Available online at www.sciencedirect.com
ScienceDirect
Cement & Concrete Composites 29 (2007) 750–759
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Carbonation of concrete bridge structures in three South African localities

M.G. Alexander [a,*], J.R. Mackechnie [b], W. Yam [c]

[a] Department of Civil Engineering, University of Cape Town, Rondebosch, 7701, South Africa
[b] Department of Civil Engineering, University of Canterbury, New Zealand
[c] HHO Consulting Engineers, Cape Town, South Africa

Received 15 February 2007; received in revised form 1 June 2007; accepted 7 June 2007
Available online 17 July 2007

Abstract

Rates of carbonation for reinforced concrete bridges were investigated for three localities in South Africa: Cape Peninsula, Durban and Johannesburg. Carbonation data from approximately 90 in-service bridges aged between 11 and 76 years were interpreted in terms of influence of materials and environment on carbonation rates. The data were grouped with respect to concrete strength grade and exposure condition prior to statistical analysis. Bridges in Johannesburg had the highest rates of carbonation owing to the relatively dry environment. Durban bridges had lower carbonation rates than Johannesburg bridges, but higher than bridges in the Cape Peninsula, ascribed to differences in ambient temperature and the nature of precipitation. Overall, average carbonation rates for Grade 30 concretes over a 30-year period varied from approximately 0.3 mm/annum in Cape Peninsula structures to approximately 0.7 mm/annum for Johannesburg structures. Exposure condition, characterised by degree of shelter, had little influence on carbonation rate in Durban and Johannesburg bridges, ascribed to the average relative humidity and duration of precipitation at these localities. Carbonation rates for older bridges were lower than for newer structures, attributed possibly to changes in cement characteristics with time related to the need for fast track construction in modern structures.

Keywords: Carbonation; Carbonation rate; Exposure conditions; Concrete bridges; Relative humidity

1. Introduction

Carbonation of concrete is a common chemical reaction in which atmospheric carbon dioxide reacts mainly with calcium hydroxide from cement hydration to form calcium carbonate in the presence of water. This reaction occurs rapidly in highly permeable concrete (e.g. concrete of high water/cement ratio with inadequate curing and/or insufficient compaction), exposed in the relative humidity range between 50% and 75% (the optimum RH range for carbonation) (ACI [1], Richardson [2]).

Carbonation of concrete reduces the pH of the pore solution as it converts calcium hydroxide to calcium carbonate. Once this acidification process advances to the steel reinforcement, depassivation of reinforcement occurs. Thereafter, corrosion of reinforcement may ensue in the presence of both moisture and oxygen. Eventually, products of corrosion will be formed, which may cause cracking and spalling of the cover concrete. Inevitably, structural and aesthetic aspects of the structure are thereby compromised, leading to high repair and rehabilitation costs for these damaged structures.

This paper reports a study on carbonation of reinforced concrete bridges aged between 11 and 76 years, in three South African localities: the environs of the coastal cities of Cape Town (the Cape Peninsula) (30 bridges) and Durban (32 bridges), and the inland city of Johannesburg (30 bridges). The study arose out of concern over increasing incidences of carbonation-induced corrosion of bridge

* Corresponding author. Tel.: +27 21 650 2584; fax: +27 21 689 7471.
E-mail address: Mark.Alexander@uct.ac.za (M.G. Alexander).

0958-9465/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2007.06.005

structures and thus the need to quantify in situ carbonation rates. The paper provides information on the major climatic factors in these localities, gives analyses of in situ carbonation data and carbonation rates, and comments on the likely effects of changes in cement characteristics with time. The analyses allowed derivation of carbonation prediction models to assist in decision-making for maintenance of reinforced concrete structures to manage carbonation-induced corrosion risk and associated costs of repair. Using the information, cover depths for design of future structures can be assessed, provided implications of any changes in cement characteristics are accounted for.

2. Climatic conditions

Climatic conditions govern the exposure relative humidity (RH), temperature, and precipitation (rainfall). The climates for the three localities vary from cool, wet winters and hot, dry summers for the Cape, to mild or hot conditions with high RH in Durban, to cold, dry winters and hot summers with mainly short precipitation periods in Johannesburg. Carbonation of concrete is a diffusion process and is sensitive to the internal RH of the concrete. Although internal RH relates to the external atmospheric RH, it does not vary as rapidly as external RH. Thus, the average external RH for "wet" and "dry" seasons for the localities was used, related to the period with high and low rainfall, respectively. Table 1 shows average locality-specific RH and temperature values for the "wet" and "dry" seasons.

Table 1 suggests that the Cape Peninsula and Durban would have relatively low rates of carbonation during the wet season with their high average seasonal RH, as the semi-saturated concrete pores would hinder diffusion of carbon dioxide. Carbonation would be faster for Durban than for Cape Town during this season due to the difference in the average temperatures. By contrast, the Johannesburg area would have a high rate of carbonation in both high and low rainfall seasons, the average seasonal relative humidities being in the range for the optimum RH for carbonation. Therefore, structures in Johannesburg should have a higher rate of carbonation than similar structures in the Cape Peninsula and Durban.

Importantly, the nature of precipitation in the three localities is not the same. Relatively short rainfall durations generally occur in Durban and Johannesburg, whilst rainfall periods are longer in the Cape, giving deeper penetration of moisture into the concrete.

Table 1 also gives an indication of the risk of reinforcement corrosion after depassivation. Richardson [2] states that the optimum concrete RH for corrosion is above 80%. Therefore, structures in the Cape Peninsula and Durban will tend to experience corrosion in the high rainfall season, with carbonation occurring predominantly in the low rainfall season. Particular attention should be paid to the design and monitoring of reinforced concrete structures in these two localities since carbonation-induced corrosion is likely to be a cause of deterioration. In contrast, structures in the Johannesburg area will in general not experience rapid corrosion as the average seasonal RH is well below the critical corrosion RH of about 80%. Therefore, carbonation of concrete may be rapid in this locality but serious corrosion is not inevitable. However, if moisture from external sources (e.g. leakage, ponding) penetrates into the structures after depassivation, corrosion could take place. Also, structures with very low cover to steel may experience corrosion-induced damage, since moisture could penetrate the limited cover layer.

