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Carbonation depth in 57 years old concrete structures

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Abstract. Carbonation depth was verified in 40 points of two 57 years old concrete viaducts. Field testing (phenolphthalein spraying) was performed on the structures. Data obtained were statistically analyzed by the Kolmogrov-Smirnov's test, one-way analysis of variance (ANOVA's test), and Fisher's method. The results revealed significant differences between maximum carbonation depths of different elements of the same concrete structure. Significant differences were also found in the carbonation of different concrete structures inserted in the same macroclimate. Microclimatic factors such as temperature and local humidity, sunshine, wind, wetting and drying cycles, among others, may have been responsible by the behavior of carbonation in concrete.

Keywords: concrete structures; environment; field testing; viaducts; statistical

1. Introduction

Knowledge about processes of concrete structures degradation is fundamental for projects conception and execution of more sustainable structures (Rincón and Lima 2006, Medeiros *et al.* 2013, Kurklu *et al.* 2013, Medeiros-Junior *et al.* 2014). This also contributes to the projection of a rational program of recovery. Among these processes it is observed that carbonation has a significant participation in reducing the service life of a reinforced concrete structure (Parrott 1992, Loo *et al.* 1994, Lundgren 2002).

Carbonation is a chemical reaction of portlandite $Ca(OH)_2$ and calcium-silicate-hydrate (C-S-H) with carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$) and water. As a first approach, CO_2 enters through the concrete pores, mainly by gaseous diffusion, for a given moisture content.

The natural conditions of high alkalinity present inside the concrete normally protect the steel from corrosion reactions. However, carbonation reduces the hydroxide concentration in the pore solution and destroys the passivity of the embedded reinforcement bars, triggering the corrosion

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process.

There are several techniques to determine the depth of carbonation in concrete. The thermalgravimetric analysis (TGA) method allows to verify the concentration distribution of $Ca(OH)_2$ and $CaCO_3$ in different layers of concrete. The X-ray diffraction analysis (XRDA) tests the intensity distribution of these same elements (Chang and Chen 2006, Villain *et al*. 2007, Han *et al*. 2012). Fourier transformation infrared spectroscopy (FTIR) test method identifies the presence of C-O in concrete as a basis for detecting the presence of $CaCO_3$ (Stevula *et al.* 1994, Lee *et al.* 2012). The Nonlinear Resonant Ultrasound Spectroscopy (NRUS) technique is also investigated (Bouchaala *et al.* 2011). However the traditional way of determining the depth of carbonation, especially in-field, is a colorimetric method based on spraying phenolphthalein in the surface of a freshly split concrete prism. This method assesses a carbonation depth corresponding to a pH value roughly equal to 9. In the noncarbonated part of concrete, a purple-red color is obtained. Furthermore, in the carbonated part, no coloration is identified.

One must note that several reports have discussed that the carbonation front is not sharp but gradual (Houst and Wittman 2002, Chang and Chen 2006, Villain *et al*. 2007). However, concerning reinforcement corrosion, the phenolphthalein method is still a good indication for initiation of corrosion by carbonation (Chang and Chen 2006).

Some studies discuss the spatial variability of the carbonation depth caused by the mesoscopic structure of the concrete and the influence of the spatial variability on the thickness of the concrete cover (Pan *et al*. 2015). The effect of cement type on concrete carbonation is also investigated (Demis and Papadakis 2012). Other studies try to understand the interaction between carbonation and chloride penetration in concrete (Demis and Papadakis 2012, Zhang and Zhao 2012).

The method based on Fick's 2nd Law is the most widely used to predict carbonation penetration in concrete. Eq. (1) considers the concrete as a homogenous medium and unidirectional flow direction.

$$x_{CO_2}(t) = k_{CO_2} \cdot \sqrt{t} \tag{1}$$

Where Xco_2 represents carbonation depth (mm), Kco_2 is a constant of carbonation (mm.year$^{-0.5}$) and t is time, in years. The carbonation constant depends on the carbon dioxide concentration in the external medium, its absorption by concrete and the material permeability (Tuutti 1982).

