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Influence of marine micro-climates on carbonation of reinforced concrete buildings

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Abstract

Although chloride is the main source for corrosion of reinforcing steel in coastal buildings, concrete carbonation leads to a uniform corrosion of the steel that would accelerate the crack formation and decrease the structures service life. The objective of this investigation was to study the effect of carbonation on public buildings located up to 800 m from the seashore. The results, based on the analysis of carbonation depth, resistivity, compressive strength and porosity data suggested that risk of concrete deterioration due to carbonation increases with the distance from the seashore as well as with the elevation. Generally, higher carbonation coefficients corresponded to the top sections of the evaluated buildings where the measured relative humidity was lower. However, concrete cracks due to corrosion were found in the lower sections where humidity was higher. Data from laboratory specimens exposed to the same tropical marine environment for 5 years were used to correlate the findings from the public buildings.

Keywords: Carbonation; Compressive strength; Corrosion; Porosity; Chloride

1. Introduction

It is well known that in marine environments, the reinforcing steel corrodes mainly due to the attack by chloride ions. However, concrete acidification due to reaction of hydrated cement compounds with atmospheric CO_2 can develop in places where the right climatic conditions are available. This concrete acidification, known as carbonation, reduces the pH of the concrete pore solution. The steel passive layer is destroyed due to the pH reduction and uniform corrosion may develop. This uniform carbonation-induced corrosion accelerates the crack formation in concrete and decreases the residual service life of the structure. Both aggressive agents can interact in marine environments and produce a faster deterioration than if either one acts alone [1]. In the North of the Yucatán Peninsula, as in other places with tropical marine climate, a combined action of chloride ions and carbon dioxide would be expected due to the aggressiveness of the atmosphere.

Humidity and temperature conditions in this region [2] may promote the advance of the carbonation front [3]. However, the actual carbonation rate will depend on several factors such as the type and amount of cement, porosity of the material, time of curing, type and quantity of pozzolanic additions [4,5], etc. Moreover, several modifications in concrete properties as compressive strength, superficial hardness and resistance to aggressive agents (e.g. sulfates) may occur due to carbonation [6].

Once the reinforcement is no longer passive, any rehabilitation of the concrete structure will be expensive [7]. From the engineering point-of-view, an alternative to prevent the corrosion behavior due to chloride ions and/or carbonation in concrete exposed to tropical marine climate, is to design structures according to their geographic orientation, marine breeze direction, sources of humidity and insolation [8], and distance and height regarding the sea (micro-climate) among other factors. However, very few research works have used this approach [9–11], and no one has correlated data of real structures with those of laboratory specimens exposed at the same micro-climate.