3. Analysis of in situ carbonation data

Data were obtained from Ronné [4] (Cape Peninsula), and from forensic studies conducted for public roads

Table 1
Average RH (based on mean hourly values) and temperatures (based on average daily values) for high and low rainfall seasons for the three localities (S.A. Weather Service [3])

Rainfall	Locality								
	Cape Peninsula			Durban			Johannesburg		
	Month	Ave. Monthly RH (%)	Ave. RH (%)	Month	Ave. Monthly RH (%)	Ave. RH (%)	Month	Ave. Monthly RH (%)	Ave. RH (%)
High ("wet")	April	76	78 [14]	Oct.	78	79 [23]	Nov.	66	68 [19]
	May	80		Nov.	79		Dec.	68	
	June	80		Dec.	79		Jan.	69	
	July	80		Jan.	80		Feb.	70	
	Aug.	78		Feb.	80		March	68	
	Sept.	76		March	79		April	64	
	–	–		April	78		–	–	
Low ("dry")	Oct.	72	71 [19]	May	75	73 [18]	May	56	51 [13]
	Nov.	70		June	71		June	52	
	Dec.	70		July	71		July	49	
	Jan.	70		Aug.	73		Aug.	46	
	Feb.	70		Sept.	77		Sept.	46	
	March	73		–	–		Oct.	57	

The values in square parentheses are the average temperature (°C) for the "wet" and "dry" seasons.

agencies by Moore [5] (Durban and adjacent areas; Johannesburg Motorway and adjacent National Route 3 (N3) Bridges). The data of Ballim and Lampacher [6] (Johannesburg/N3 Bridges) were also used. In general, average carbonation depths were obtained from multiple measurements using phenolphthalein solution sprayed on cores or wedges cut from elements of the structures.

Fig. 1a–c show in situ carbonation data as a function of age of the structure. The data exhibit a remarkably wide scatter, not only because concrete itself is a variable material, but also due to variable construction factors and climatic conditions. Therefore, the data were grouped in terms of exposure conditions and grade of concrete in order to minimise the scatter and gain a better understanding of carbonation rate.

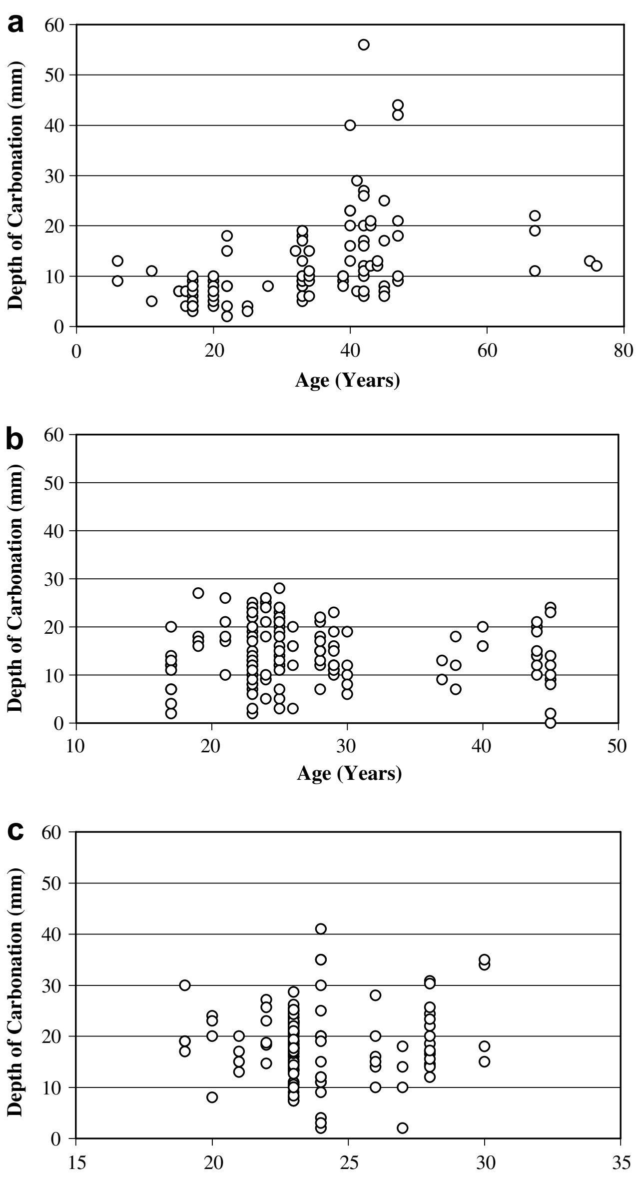

Fig. 1. Overview of carbonation data (a) Cape Peninsula (b) Durban and (c) Johannesburg localities.

There appear to be two population groups with different carbonation rates for Durban (Fig. 1b). One group represents "modern" concretes with higher carbonation rates whilst the other group shows older concretes (>35 years) with lower carbonation rates. A similar situation might be evident for Cape Peninsula data (Fig. 1a), for structures older than 60 years, but data points are very limited.

3.1. Grouping the data

The carbonation data were grouped according to exposure condition (exposed or sheltered from the weather) and concrete strength grade. Concrete strength can be regarded as a rough indication of permeability, which will influence carbonation rate. As far as could be ascertained, ordinary Portland cement was used for all structures.