Different studies on the concrete carbonation are presented in the literature, however, most of these verify the carbonation behavior in test specimens molded in laboratory and exposed to the external environment (Lee *et al.* 2012). Some other researchers verified the accelerated carbonation in a carbonation chamber (Chang and Chen 2006, Jia *et al*. 2011, Kandasami *et al.* 2012, Harrison *et al.* 2012), often with controlled temperature, relative humidity and CO_2 concentration. These studies have their due importance but may often distance themselves from reality. Actually, few studies discuss the natural carbonation process in real structures (Houst and Wittman 2002, Alexander *et al*. 2007, Neves *et al*. 2012, Guiglia and Taliano 2013). It is important to take into consideration that a real concrete structure generally has larger dimensions and is subjected to a number of factors that are not taken into account in concrete test specimens. Among such factors the varied load resulting from its operating activities can be highlighted. Besides this, it is possible to highlight the microclimate factor that can result in different conditions of aggressiveness in a same concrete structure.

Therefore, the purpose of this work is to analyze the depths of natural carbonation in concrete structures exposed in urban environments. This work is based on carbonation tests in 40 points of two 57 years old concrete viaducts.

2. Method

The methods of this article were divided into two stages. The first one was to gather information concerning the studied concrete viaducts. The second one consisted in carbonation tests in these concrete viaducts and statistical treatment of obtained data.

2.1 Analyzed structures

The concrete structures analyzed in this article are two viaducts built in 1950 and located in a major highway that runs through the state of Sao Paulo, Brazil. Both viaducts were built in reinforced concrete, finished predominantly in exposed concrete. In this article, the viaducts are mentioned as viaduct 1 and viaduct 2. The distance between them is 2 km.

Viaducts 1 and 2 have 40 meters long beams and columns with 4.5 and 3.0 meters, respectively. Both were built with the same concrete technology practiced in the 50s in Brazil, i.e., concrete molded in place with ordinary Portland cement (no additions were used), compressive strength at 28 days of 24 MPa and without the use of chemical additives.

According to data from the Brazilian Air Force's Weather Station, for the region where the viaducts are located, the annual average, maximum and minimum temperatures, observed in a period of 30 years are 22°C, 37°C and 0°C, respectively. The maximum relative humidity for the same period is 100%, reaching the minimum value in summer of 35%, and the minimum in winter of 15%. These environmental data were the only ones that the authors of the article had access to in the region.

The carbonation tests were performed on the viaduct beams and columns after 57 years of exposure in urban environment. It is important to note also that none of the viaducts went through maintenance or recuperation processes during this period. Carbonation data in this study were formed during natural carbonation and are the result of structures exposure throughout their service life.

2.2 Determination of carbonation depths

A solution of 1% phenolphthalein in 70% ethyl alcohol was used for determining the carbonation depth in the concrete, as proposed by RILEM (1988) and EN 14630 (2006).

In order to do this, the concrete surface of the structural elements was broken at approximately 20 cm of width. After this, the indicated solution was sprayed, always respecting a maximum interval of 10 minutes.

After applying the indicated solution, a wavy line of color change was observed in the concrete. The average depth of colorless phenolphthalein region was measured from fifteen spots spaced every centimeter (Fig. 1). Subsequently, the arithmetic mean (*X-ave*) of these values was calculated. In addition to the average depth, the maximum depth carbonation was measured (*X-max*) for each testing area. The described procedure allowed to obtain the depth reached by carbonation from the surface of the structural element. The concrete cover was determined as the arithmetic mean of three measurements in each testing area. For all measurements, a digital pachymeter accurate to one hundredth of a millimeter was used.

Carbonation depths relative to front face and bottom face were obtained for each hole made in the beams, according to the scheme in Fig. 2(a). In viaduct one, 10 points were performed in beams, being 5 for each traffic direction. In this study, traffic directions were named as North-South and South-North. Considering the left end of the viaduct as point of coordinate equal

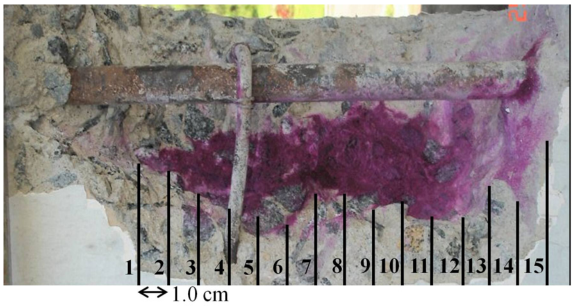


Fig. 1 Example measure of carbonation on beam

to zero, the 5 analysis points of tests were: 2.6; 13.7; 19.8; 25.8; and 36.9 meters, such as the example shown in Fig. 3. These points were also analyzed in viaduct 2.

In each one of the 4 columns of viaduct 1, three points were performed, with two columns facing each traffic direction. As in the beams, for each one of the sections in the columns, measurements were made in the front face and in the side face of the column, according to the scheme in Fig. 2(b). Assuming zero coordinates in the column encounter with the terrain, the 3 analyzed points had coordinates: 0.5; 2.3; and 4 meters (see Fig. 3).