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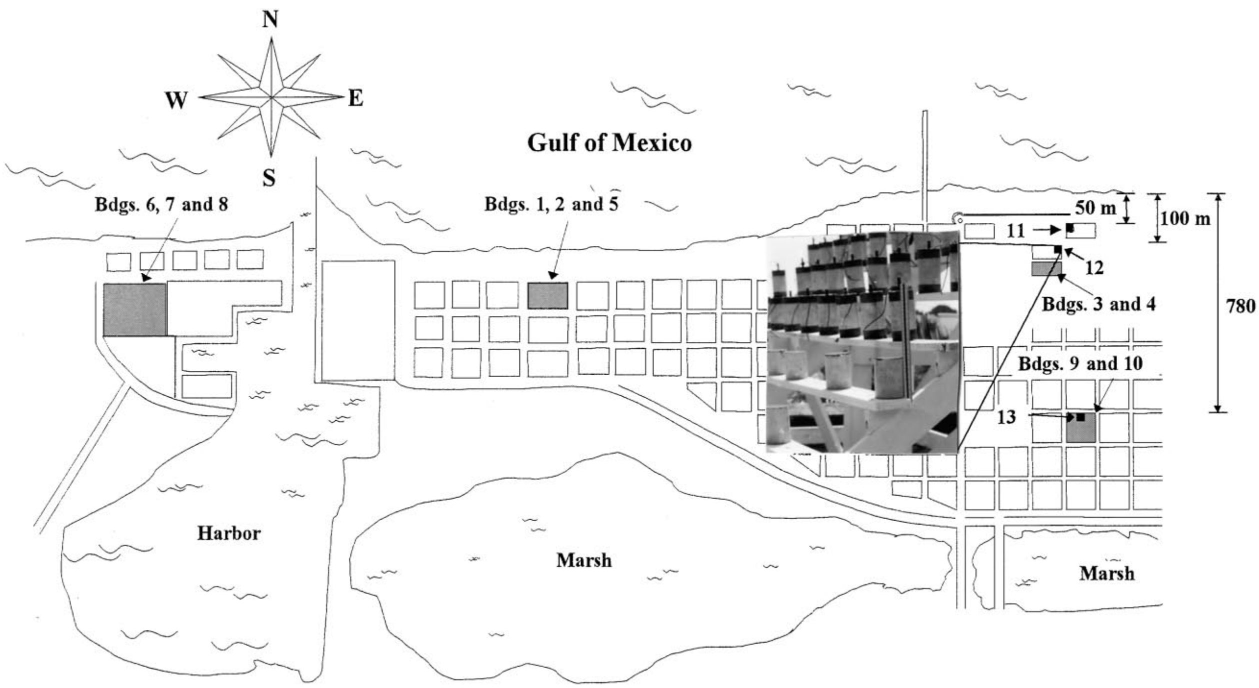

Fig. 1. Sketch with the geographical position of the tested buildings and specimens. Numbers 11, 12 and 13 correspond to the places where the cylinders were exposed.

In order to propose modifications to the design of concrete structures situated in coastal regions, research has been initiated on the susceptibility of structures to corrosion initiation as a function of concrete quality and micro-climatic conditions. This paper discusses carbonation data obtained from 10 buildings under different micro-climates (distances from the seashore). The results are compared with those from cylindrical specimens, which were exposed to the same conditions for 5 years [12–14].

2. Experimental

A preliminary inspection was conducted following the guidelines given in Ref. [15] in order to select the buildings for evaluation. Several factors such as type of deterioration (visual inspection), age, distance and orientation regarding the seashore and position regarding the sources of aggressive agents were taken into account. All the selected buildings were from a typical design of the Mexican Committee for School Construction (CAPFCE); thus ensuring that the concrete used in those buildings had similar mix design characteristics as cement content, water/cement ratio, type of aggregate, etc. The concrete cover thickness was 40 mm as determined in the field. Field concrete resistivity, measured with a commercial corrosimeter, was evaluated in each column of the selected buildings. Three or four columns having comparable concrete resistivity values were selected from each building according to the geographic orientation. The selected columns were located in the north face of the buildings, facing the seashore. The only exception was that of building #3, with East-oriented columns. Fig. 1 shows a sketch with the geographical orientation of the evaluated buildings.

Three 75-mm diameter cores were drilled from each selected column at three different elevations as observed in Fig. 2. Each core was ~200-mm long. After extraction, the core was cut in two parts *a* and *b*: the first part *a* (~50-mm long including the concrete surface) was used for carbonation and porosity measurements. The advantage of using this part is that the actual porosity of the concrete cover is the most important one for concrete durability, even though