3.1.1. Exposure conditions

Exposed elements are of particular interest as corrosion of steel occurs mainly in these elements due to their higher moisture content. Exposed elements included parapets and balustrades, deck edges, certain abutments (depending on the position of the sample), wing walls, ear walls and edge columns. Sheltered elements were other abutments, deck soffits and internal columns. Data for sheltered elements in the Cape Peninsula were very sparse, making statistical analysis difficult. Therefore carbonation prediction models were derived only for exposed elements in this locality.

3.1.2. Concrete strength grade

Concrete strength grades of the bridge elements were inferred by various means: the specified minimum compressive strength at 28 days (inferred from bridge drawings); from measured core strengths of bridge elements (in the case of most Cape Peninsula data); from similar elements some of which had known strengths (as marked with asterisks in Tables A1–A4 in the Appendix); or from knowledge of strengths based on common bridge design and construction practice. Where measured, the compressive strengths of the elements represented different ages related to the ages of the bridges. Concrete strength changes with time, and in order to make meaningful comparisons, strengths were normalised to 28 days using information in Fulton [7]. The inferred 28-day compressive strengths were used to estimate a concrete strength grade, using the fact that in construction, mean (target) concrete strength would be between 5 and 10 MPa higher than specified (grade) strength. To simplify matters, concrete strength grade was taken as 10 MPa less than the estimated 28-day compressive strength. Concrete strength grades (MPa) were identified as follows: Cape Peninsula, Grades 20, 30 and 40; Durban, Grades 25, 35, and 45; and Johannesburg, Grades 30 and 35.

3.2. Statistical analysis

To analyse the data, a form of carbonation prediction model (which relates depth of carbonation and age) must be chosen. This allows variability to be quantified and trends to be established. A common model is the simple power equation:

$$d_c = kt^n \quad (1)$$

where

d_c is the depth of carbonation, mm
k is the carbonation coefficient allowing for material and environmental effects, mm/year^n
n is the power series constant

The power series constant n is usually taken as 0.5 under ideal diffusion conditions, i.e. uniform pore structure and constant exposure environment (Ballim and Lampacher [6], Bakker [8], Neville [9]). If conditions are not ideal, for example the pore structure is not constant with time or depth and the exposure environment varies with time, an n value of 0.5 may not be appropriate. For instance, n may be smaller than 0.5 if the concrete is subject to wetting cycles since the diffusion of carbon dioxide is slower through moisture-filled pores. On the other hand, n may be greater than 0.5 in the case of cracked concrete as the presence of cracks provides pathways for the direct passage of carbon dioxide.

Eq. (1) was chosen to represent trend lines for the data and to explore the implications of variability. It was necessary to select suitable values for k and n for each data set. This was done using the Method of Least Squares, which minimizes the sum of the squares of residuals (error) between the predicted carbonation depth and the measured depth (d_{ci}) at any given time (t_i) by optimising the variables k and n of the fitted model. To simplify the analysis, a series of n values (0.3, 0.4, 0.5 and 0.6) was selected. With the value of n selected, only the variable k needs to be optimised. The corresponding k values can be calculated using the following equation:

$$k = \frac{\sum_{i=1}^{r} d_{ci} t^n}{\sum_{i=1}^{r} t^{2n}} \quad (2)$$

where

k is the carbonation coefficient
d_{ci} is the measured depth of carbonation
t_i is the time of measuring the depth of carbonation
n is the power series constant
r is the rth data

This method of analysis allows the most appropriate n value as well as k value to be established by comparing the sums of the squares of residuals obtained using the various n values.

3.3. Detection of gross outliers

Outliers are defined as data points that differ significantly from the rest of the data set, based on the likelihood that they do not arise from normal statistical randomness. Fig. 1a–c indicate the possibility that such outliers may exist; these can affect the models significantly and may be discarded. A simple technique of detecting gross outliers was chosen according to Montgomery and Runger [10], in which a data point of a data set was regarded as a gross outlier if its residual was more than twice the residual standard deviation.

4. Rate of carbonation, and prediction models

To illustrate the method used and the derivation of the prediction models, data analysis for exposed Grade 40 concretes of the Cape Peninsula is shown. Derivation of prediction models for the other data sets followed the same procedures (Yam [11]).

4.1. Worked example: Cape Peninsula, exposed grade 40 concrete elements

Fig. 2 shows the overview of all data of exposed Grade 40 concrete elements before the elimination of gross outliers. Tables A1–A4 in the Appendix show the analytical procedures using the method of least squares when n was selected as 0.4, including the evaluation of k, and detection and elimination of gross outliers.

The data points with d_c equal to 13, 15, 18 and 19 mm were eventually eliminated as gross outliers. A k value of 2.04 was thus obtained corresponding to $n = 0.4$ for this grade of concrete. The same procedure was applied for other n values. Table 2 shows the n and k values as well

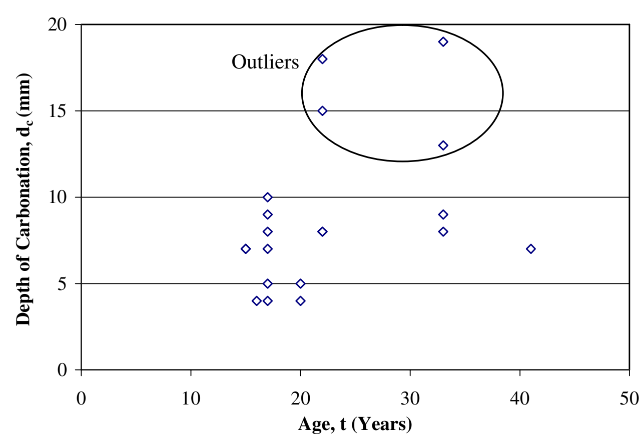

Fig. 2. Carbonation data for exposed Grade 40 concrete elements in the Cape Peninsula.

