanism to be captured and modelled mathematically. Theoretically, a robust carbonation prediction model should be capable of depicting the various natural exposure environments, the material systems used, and time-based effects. Presently, carbonation prediction modelling remains challenging despite numerous research efforts over the past half a century.

Considering that atmospheric CO_2 is the primary constituent and driver of climate change, the need for design of concrete infrastructures towards adaptation and resilience to the associated environmental changes, has become a crucial challenge for engineering practice. Hitherto, the design approaches for concrete structures have been primarily developed on the basis of resistance to applied loads, in the physical forms of dead and live loads. In structural design, durability considerations generally take a secondary place. In design codes including SANS 10100-1 (2000), BS 8100 (1997) and EC 2 (2004), a prescriptive approach is used to meet the minimum requirements deemed to satisfy durability considerations. In SANS 10100-1, the main durability requirements specified are: (i) the environmental exposure conditions which are divided into five (5) classes comprising the *mild, moderate, severe, very severe* and *extreme* condition, (ii) minimum concrete cover, and (iii) minimum concrete strength grade for each of the exposure classes. For a given strength grade, concrete mixture parameters of water

/cement ratio and minimum cement content are also prescribed. Evidently, no quantitative engineering design for service life modelling is presently engaged as part of structural design. One of the reasons for this limitation is the lack of practical carbonation prediction models for lifespan design. There are numerous carbonation models proposed in the scientific literature but most of them are experimental while those needed for practical lifespan design are few or lacking (Ikotun & Ekolu, 2012; Ekolu, 2015, 2016, 2018). The *fib* MC (2010) and the natural carbonation prediction (NCP) model (Ekolu, 2018) are two candidate models for potential practical application to service life design. These models have been comparatively validated as shown in Figure 1. Ekolu (2018) contains more data of the validations. The data used in the comparative validations were taken from Guiglia and Taliano (2013), comprising 346 data sets extracted from highway structures including bridge piers, abutments, tunnels etc.

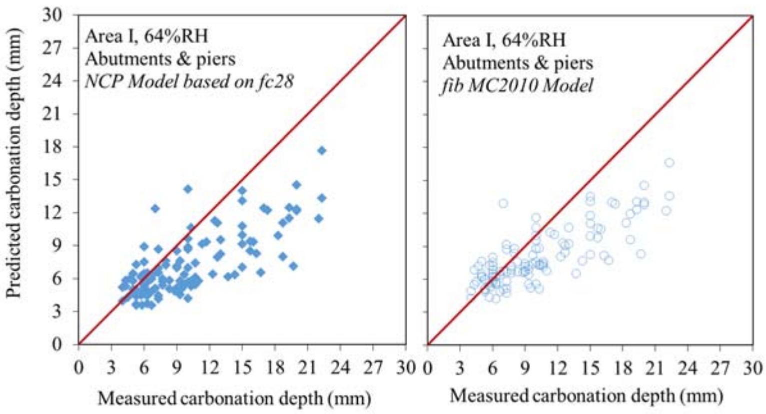

Figure 1. Comparative validation of the NCP and *fib* MC 2010 models (Ekolu, 2018).

This paper concerns the application of the NCP model to evaluation of durability factors in concrete structures. The study focussed on examining the effects of durability design parameters specified in SANS 10100-1 (2000). These include concrete strength, cover depth, and the type of cementitious materials. The input variables selected based on Johannesburg weather conditions, were used in the model. The responses of specified concretes and the associated durability parameters to carbonation, were modelled over a period of 120 years.