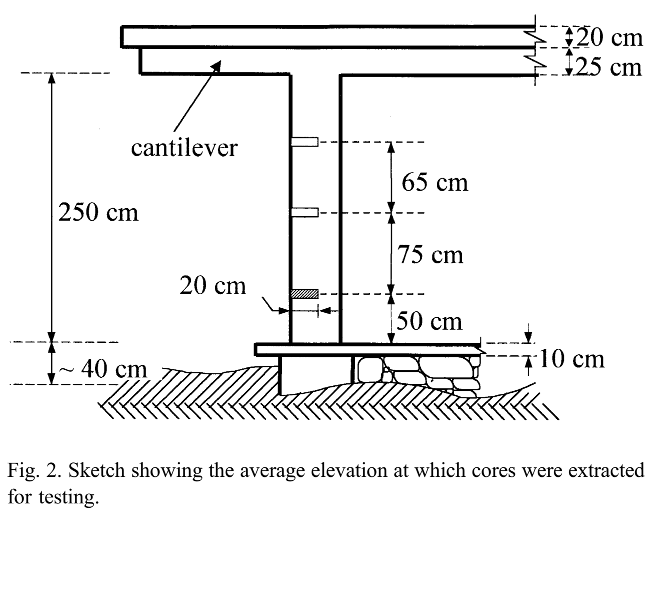

Fig. 2. Sketch showing the average elevation at which cores were extracted for testing.

Table 1
Type and number of tests for each building

Number of elements and tests performed							
Building #	Blocking to the marine breeze	Columns	Compressive strength	Total porosity	Effective porosity	Carbonation depth	Resistivity
1	No	4	5	7	8	11	4
2	No	4	10	11	10	12	4
3	Partial	3	7	n.a.	n.a.	9	3
4	Partial	3	7	n.a.	n.a.	9	3
5	No	4	3	7	6	10	4
6	Partial	3	6	8	8	9	3
7	Partial	3	8	7	7	9	3
8	No	3	7	9	9	9	3
9	No	3	6	6	n.a.	6	3
10	No	3	7	8	n.a.	9	3

n.a. = not available.

the porosity value with time is known to be affected by carbonation [16]. The remaining part *b* was used for compressive strength tests [17]. Slice *a* was cut in two half-cylinders and carbonation test with phenolphthalein solution [15] was performed in both fresh cut faces. In order to avoid misleading results due to residual uncarbonated cement powder, the fresh cut faces were brushed prior to the test. After the carbonation test, a capillary absorption test [15,18] was performed on one of the half-cylinders to estimate the effective porosity, and total porosity tests [15,19] were performed on the other half.

Laboratory cylinders (approximately 75-mm diameter and 150-mm long) were exposed for ~4 years to the same environment and monitored periodically. Five water-to-cement (w/c) ratios (0.46–0.76) and three curing times (tc) of 1, 3 and 7 days were tested. Six plain concrete cylinders were made for each combination of w/c ratio and tc. Two cylinders from each combination were exposed at three different distances from the seashore, 50, 100, and 780 m. The cylinders were used for measuring carbonation depths and chloride profiles at 6, 12, 24 and 48 months of exposure. Refs. [13,20] offer more details on construction, exposure and measurements of those cylinders.

3. Results

Table 1 shows the number of tests that were performed on the cores extracted from each building. The number of tests is representative of each building although it is not the same for every one. Technical limitations impeded the acquisition of porosity data from buildings 3, 4, 9 and 10. Table 2 shows average values for each type of test per building. In general, the average of the measurements

Table 2
Average value for each type of test at different heights in the tested buildings

Building #		1	2	3	4	5	6	7	8	9	10
Age (years)		12	16	12	19	13	25	25	25	3.5	5.5
Distance from the sea (m)		97	105	126	132	155	166	188	213	752	776
Total porosity (%)	Top	24	26	n.a.	n.a.	25	23.00	25	22.32	28.57	21.72
	Middle	25	25	n.a.	n.a.	21	24.00	22	20.03	23.20	21.03
	Bottom	25	25	n.a.	n.a.	21	22.00	20	20.51	23.92	21.57
Effective porosity (%)	Top	24	23	n.a.	n.a.	17	24	20	0.21	n.a.	n.a.
	Middle	19	22	n.a.	n.a.	19	19	18	0.19	n.a.	n.a.
	Bottom	20	20	n.a.	n.a.	15	16	17	0.18	n.a.	n.a.
Compressive strength (MPa)	Top	n.a.	17.7	23.8	24.0	31.9	18.4	21.6	28.2	23.1	34.1
	Middle	16.3	20.4	24.6	22.9	23.1	31.2	26.2	23.9	23.2	35.9
	Bottom	20.2	30.0	24.9	24.2	41.7	31.3	24.4	29.0	n.a.	34.4
Carbonation depth (mm)	Top	20.0	28.5	23.7	26.0	20.7	40.3	38.7	38.7	3.3	6.7
	Middle	20.0	23.8	20.0	23.3	11.0	27.7	31.3	31.7	1.7	5.0
	Bottom	12.5	16.5	17.7	19.3	6.3	26.0	26.7	26.3	0.0	3.3
Carbonation coefficient (mm/year$^{1/2}$)	Top	5.8	7.1	6.8	6.0	5.7	8.1	7.7	7.7	1.8	2.8
	Middle	5.8	5.9	5.8	5.4	3.1	5.5	6.3	6.3	0.9	2.1
	Bottom	3.6	4.1	5.1	4.4	1.8	5.2	5.3	5.3	0.0	1.4
Resistivity (KΩ cm)	Top	816	531	1617	1602	949	1444	1598	1606	1341	1522
	Middle	1064	1111	1621	1646	789	1181	1598	1605	750	1192
	Bottom	873	798	1718	1598	743	1324	1613	1623	418	1213