Table 2
Values of k and sum of squares of residuals (e^2) for n values for exposed Grade 40 concretes in the Cape Peninsula

n	k	e^2
0.3	2.77	52.8
0.4	2.04	54.9
0.5	1.56	76.8
0.6	1.14	80.2

as the sum of squares of residuals (e^2). Fig. 3 shows the processed data as well as the prediction models for all selected n values.

Fig. 3 shows that all prediction models lie reasonably close to each other within the ages of the in situ data. It is also important to understand the nature of the data, which is that they are generally limited to medium-term (approximately 20–40 years) and show high variability.

The statistical procedure can help to decide the values for k and n which represent the best fit to the data, as being those giving the smallest sum of squares of residuals. For the case above, the smallest sum of squares of residuals is given by $n = 0.3$. However, for ideal diffusion, the power series constant n should be 0.5. Values of n greater than 0.5 are difficult to justify unless it is known that the concrete is damaged (for example, micro-cracking), while values of n less than 0.4 are in general unrealistic (leading to underestimation) for normal exposed concrete. Thus, statistical analysis alone cannot provide the sole justification for selection of the prediction model. Selection should also be based on an understanding of the process of carbonation, scientific principles, and engineering judgement.

In this case, the elements were exposed in the Cape Peninsula environment, subject to wetting from sustained periods of rain in winter. Carbonation rate decreases when the moisture content of the near-surface concrete is high. The average RH for the wet season is high (see Table 1), being above the optimum RH range for carbonation. Densification of the pore structure due to the formation and deposition of calcium carbonate in the pores can slow the rate of carbonation with time. Therefore, it was argued that the n value should be lower than the theoretical value of 0.5. Taking the various considerations into account, the n value for all concrete in this locality was taken as 0.4.

The prediction models for other grades of concrete in the Cape Peninsula were similarly obtained and are shown in Table 3.

Grade 20 concretes have the highest k value which indicates the most rapid rate of carbonation. This is due to the relatively porous and permeable nature of these concretes. The k values for Grade 30 and Grade 40 are more comparable, indicating similar permeability of these two grades of concrete.

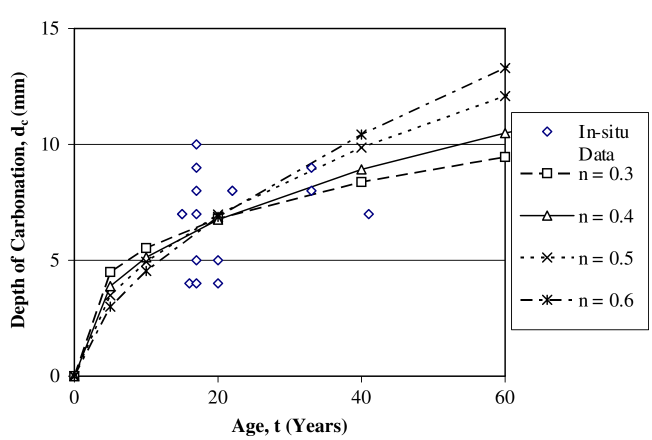

Fig. 3. Carbonation predictions for different n (and corresponding k) values for exposed Grade 40 concretes in the Cape Peninsula.

Table 3
Prediction models for Grades 20, 30 and 40 exposed concretes in the Cape Peninsula locality

Concrete strength grade	Carbonation prediction model
Grade 20	$d_c = 3.72t^{0.4}$
Grade 30	$d_c = 2.61t^{0.4}$
Grade 40	$d_c = 2.04t^{0.4}$

4.2. Durban and Johannesburg localities

As reasoned earlier, the derivation of carbonation prediction models should be based on a synthesis of statistical analysis, understanding of the process of carbonation, and scientific principles. In the Durban locality, moisture content of the near-surface concrete would be relatively high due to the high RH values, especially in the wet season (see Table 1), giving slow rates of diffusion of carbon dioxide. Consequently, the n value was selected to be 0.4 as was the case for the Cape. On the other hand, a more conservative n value of 0.5 was selected for the Johannesburg locality due to the relatively dry environment (within the optimum relative humidity range for carbonation) which allows rapid carbonation throughout the year.

Table 4 summarises all the prediction models derived. Comparison of the rates of carbonation for these localities will be discussed in the next section. (Durban data have been divided into newer structures (built 1970–1982) and older structures (1956–1964), whilst the older (>60 years) Cape Peninsula data have been excluded in the respective analyses).

4.3. Comparison of carbonation rates between localities

Rates of carbonation between different localities for elements with the same exposure conditions and similar con-

Table 4
Carbonation prediction models for the chosen localities

Locality	Strength grade	Exposure conditions	
		Exposed	Sheltered
		Prediction model	
Cape Peninsula	Grade 20	$d_c = 3.72t^{0.4}$	–
	Grade 30	$d_c = 2.61t^{0.4}$	–
	Grade 40	$d_c = 2.04t^{0.4}$	–
Durban (1970–1982)	Grade 25	$d_c = 4.93t^{0.4}$	$d_c = 4.82t^{0.4}$
	Grade 35	$d_c = 3.75t^{0.4}$	$d_c = 3.44t^{0.4}$
	Grade 45	–	$d_c = 2.64t^{0.4}$
Durban (1956–1964)	Grade 25	$d_c = 3.08t^{0.4}$	$d_c = 3.04t^{0.4}$
Johannesburg	Grade 30	$d_c = 3.76t^{0.5}$	$d_c = 2.99t^{0.5}$
	Grade 35	$d_c = 3.20t^{0.5}$	$d_c = 3.95t^{0.5}$

crete quality (strength grade) were compared in order to understand environmental effects on carbonation rates better. As an example, see Fig. 4.