2. NCP model

The NCP model comprises Equations (1) to (7), covering (i) three environmental parameters i.e. ambient relative humidity (RH), weather exposure condition (sheltering), and ambient CO_2 concentration, (ii) two material parameters of concrete strength and cement types, and (iii) a mathematical function relating carbonation progression in concrete with the dynamic changes in environmental and material properties. The model dynamically adjusts carbonation progression to account for various environmental and material parameters, thereby adapting to different concrete materials, various geographical locations and climates. A detailed description is given in Ekolu (2018) regarding the model's concept and formulation.

$$d_{(f,t)} = e_h \cdot e_s \cdot e_c . cem \left(F_{c(t)}\right)^g . \sqrt{t} \tag{1}$$

Environmental factors for relative humidity (RH) and shelter:

$$e_h = 16\left(\frac{RH - 35}{100}\right)\left(1 - \frac{RH}{100}\right)^{1.5} \text{ for } 50\% \leq RH \leq 80\% \tag{2}$$

$$e_s = \begin{cases} 1.0 \text{ for sheltered outdoor exposure} \\ f_c^{-0.2} \text{ for unsheltered outdoor exposure; } f_c \text{ is } 28-\text{day strength} \end{cases} \tag{3}$$

Environmental factors for varied CO_2 concentrations:

$$e_{co} = \begin{cases} \alpha f_c^{\,r} \text{ for } 20 < f_c < 60\,\text{MPa} \\ 1.0 \text{ for } f_c \geq 60\,\text{MPa} \end{cases} \quad (4)$$

where α,r are correction factors for natural carbonation under varied CO_2 concentrations:

28-day strength (MPa)	Correction factor		CO_2 concentration level (ppm)				
			200	300	500	1000	2000
$20 < f_c < 60$	$e_c = \alpha f_c^{\,r}$	α	1.4	1.0	2.5	4.5	14
		r	-1/4	0	-1/4	-2/5	-2/3
$f_c \geq 60$	$e_c = 1.0$						

Time-dependent strength growth function ($F_{c(t)}$):

$$F_{c(t)} = \frac{t}{a + bt}.f_c$$, where $f_c = f_{c28}$ or f_{cbn}

(a) Using 28-day strength, (f_{c28})

(i) Short-term ages, t < 6 years

$$a = 0.35,\ b = 0.6 - t^{0.5}/50 \quad (5a)$$

(ii) Long-term ages, t ≥ 6 years

$$a = 0.15t,\ b = 0.5 - t^{0.5}/50 \quad (5b)$$

(b) Using long-term (field) strength, (f_{cbn})

(i) Short-term ages, t < 15 years

$$a = 0.35,\ b = 1.15 - t^{0.6}/50 \quad (6a)$$

(ii) Long-term ages, t ≥ 15 years

$$a = 0.15t,\ b = 0.95 - t^{0..6}/50 \quad (6b)$$

Cement factors for carbonation conductance: (7)

SCM	Cement types	Scalar,	Conductance

		cem	factor, *g*
20% any	CEM I, CEM II/A	1000	-1.5
30% fly ash	CEM II/B, CEM IV/A	1000	-1.4
50% slag	CEM III/A, CEM IV/B	1000	-1.4

*SCM – supplementary cementing materials

Notes: Cube strength (f_c) is related to core or cylinder strength (f_{cyl}) through the conversion, $f_c = 1.25\ f_{cyl}$. Strength values used in the equations must be ≥ 20 MPa. Moist-cured 28-day strength (f_{c28}) is related to insitu strength (f_{cbn}) using the expression, $f_{cbn} = f_{c28}+13$.

3. Interpretation and engineering applications

The environmental parameters used in the model were based on data recorded at a carriageway location close to the Johannesburg central business district. Johannesburg is an economic hub located in Gauteng province, one of the highest CO_2 emission points in South Africa. The high CO_2 emissions in the city and its surroundings, are a result of intense coal mining activities, heavy engineering industries, and vehicular traffic. It can be seen in Figure 2 that the CO_2 levels ranged between 400 and 600 ppm with an average of 440 ppm. RH levels were between 50 to 60% in the night and mornings while lower during the day. Temperatures of 16 to 34°C were measured during daytime.