n.a. = not available.

Table 3
Carbonation depth and chloride concentration in representative columns

From building #:		2	4	5	6	10
Carbonation depth (mm)	Top	38	24	3	48	9
	Middle	25	21	6	44	7
	Bottom	17	14	9	42	4
Chloride content[a]	Top	5.4	1.8	3.6	1.3	0.6
	Middle	6.6	2	3.6	1.2	0.7
	Bottom	4.2	1.2	2.1	2.4	0.7

[a] Average in kilogram of Cl^- per cubic meter of concrete at rebar level assuming a nominal unit weight of 2200 kg/m^3.

suggests that porosity increases and compressive strength decreases from the bottom to the top of the columns, although this is not true for all buildings. The carbonation front showed a tendency to increase from the bottom to the top of the columns as seen in Table 2 for averaged values per building, and in Table 3 for selected, individual columns. The carbonation coefficient, K [15,21], increased from seashore to inland with few exceptions, which are discussed later. This tendency was the same for both, buildings and cylindrical probes.

Fig. 3 shows that the carbonation front maintained the same tendency (increasing from bottom to top) independently of the age and distance from the sea. However, the carbonation front was influenced by the geographic orientation as seen in Fig. 4. This figure shows selected cases of buildings where the carbonation depth decreased from East to West at different distances from the seashore, even though the difference in carbonation depth was small in some cases. This effect changed when the buildings were partially blocked to the marine breeze (buildings 3, 4, 6 and 7) as observed in Fig. 5. In this figure, an increase of the carbonation depth is observed from seashore to inland but the carbonation front of the columns in the middle of the building was deeper than from those columns at the end of the building. The compressive

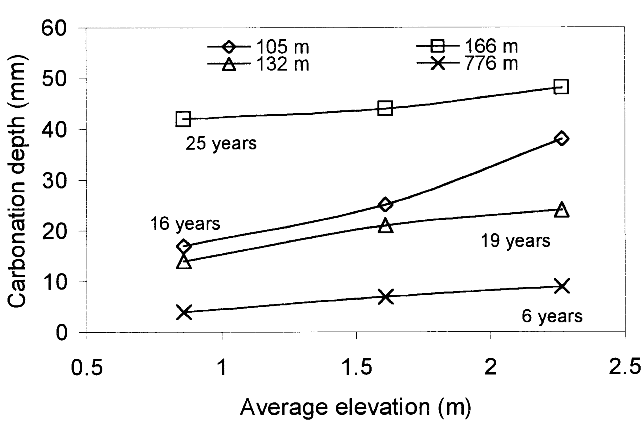

Fig. 3. Carbonation depth at different elevations, ages and distances from the sea.