Johannesburg structures clearly have the highest rates of carbonation, primarily due to the climate in which RH for both high and low rainfall seasons (68% and 51%, respectively) are within the optimum range for carbonation. Durban has a higher rate of carbonation than the Cape Peninsula, due to higher temperature and the different rainfall pattern. In the high rainfall season, the average temperature for Durban is 9 °C higher than the Cape (see Table 1), thus accelerating the rate of carbonation.

In both Durban and Johannesburg, the general pattern of short duration rainfall allows the near-surface moisture content of exposed elements after being wetted to revert to values in equilibrium with ambient relative humidity in a relatively short period, i.e. the concrete dries out quickly after surface wetting (Blight [12]). Therefore, the effects of rain on carbonation rate for the exposed elements in these two localities are not likely to be substantial. This is reflected in the similar carbonation rates for the exposed and sheltered elements with similar concrete strength grade in these two localities, shown in Figs. 5 and 6, respectively. This suggests that all exposed and sheltered elements for a given strength grade could be combined as one group in these localities. While the variability in the Johannesburg trends is higher than that for Durban, and the trends are not entirely consistent, this is of secondary concern considering the overall scatter of the data shown in Fig. 1c).

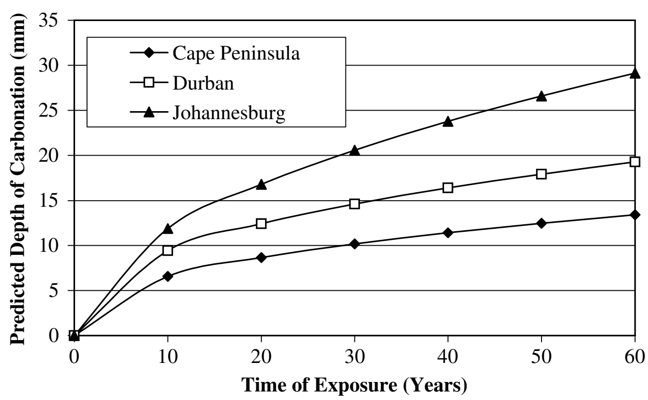

Fig. 4. Comparison of carbonation rates of exposed Grade 30 or 35 concretes for the localities (Durban data post-1970).

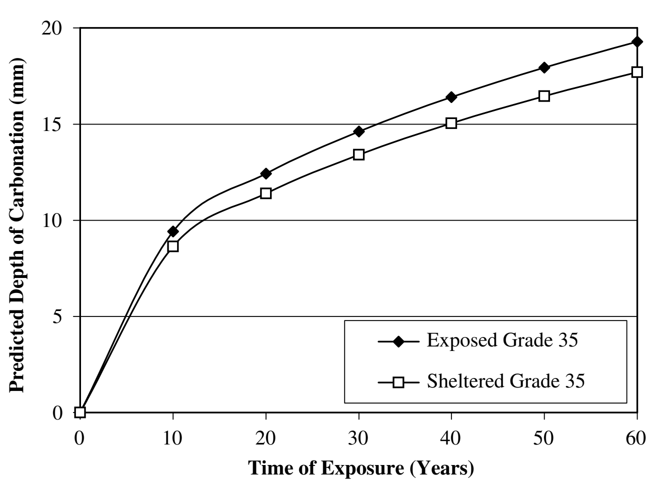

Fig. 5. Carbonation rates for exposed and sheltered Grade 35 concretes in Durban.

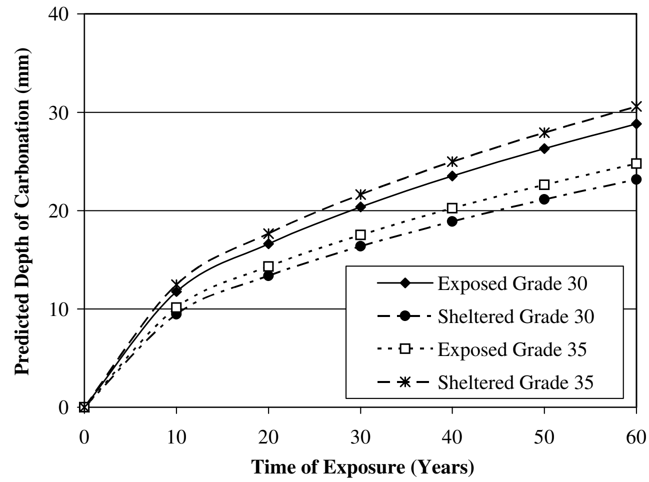

Fig. 6. Carbonation rates for exposed and sheltered elements in Johannesburg.

On the other hand, the Cape Peninsula has periods of prolonged winter rainfall promoting near-saturated surface moisture conditions for several months of the year, thus retarding the rate of carbonation. It is instructive to note from Fig. 4 that Cape Peninsula bridge structures experience approximately one third lower carbonation depths at any given age than Durban structures, a factor similar to the 4 months or so of the year when conditions are at their wettest.

5. Carbonation rates in "OLD" and "NEW" structures

Visual examination of the Durban data (Fig. 1b) shows two "populations", and the statistical analyses have allowed for this. A clearer differentiation in carbonation rates between these two populations can be seen after dividing the data in terms of concrete strength grade – see Fig. 7 (Fig. 5 indicated that different exposure conditions had little effect). Reasons for the differentiation must be sought in material factors, mainly the cement constituent, as other constituents (such as aggregates and mixing water) should have similar properties over the years concerned. A brief discussion on this follows.