For viaduct 2 the procedure was repeated. However, as the beams from viaduct 2 had smaller dimensions than those from viaduct 1, two points per column instead of three were performed: 0.5

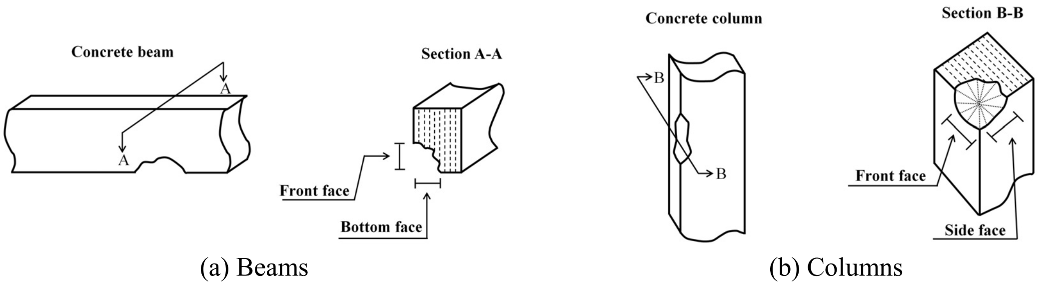


Fig. 2 Scheme of method used to measure

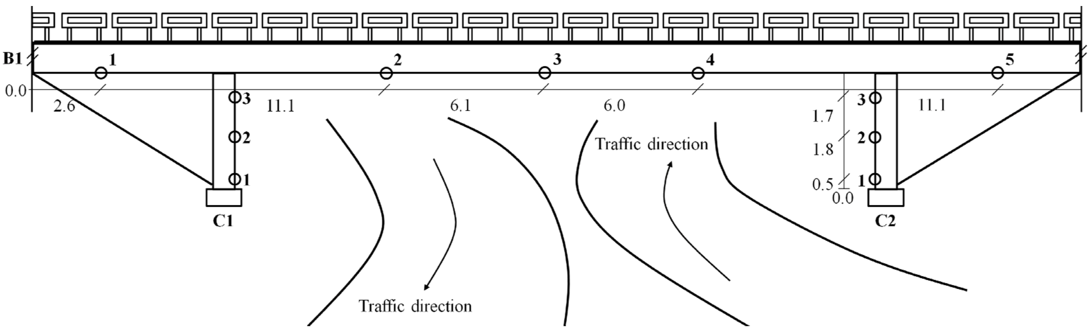


Fig. 3 Carbonation measures along the viaduct 1

Table 1 Identification of structural elements

Code	Type	Viaduct	Traffic direction	Position	Amount of points
B1	beam	1	South-North	-	5
B2	beam	1	North-South	-	5
C1	column	1	South-North	Left	3
C2	column	1	South-North	Right	3
C3	column	1	North-South	Left	3
C4	column	1	North-South	Right	3
B3	beam	2	South-North	-	5
B4	beam	2	North-South	-	5
C5	column	2	South-North	Left	2
C6	column	2	South-North	Right	2
C7	column	2	North-South	Left	2
C8	column	2	North-South	Right	2

and 2.3 meters. A total of 40 points were analyzed in both viaducts. Table 1 describes the symbology used for each one of the structural elements of the viaducts.

In the moment previously the average calculation (*X-ave*), data obtained in 15 measurements of carbonation for each test point were tested for normality by applying Kolmogorov-Smirnov's test. This test is designed to check possible null hypothesis coming from independent observations (Loader 1992). The test measures the $Dmax_s$ relative index for the maximum differences between the empirical and normal distribution functions over the whole real line, Eq. (2) (Zelterman 1984, Bain and Engelhardt 1992). Verdier *et al.* (2002) and Song *et al.* (2005) also performed this type of analysis for verifying the hypothesis of normal distribution in data of concrete permeability and concrete resistance, respectively.

$$D\max_S = \sup\left|F_S(z) - \phi(z)\right| \tag{2}$$

Where: *sup* are the maximum differences; ($F_s(z)$) is the observed distribution function of n performed measures (n = 15 for each test); and ($\phi(z)$) are the normal distribution functions normalized by their respective exact means and standard deviations.