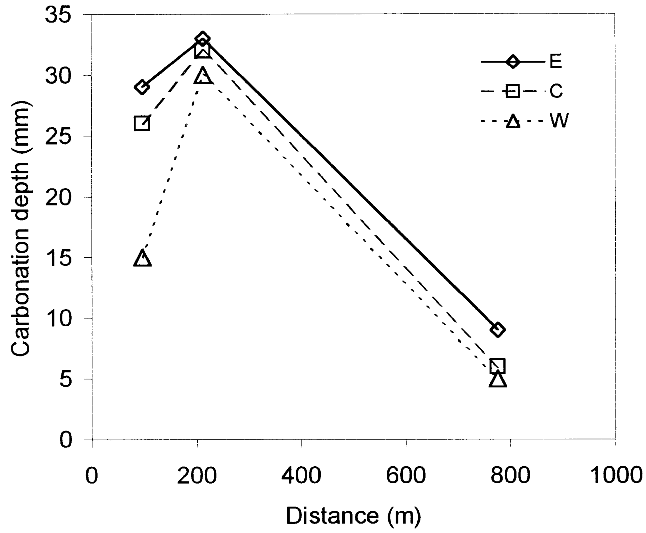

Fig. 4. Carbonation depth as a function of geographical orientation from selected buildings at different distances from the sea. E = East, W = West, and C = Central part.

strength in these buildings seems to be unaffected by the marine breeze blocking.

4. Discussion

México has more than 10,000 km of coastline and in most locations, structures have been made with ordinary Portland cement (type I) concrete that does not resist the environmental action despite the concrete passing the mechanical tests. Thus, a premature deterioration appears due to the interaction of chloride and carbon dioxide with concrete. However, each of these agents has a different

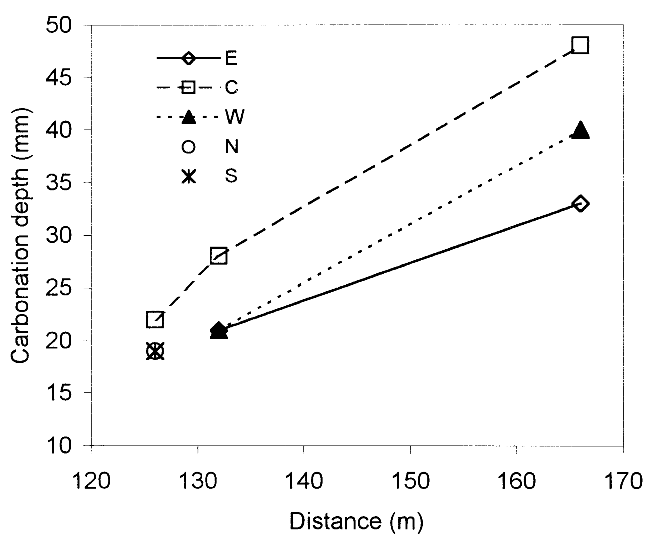

Fig. 5. Carbonation depth as a function of geographical orientation for selected buildings with blocking at different distances from the sea. E = East, W = West, N = North, S = South and C = Central part.

influence, which depends, besides on the concrete characteristics, on variables such as the structure elevation, geographic orientation and micro-climate. Even though several researchers [10,11] have advised about the influence of such variables, their influences on the carbonation depth are not known in detail. The discussion of this work is focused on understanding the carbonation behavior according to the structure elevation, geographic orientation and distance from the sea (micro-climate). The concrete characteristics (such as cement factor, w/c ratio, aggregate type, etc.) and the time of curing were not taken into consideration under the assumptions of employing similar concrete quality for all the analyzed buildings and that the natural curing of the columns in this investigation compensated any deficiency due to the original curing.

4.1. Influence of the elevation

There is a distribution of temperature and humidity as a function of the elevation along the columns. The foundation of the columns was cast close to the water table. This situation has allowed moisture and chloride transport from the ground to the bottom of the columns during the structure's service life, the extent of which changes according to seasonal variations. Table 4 shows the temperature and humidity as a function of height for two typical columns from building 2. Generally, temperature remains constant but humidity has a tendency to decrease with height. This humidity variation may result in the lower parts of the columns allowing less access of carbon dioxide (due to partial water saturation of the pores) than the higher ones. As a result, less carbonation depth was observed, on the average, at the bottom of the columns (Table 2). However, as discussed below, in a few cases (as that of the column from building 5 in Table 3), the opposite was observed.