A change in the properties of South African ordinary Portland cement over the years studied is reported in Fulton [7] where it is stated *"most of the normal Portland cements at present manufactured in South Africa comply with the requirements of SABS 471 in respect of rapid-hardening cements"*. It is presumed that there was an increase in both the fineness of ordinary Portland cements and the tricalcium silicate content while the content of dicalcium

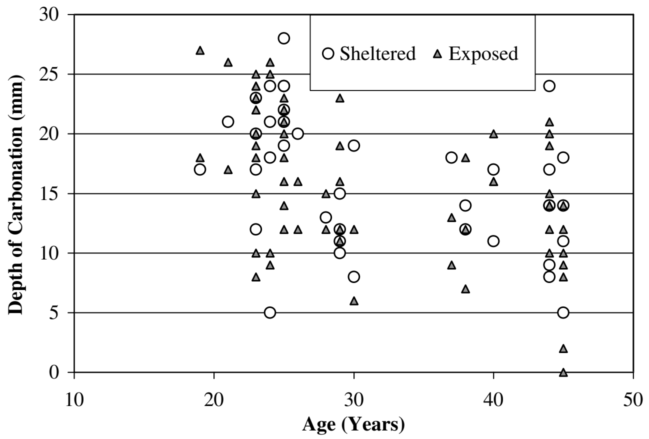

Fig. 7. Carbonation data for exposed and sheltered Grade 25 concretes in Durban.

silicate was reduced correspondingly. Fulton [7] and Raath and Horton [13] state that these changes came about to increase the rate of early strength development due to the demand for fast track construction. The main effect would be a higher water/cement ratio to achieve the same compressive strength, leading to more porous and permeable concrete even though strength may be adequate. These changes in cement would also increase the heat of hydration leading to higher thermal stresses and higher drying shrinkage as reported by Mehta [14] and Raath and Horton [13], with the possibility of micro-crack formation. Interconnection of micro-cracks form channels for carbon dioxide to penetrate into the concrete. Hence, the rate of carbonation is likely to be faster in bridges in the younger population group made from the "modern" cements. These comments would require further investigation to confirm the hypotheses.

An important consequence of these findings is that carbonation prediction models based on in situ data are only suitable for structures constructed in the similar period (age) for the data obtained. The present models should therefore preferably be used only for informing or preparing maintenance plans for existing structures.

6. Carbonation prediction for design

For design purposes, it is more useful to predict carbonation depths for the concrete strength grade bands in a probabilistic manner in order to have a realistic prediction model with a higher "factor of safety" to allow for the highly variable conditions for field concretes. Different percentile carbonation depths can be considered. Using the present data illustratively, a 90th percentile carbonation depth value based on an appropriate k value was assumed to suffice as this value represents 90% of the in situ data having less than or equal to this depth. Prediction models for the 90th percentile carbonation depths for exposed structures are given in Table 5, and Fig. 8 shows 50th and 90th percentile carbonation depths for Grade 40 exposed concretes in the Cape Peninsula. The differences in the predicted carbonation depths between the 50th and 90th percentile carbonation predictions are due to the highly variable nature of the data. Therefore, it is advisable to use the 90th percentile prediction models, which are more conservative, for design purposes.

Table 5
90th Percentile carbonation prediction models for exposed conditions in the chosen localities

Locality	Strength grade	Prediction model
Cape Peninsula	Grade 20	$d_c = 5.94t^{0.4}$
	Grade 30	$d_c = 3.48t^{0.4}$
	Grade 40	$d_c = 2.95t^{0.4}$
Durban (1970–1982)	Grade 25	$d_c = 7.01t^{0.4}$
	Grade 35	$d_c = 5.53t^{0.4}$
	Grade 45 (sheltered)	$d_c = 4.38t^{0.4}$
Durban (1956–1964)	Grade 25	$d_c = 4.18t^{0.4}$
Johannesburg	Grade 30	$d_c = 5.00t^{0.5}$
	Grade 35	$d_c = 4.65t^{0.5}$

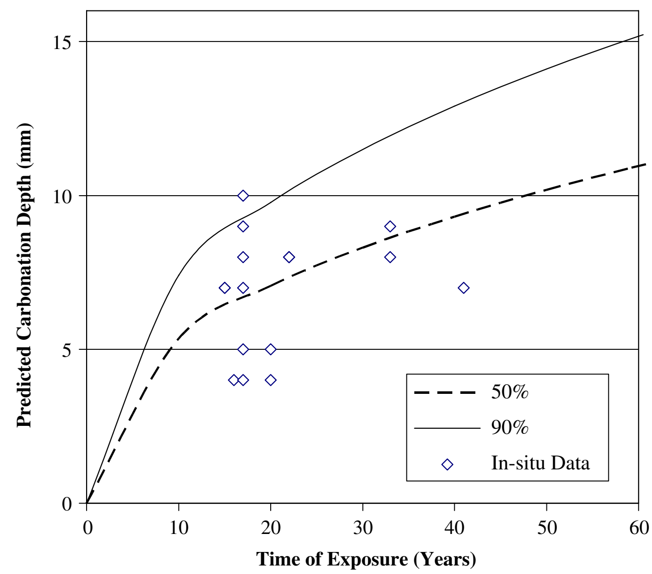

Fig. 8. 50th and 90th percentile carbonation depth for Grade 40 exposed concrete elements in the Cape Peninsula.

7. Closure

Carbonation data were obtained from in situ bridge structures aged between 11 and 76 years in the Cape Peninsula, Durban and Johannesburg localities in order to study field carbonation rates under different material and environmental conditions, and hence derive carbonation prediction models.

Due to the relatively dry environment, Johannesburg bridges had the highest rate of carbonation but lowest risk of corrosion of reinforcement. Bridges in Durban with its relatively high RH and temperature and short duration of rainfall had faster rates than Cape Peninsula bridges, but slower than Johannesburg bridges. Bridges in the Cape Peninsula and Durban tend to have a higher risk of carbonation-induced corrosion with the dry season favouring carbonation whilst the wet season promotes reinforcing steel corrosion.