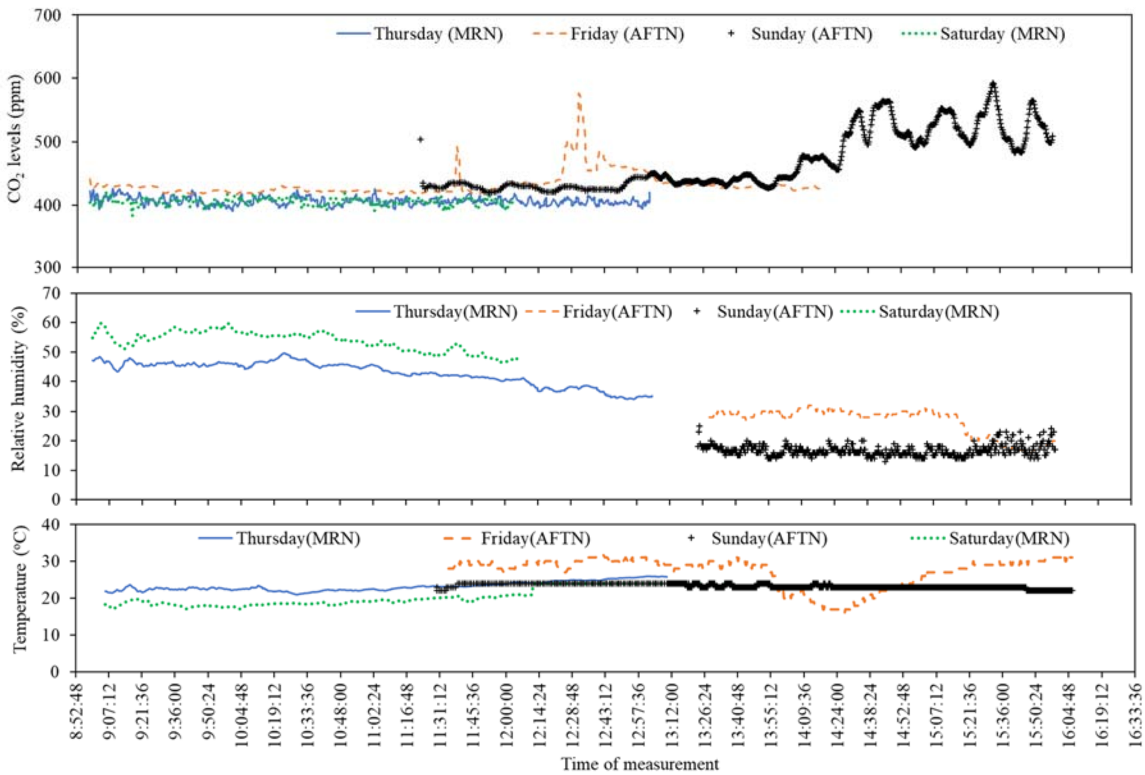

Figure 2. Macroclimate conditions measured at Johannesburg central business district.

As already mentioned, the national code for design of concrete structures SANS 10100-1 (2000) specifies five exposure classes consisting of the *mild, moderate, severe, very severe* and *extreme* conditions. The respective specified minimum concrete strength /minimum cover for the various exposure classes are 20 MPa /20 mm, 25 MPa /35 mm, 30 MPa /40 mm, 40 MPa /45 mm, 50 MPa /40 mm. In the present study, the effects of these parameters are investigated for (i) varied strengths of 25, 30, 40, 50 MPa at a fixed cover depth, (ii) varied cover depths of 25, 30, 40, 50 mm for a fixed concrete strength, (iii) types of cementitious materials, limited to CEM I and II.