In the older buildings (>10 years), regional construction techniques did not ensure adequate curing of the concrete elements after casting. Therefore, the water at the higher parts of the columns evaporated and/or descended by gravity promoting a better natural curing at the bottom than at the top of the columns. Although this differential curing was not easily perceived with traditional methods, it was observed through a small but significant increase of the porosity and decrease of the compressive strength with height, as also observed in Table 2. In the newer buildings (< 10 years), this effect was not observed, probably due to better curing techniques enforced at the time of casting.

Table 4
Typical distribution of temperature and relative humidity in two columns of building 2 during the summer

Column number		Temperature (°C)	RH (%)
15	Top	29.5	63.6
	Middle	29.7	69.0
	Bottom	31.4	75.2
19	Top	29.5	69.1
	Middle	29.7	70.6
	Bottom	29.7	81.5

Chloride concentration inside concrete changes along the year depending on the prevailing penetration mechanism (leaching during the rainfall season, inside flux otherwise) [22,23]. High concentrations can cause water saturation due to chloride hygroscopy and, as a consequence, the film of water inside the pores would be thicker than without chloride contamination, thus decreasing the carbonation rate. An example of this situation is observed in Table 3, where building 5 showed an increase in chloride concentration and a decrease in carbonation depth from bottom to top. However, in older buildings (>10 years) with high concrete porosity values, the chloride penetration mechanisms can change each season, resulting in no clear tendencies in the chloride concentration from bottom to top at large. Therefore, chlorides no longer have influence on the carbonation depth distribution from bottom to top as observed in buildings 2, 4, 6 and 10 from Table 3. Chloride then plays an important role on the carbonation rate at early stages but it is loosed at large.

The results in terms of elevation are demonstrating that the observed variations in porosity, compressive strength, humidity and temperature of concrete, although small, are reflected in the carbonation behavior.

4.2. Influence of the geographic orientation

Geographic orientation regarding the marine breeze, blocking of the marine breeze by trees and/or other buildings, and the sun movement are factors that have an influence on the carbonation rate. More than 50% of the tested buildings were not blocked from the marine breeze but the regional atmospheric conditions [2] allowed less time of wetness (TOW) in the east than in the west side of the buildings. This low TOW can promote less humidity in the East than in the West and then faster carbonation rates in the East than in the West. On the other hand, as mentioned before, chlorides would have an influence on the carbonation rates at early ages but none at large. Therefore, it seems to be that TOW is playing a more important role than chlorides in the distribution of carbonation shown in Fig. 4.

On the other hand, when the sun and/or marine breeze are partially blocked, carbonation can be favored or it may not depend on the environmental humidity. More than 30% of the tested buildings showed an increase of carbonation in their central part with respect to the geographical direction as seen in Fig. 5. The buildings at 132 and 166 m had a partial blocking of the marine breeze by other buildings and a concrete wall at the front central part. This probably produced a variation in the concrete internal conditions that promoted deeper carbonation depth in the columns located at the front central part of the building. Regarding the building at 126 m from the seashore in Fig. 5, it was the only building that was North–South oriented with the examined columns facing East. This building had the

Table 5
Carbonation coefficients, K (mm/year$^{1/2}$) as a function of the distance from the sea