Carbonation rates for exposed and sheltered elements with comparable concrete strength grades in Durban were

Table A1
Evaluation of k and the sum of squares of residuals for Grade 40 exposed concrete in the Cape Peninsula locality when n is selected to be 0.4 (all data)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	7.6	−0.6	0.4
15	49.4[a]	7	2.95	8.73	20.68	7.6	−0.6	0.4
16	42.5	4	3.03	9.19	12.13	7.8	−3.8	14.4
17	46.38	8	3.11	9.65	24.85	8.0	0.0	0.0
17	46.38[a]	7	3.11	9.65	21.74	8.0	−1.0	1.0
17	43.8[a]	5	3.11	9.65	15.53	8.0	−3.0	8.9
17	43.8	4	3.11	9.65	12.42	8.0	−4.0	15.9
17	43.3	9	3.11	9.65	27.95	8.0	1.0	1.0
17	43.3	10	3.11	9.65	31.06	8.0	2.0	4.0
20	44.4[a]	4	3.31	10.99	13.26	8.5	−4.5	20.5
20	44.4	5	3.31	10.99	16.57	8.5	−3.5	12.4
22	45[a]	8	3.44	11.86	27.55	8.9	−0.9	0.7
22	45	8	3.44	11.86	27.55	8.9	−0.9	0.7
22	41.6[a]	15	3.44	11.86	51.65	8.9	6.1	37.7
22	**41.6**	**18**	**3.44**	**11.86**	**61.98**	**8.9**	**9.1**	**83.6**
33	40.5	8	4.05	16.40	32.40	10.4	−2.4	5.8
33	40.5	9	4.05	16.40	36.45	10.4	−1.4	2.0
33	48.8	13	4.05	16.40	52.64	10.4	2.6	6.7
33	**48.8[a]**	**19**	**4.05**	**16.40**	**76.94**	**10.4**	**8.6**	**73.6**
41	41.6	7	4.42	19.51	30.92	11.4	−4.4	19.0
			Sum	**239.02**	**614.93**	Mean	**−0.1**	**309**
						Std. Dev.	**4.0**	
						+2× (Std. Dev.)	**8.1**	
						−2× (Std. Dev.)	**−8.1**	

Note: values in bold are outliers.
[a] Refers to assumed value (See Section 3.1.2) $k = 614.93/239.02 = 2.57$ (Eq. (2)).

Table A2
Evaluation of k and the sum of squares of residuals for Grade 40 exposed concrete in the Cape Peninsula locality when n is selected to be 0.4 (after the first elimination of gross outlier, 2 No.)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.7	0.3	0.1
15	49.4[a]	7	2.95	8.73	20.68	6.7	0.3	0.1
16	42.5	4	3.03	9.19	12.13	6.8	−2.8	8.1
17	46.38	8	3.11	9.65	24.85	7.0	1.0	1.0
17	46.38[a]	7	3.11	9.65	21.74	7.0	0.0	0.0
17	43.8[a]	5	3.11	9.65	15.53	7.0	−2.0	4.1
17	43.8	4	3.11	9.65	12.42	7.0	−3.0	9.1
17	43.3	9	3.11	9.65	27.95	7.0	2.0	3.9
17	43.3	10	3.11	9.65	31.06	7.0	3.0	8.9
20	44.4[a]	4	3.31	10.99	13.26	7.5	−3.5	12.1
20	44.4	5	3.31	10.99	16.57	7.5	−2.5	6.2
22	45[a]	8	3.44	11.86	27.55	7.8	0.2	0.0
22	45	8	3.44	11.86	27.55	7.8	0.2	0.0
22	**41.6[a]**	**15**	**3.44**	**11.86**	**51.65**	**7.8**	**7.2**	**52.2**
33	40.5	8	4.05	16.40	32.40	9.1	−1.1	1.3
33	40.5	9	4.05	16.40	36.45	9.1	−0.1	0.0
33	48.8	13	4.05	16.40	52.64	9.1	3.9	14.9
41	41.6	7	4.42	19.51	30.92	10.0	−3.0	8.9
			Sum	**210.77**	**476.01**	Mean	**0.0**	**130.9**
						Std. Dev.	**2.8**	
						+2× (Std. Dev.)	**5.6**	
						−2× (Std. Dev.)	**−5.6**	

Note: values in bold are outliers.
[a] Refers to assumed value (See Section 3.1.2) $k = 476.01/210.77 = 2.26$ (Eq. (2)).

similar, as was the case in Johannesburg. It was surmised that the short duration of rainfall and the high relative humidity in Durban yields only small differences in the near-surface moisture content between exposed and sheltered elements. Short rainfall duration and low relative humidity in Johannesburg would render the near-surface moisture content for exposed elements similar to those for sheltered elements.

The Durban results also showed that carbonation rates between old and modern structures are not the same, with older structures (>35 years) having slower carbonation rates. This was ascribed possibly to changes in cement characteristics such as increased cement fineness over the years leading to detrimental effects on the permeability of modern concretes. Further investigation on this aspect is necessary.