The stochastic applicative method was employed to calculate failure probability of concretes for each of the exposure classes. In applying the stochastic approach, carbonation progression is considered as loading (S) while the concrete cover (R) represents the concrete resistance to carbonation ingress. Failure occurs when the condition R(t) < S(t) is reached. Failure probability is calculated using the reliability index given in Equation (8) (RILEM, 1996). The input variables given in Table 1 were selected for use in the analysis.

$$\beta(t) = \frac{\mu[R,t] - \mu[S,t]}{\sqrt{\sigma^2[R,t] + \sigma^2[S,t]}} \quad (8)$$

where μ = indicates the mean of, σ = standard deviation, β = the value along x-axis of NORMDIST curve (0,1)

Table 1. Parameters and random input variables.

Category of factors	Random variable	Mean	Coefficient of variation	Parameters in the model
Environmental factors	RH	60%		$e_h = 1.0$
	Weather	sheltered		$e_s = 1.0$
	CO_2 (ppm)	450 ppm		e_c – varied with fc
Material factors	fc (MPa)	25, 30, 40, 50		
	Cover (mm)	25, 30, 40, 50	0.2	R - varied, Eq. (8)
	Cement type (cem, g)	CEM I, II		(1000, -1.5/-1.4)
Mathematical function	F(t)			Eq. (6b)
	d(t)		0.4	S – varied

4. Evaluation of durability design factors

Figure 3 gives the influence of concrete strength on carbonation ingress into concrete. Various concrete strengths of 25, 30, 40, 50 MPa were evaluated at 30 mm cover depth. Similar graphs were obtained for various cover depths. As expected, carbonation progression decreased with increase in concrete strength. This relationship leads to geometric increase in service lifespan for small increments in strength. For 40 mm cover, for example, increment of strength from 30 to 40 MPa gave x2.4 and x4.0 lifespan increments for CEM I and CEM II concretes respectively. Generally, lifespan increased by x2.5 to x5.0 for every 10 MPa strength increment, regardless of the cement type.

Table 2 gives expanded data covering 30, 40, 50 mm cover depths for each of the strengths 25, 30, 40, 50 MPa. It is clear from the data that small increases in cover depth leads to corresponding geometric increase in service lifespan. For 30 MPa strength, a 10 mm increment of cover from 30 to 40 mm gave lifespan increases of x2.5 for both CEM I and CEM II concretes. Generally, lifespans increased by x2.0 to x2.5 for every 10 mm increment in cover.

Failure probabilities were generated for both cement types CEM I and CEM II as shown in Figure 4, for 30 mm cover. Again, similar graphs were obtained for the other cover depths of 40 and 50 mm. Evidently, the low strength concretes are more susceptible to failure at early ages. For 10% failure probability, 10 and 40 years of service lifespan were observed for CEM I concrete strengths of 30 and 40 MPa respectively. These lifespan values reduced by about one-half for CEM II concretes.

The results discussed in the foregone indicate that cements that contain supplementary cementitious materials (SCMs) e.g. CEM II etc., give inferior carbonation resistance relative to their CEM I counterpart. Indeed, it is well-established the SCMs promote carbonation progression into concrete, firstly by reducing early-age strength and secondly, due to dilution effect resulting from the reduced content of Portland cement in the mixture. The term '*conductance*' is used in the model to depict this effect of SCMs on carbonation. Detailed discussions regarding this effect of SCMs are presented in Ekolu (2016, 2018). As such, it is common practice to adjust mixture designs in order to account for the reduced strength of concrete when SCMs are incorporated into mixtures. Similar actions can be done to improve carbonation resistance of SCM concretes. It was found that for any given strength level (fc) of CEM I concretes, the same carbonation resistance (as that of CEM I concretes) is obtained with CEM II concretes of additional 10 MPa i.e. fc+10 MPa.