Building #	1	2	3	4	5	6	7	8	9	10
Carbonation coefficients from buildings										
Distance from the sea (m)	97	105	126	132	155	166	188	213	752	776
Age of the structure (years)	12	16	12	19	13	25	25	25	3.5	5.5
No. of tests	11	12	9	9	10	9	9	9	9	9
Average carbonation coefficient	5.0	5.7	5.9	5.2	3.5	6.3	6.4	6.4	0.9	2.1
Standard deviation	2.2	2.0	0.9			2.6	1.3	1.2		0.9
Maximum value	8.4	9.5	7.5	6.7	8.3	9.6	9.0	8.0	2.7	3.8
Minimum value	0.6	3.0	4.6	3.2	1.7	2.2	5.2	4.2	0.0	1.7
Equivalent carbonation coefficients from concrete cylinders										
Distance from the sea (m)			50			100			780	
Exposure time (years)			3.8			3.8			3.8	
No. of tests			24			24			24	
Average carbonation coefficient			2.4			2.6			2.7	
Standard deviation			1.1			1.1			1.3	
Maximum value			4.3			4.7			4.3	
Minimum value			1.2			1.6			1.2	

particularity of having trees in its front central part that are blocking the sun and marine breeze. It seems that the blocking effect in two different orientations plays a relevant role in the concrete, increasing the carbonation. More data are necessary to separate the contribution of TOW and chlorides in the carbonation of the central parts.

From the engineering point-of-view, it seems that a coastal building could be protected from the chloride action of marine breeze by adequate blocking (trees, walls, etc.), although this blocking may increase the carbonation rate in case of bad curing techniques or low quality concrete.

4.3. Influence of the distance to the sea (micro-climate)

The marine breeze and chloride availability decrease in intensity with the distance from the sea. The existence of these profiles promotes the formation of micro-climates that attack the materials with different intensities. This was demonstrated by the exposure of concrete cylinders to the atmosphere where an increment in the carbonation coefficient, K, with the distance from the sea was observed. However, this tendency must be corroborated in real structures. Data from Table 5 show that the carbonation coefficient followed the same trend in both buildings and concrete cylinders. The data from concrete cylinders were converted from carbonation depths in a cylinder to carbonation depths that would have taken place in concrete with an infinite flat surface; K was calculated according to Ref. [21]. The tendency of K to increase with the distance from the sea in these buildings confirmed the previous findings with the cylindrical probes.

In a recent investigation in a hot–dry climate [9,24], K values of 2.6 and 4.3 mm/year$^{1/2}$ were determined in coastal buildings located at 0.5 and 2 km, respectively. The age of the structures ranged from 7 to 10 years. For the same investigation, it was found that beyond coastal areas, the K values decreased as a function of the distance from the sea. In the Yucatán Península, the coastal area has a warm–dry climate although inland, the climate is warm–semihumid. Therefore, beyond coastal areas, the K values from buildings with similar mix design properties would be expected to decrease. Nevertheless, the carbonation behavior found in the buildings, regarding the distance from the sea in the coastal area, seems to corroborate the data in the literature.

The values of K regarding the distance from the sea of buildings 5, 9 and 10 showed a different tendency from the rest (Table 5) which may be attributed, among several possibilities, to the higher compressive strength in the case of buildings 5 and 10, and to the degree of water saturation in the case of buildings 5 and 9, as evidenced by the low concrete resistivity measured (Table 2).

From the engineering point-of-view, it seems that in coastal areas, the risk of carbonation should be taken into account when the marine influence decreases, i.e., that for buildings with similar mix design properties, the risk of concrete deterioration due to chlorides decreases and that due to carbonation increases with the distance from the sea.

5. Conclusions

Experimental data (porosity, compressive strength, carbonation depth and chloride content) on cores taken from several buildings in the northern coastal zone of the Yucatán Península at different elevations and orientations have shown reasonable trends regarding elevation, geographic orientation and distance from the sea on concrete structures.

For buildings with similar mix design properties, the carbonation depth increased with the elevation, and from West-to-East orientation for the conditions of the tropical marine climate investigated. For the same buildings, the carbonation coefficient increased with the distance from the seashore. These observations are important for designing concrete structures in terms of durability.

Although chloride was found to be the main cause of corrosion and cracks at the bottom of the columns, the carbonation front had reached the rebar level at the top of the columns in several buildings, which were at least 19-years-old. Thus, carbonation-induced corrosion is expected to cause similar damage at the top of the columns in the near future.

The data from laboratory specimens confirmed the increment in carbonation depth as a function of distance from the sea observed in real structures.

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