Table A3
Evaluation of k and the sum of squares of residuals for Grade 40 exposed concrete in the Cape Peninsula locality when n is selected to be 0.4 (after the second elimination of gross outlier, 1 No.)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.3	0.7	0.5
15	49.4[a]	7	2.95	8.73	20.68	6.3	0.7	0.5
16	42.5	4	3.03	9.19	12.13	6.5	−2.5	6.1
17	46.38	8	3.11	9.65	24.85	6.6	1.4	1.9
17	46.38[a]	7	3.11	9.65	21.74	6.6	0.4	0.1
17	43.8[a]	5	3.11	9.65	15.53	6.6	−1.6	2.6
17	43.8	4	3.11	9.65	12.42	6.6	−2.6	6.9
17	43.3	9	3.11	9.65	27.95	6.6	2.4	5.6
17	43.3	10	3.11	9.65	31.06	6.6	3.4	11.4
20	44.4[a]	4	3.31	10.99	13.26	7.1	−3.1	9.4
20	44.4	5	3.31	10.99	16.57	7.1	−2.1	4.3
22	45[a]	8	3.44	11.86	27.55	7.3	0.7	0.4
22	45	8	3.44	11.86	27.55	7.3	0.7	0.4
33	40.5	8	4.05	16.40	32.40	8.6	−0.6	0.4
33	40.5	9	4.05	16.40	36.45	8.6	0.4	0.1
33	**48.8**	**13**	**4.05**	**16.40**	**52.64**	**8.6**	**4.4**	**19.0**
41	41.6	7	4.42	19.51	30.92	9.4	−2.4	5.9
			Sum	**198.91**	**424.36**	Mean	**0.0**	**75.6**
						Std. Dev.	**2.2**	
						+2× (Std. Dev.)	**4.3**	
						−2× (Std. Dev.)	**−4.3**	

Note: values in bold are outliers.
[a] Refers to assumed value (See Section 3.1.2) $k = 424.36/198.91 = 2.13$ (Eq. (2)).

Table A4
Evaluation of k and the sum of squares of residuals for Grade 40 exposed concrete in the Cape Peninsula locality when n is selected to be 0.4 (after the third elimination of gross outlier, 1 No.)

Age (t)	Grade	d_c	$t^{0.4}$	$t^{0.8}$	$d_{ci}t_i^{0.4}$	Predicted	Residual	Residual^2
15	49.4	7	2.95	8.73	20.68	6.0	1.0	1.0
15	49.4[a]	7	2.95	8.73	20.68	6.0	1.0	1.0
16	42.5	4	3.03	9.19	12.13	6.2	−2.2	4.7
17	46.38	8	3.11	9.65	24.85	6.3	1.7	2.8
17	46.38[a]	7	3.11	9.65	21.74	6.3	0.7	0.5
17	43.8[a]	5	3.11	9.65	15.53	6.3	−1.3	1.8
17	43.8	4	3.11	9.65	12.42	6.3	−2.3	5.4
17	43.3	9	3.11	9.65	27.95	6.3	2.7	7.2
17	43.3	10	3.11	9.65	31.06	6.3	3.7	13.5
20	44.4[a]	4	3.31	10.99	13.26	6.8	−2.8	7.6
20	44.4	5	3.31	10.99	16.57	6.8	−1.8	3.1
22	45[a]	8	3.44	11.86	27.55	7.0	1.0	1.0
22	45	8	3.44	11.86	27.55	7.0	1.0	1.0
33	40.5	8	4.05	16.40	32.40	8.2	−0.2	0.1
33	40.5	9	4.05	16.40	36.45	8.2	0.8	0.6
41	41.6	7	4.42	19.51	30.92	9.0	−2.0	4.0
			Sum	**182.51**	**371.72**	Mean	**0.1**	**54.9**
						Std. Dev.	**1.9**	
						+2× (Std. Dev.)	**3.8**	
						−2× (Std. Dev.)	**−3.8**	

[a] Refers to assumed value (See Section 3.1.2) $k = 371.72/182.51 = 2.04$ (Eq. (2)).

Acknowledgements

The authors acknowledge with gratitude the permission to access the data on carbonation that are reviewed in this paper. Much of this data came from major bridge repair contracts that were managed by the South African National Roads Agency Ltd. (SANRAL). The assistance of Mr Edwin Kruger, in particular, of SANRAL is acknowledged. Likewise, the assistance of Mr Philip Ronné of BKS and Mr Graham Moore in obtaining the bridge data of respective localities is gratefully acknowledged.

Appendix. Statistical analysis example (Exposed Grade 40 elements, Cape Peninsula)

(See Tables A1–A4).

References

[1] ACI Committee 201. Guide to durable concrete. ACI Manual of Concrete Practice: Part 1, Farmington Hills: American Concrete Institute, 2003.
[2] Richardson MG. Fundamentals of durable reinforced concrete. London: Spon Press; 2002.
[3] South African Weather Service. Report on Mean Hourly Relative Humidity and Mean Average Temperature Data. South African Weather Service, in press.
[4] Ronné P. Private communication, 2003.
[5] Moore G. Private communication, 2003.
[6] Ballim Y, Lampacher BJ. Long-term carbonation of concrete structures in the Johannesburg environment. SAICE J First Quar 1996;38(1):5–9.
[7] Fulton FS. Concrete technology: a South African handbook. 5th ed. (Rev Metric). Johannesburg: The Portland Cement Institute; 1977.
[8] Bakker RFM. Initiation period. In: Schiessl P, editor. Corrosion of steel in concrete. Report of Technical Committee 60-CSC RILEM. London: Chapman and Hall; 1988. p. 22–55.
[9] Neville AM. Can we determine the age of cracks by measuring carbonation? – Part 1. Concrete Int 2003;25(12):76–9.
[10] Montgomery DC, Runger GC. Applied statistics and probability for engineers. 3rd ed. New York: John Wiley and Sons; 1999.
[11] Yam WK. Carbonation of concrete bridge structures in three South African localities. MSc (Eng.) Thesis. University of Cape Town, Cape Town; 2004.
[12] Blight GE. A study of four waterproofing systems for concrete. Mag Concrete Res 1991;43(156):197–203.
[13] Raath B, Horton J. Is faster and faster, better and better. In: Proceedings of Conference on Concrete for the 21st Century: Modern Concrete Progress through Innovation. Concrete Soc Southern Africa; 2001. p. 13–4.
[14] Mehta PK. Greening of the concrete industry for sustainable development. Concrete Int 2002;24(7):23–8.