For each carbonation test performed, $Dmax_s$ values have been compared with the $Dmax_c$ critical value equal to 0.338, with respect to the sample size (n = 15) at a significance level $\alpha = 0.05$ (Bain and Engelhardt 1992, Loader 1992). Continuing the analyzes, the null hypothesis adopted in this study considers that data are normally distributed. The null hypothesis is accepted if $Dmax_s$ is less than $Dmax_c$. Otherwise, the null hypothesis must be rejected and the conclusion is that the sample data in this study do not follow a normal distribution.

After applying the Kolmogorov-Smirnov's test, one-way analysis of variance, also known as ANOVA, was performed. In order to do that, the PASW Statistics v. 18 software has been used. One-way ANOVA produces an analysis for a quantitative dependent variable affected by a single factor (independent variable). This analysis is commonly used to verify the significance of differences between two or more means (Hollar *et al.* 2013).

In the present study, the null hypothesis for ANOVA's test states that data of maximum carbonation depth of the compared elements show the same behavior and are not different from each other. In contrast, the alternative hypothesis states that these measures are different and thus did not had the same kind of behavior. The significance level threshold was also α=0.05. Thus, if α is less than 0.05, the null hypothesis should be rejected.

First, the test was performed in order to identify if the maximum carbonation frontal (*Xf-max*) and bottom depths (*Xb-max*, or side *Xs-max* in the case of columns) for the same structural element analysis (i.e., beam or column) are significantly different. Subsequently, the test was applied to compare data of maximum depth of carbonation between different structural elements, taking notice that these elements belong to the same group.

Finally, Fisher's method was applied with the combination of all beams and columns of viaducts 1 and 2. This method was used to identify which groups are formed with structural elements that have the same behavioral tendency of carbonation penetration. For that, the Minitab statistical software v. 16 has been used.

3. Results and discussion

3.1 Carbonation measurements

The results of carbonation measurements are graphically shown in Figs. 4-6, where *Xf-ave* and *Xf-max* respectively mean the average and maximum carbonation depth obtained on front face; *Xb-ave* and *Xb-max* respectively mean the average and maximum carbonation depth obtained on bottom face; and *Xs-ave* and *Xs-max* respectively mean the average and maximum carbonation depth obtained on side face.

According to Fig. 4, visual analysis allows the observation that, generally, beams of viaduct 1 (B1 and B2) had higher carbonation depths that beams of viaduct 2 (B3 and B4). The same behavior was observed for columns analyzed according to Figs. 5-6.