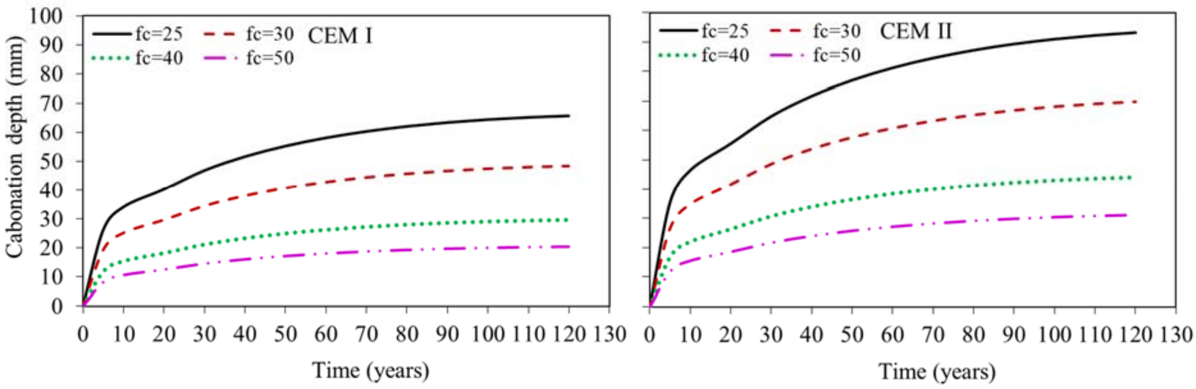

Figure 3. Carbonation progression in concretes of varied strengths evaluated at 30 mm cover.

Table 2. Relationship between design factors and service lifespan

Concrete strength (MPa)	Cover (mm)	Time taken for carbonation to reach steel reinforcement (years)	
		CEM I	CEM II
25	30	7.4	4.3
	40	20	7.0
	50	37	13.7
30	30	20	7.0
	40	50	17.5
	50	>120	32.5
40	30	120	30
	40	>120	70
	50	>120	>120
50	30	>120	100
	40	>120	>120
	50	>120	>120

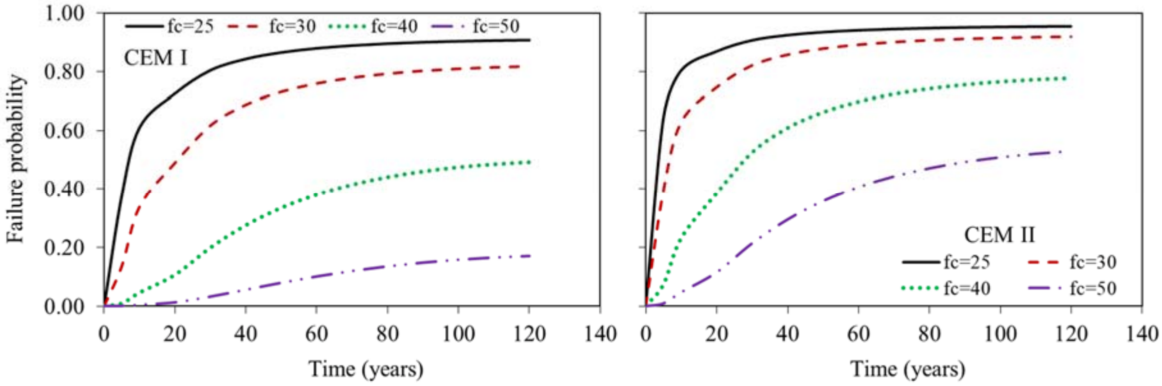

Figure 4. Failure probabilities for concretes of varied strengths evaluated at 30 mm cover

5. Conclusions

The possibility of rational service life design has been shown by employing the natural carbonation prediction (NCP) model to evaluate durability design factors often specified prescriptively in national design codes i.e. strength, cover depth and cement type. The influences of these factors on service lifespan of concrete structures were evaluated. It was shown that the lifespan of structures increases geometrically 2.5 to 5.0 times for every 10 MPa strength increment, regardless of the cement type. Similarly, 10 mm cover increment increases the lifespan of structures 2.0 to 2.5 times. Generally, CEM II concretes with 10 MPa additional strength above that of CEM I concrete, gave the same carbonation resistance as the latter.

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