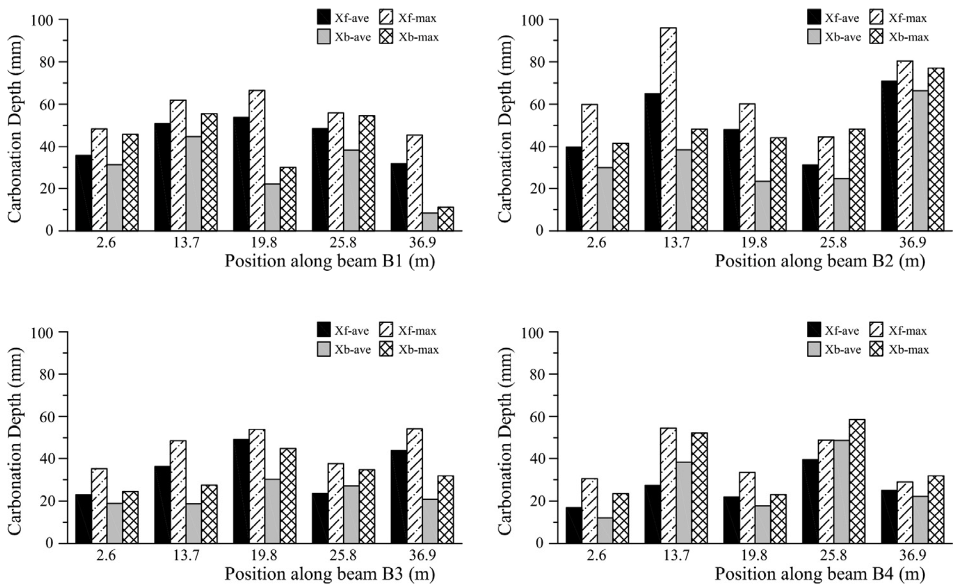


Fig. 4 Carbonation depth of beams in viaducts 1 and 2

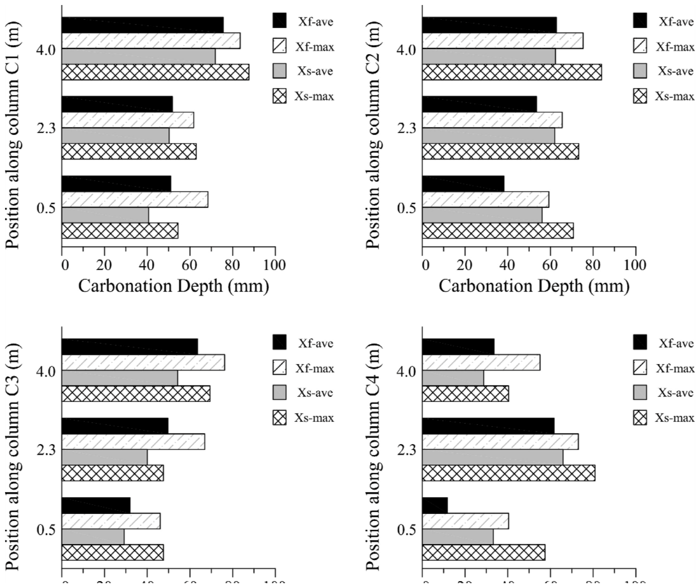


Fig. 5 Carbonation depth in columns of viaduct 1

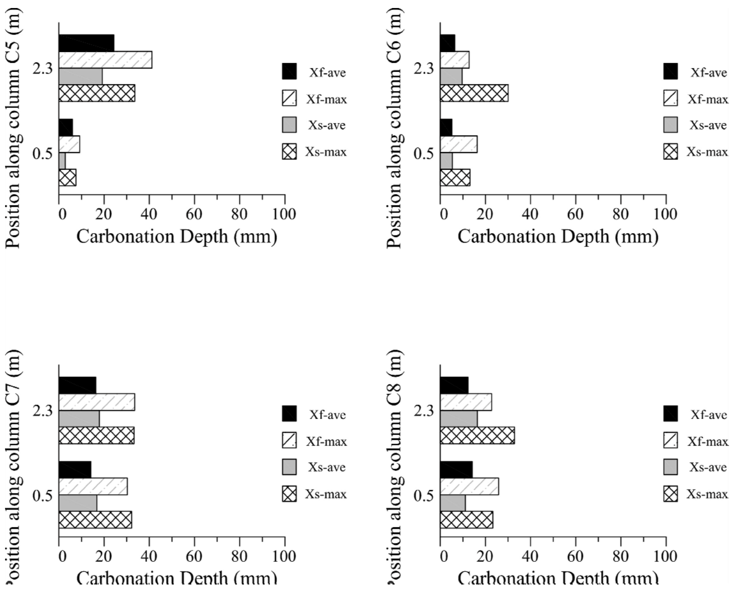


Fig. 6 Carbonation depth in columns of viaduct 2

Most columns had a higher carbonation in tests performed at points of greatest height; this could be an evidence that CO_2 has less action in lower points (i.e., height equal to 0.5 m).

The maximum carbonation depth was 97.3 mm. This value was found at position 13.7 m along beam B2. The minimum value was found at the height of 0.5 m in column C5 and is equal to 7.5 mm.

The application of the Kolmogorov-Smirnov's statistical test allowed to verify that the analyzed samples confirmed the null hypothesis adopted in the present study, i.e., $Dmax_s < Dmax_c$ (= 0.338, for n = 15 and α = 0.05). Thus, Kolmogorov-Smirnov's test indicated that statistical and theoretical distributions were close enough to conclude that data followed a normal law. An example is provided in Fig. 7.

The results of ANOVA test for combinations of front and bottom (or side) measurements of the same structural element are given in Table 2.

According to Table 2, only beams B2 and B3 did not confirm the null hypothesis. All other analyzed structural elements had a significance level greater than 0.05 for comparisons between measurements taken in front face and bottom face (or side). This indicates that the null hypothesis cannot be rejected meaning there is no statistically significant difference between the two measurements. Therefore, it has been considered that the measurements performed in the front and

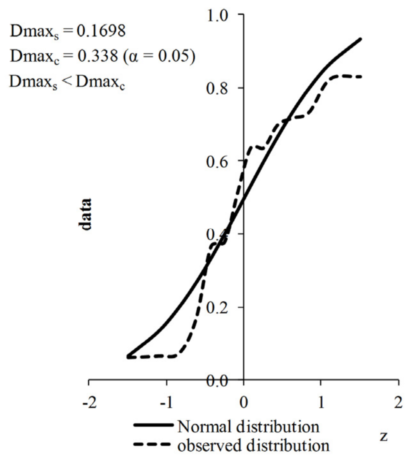
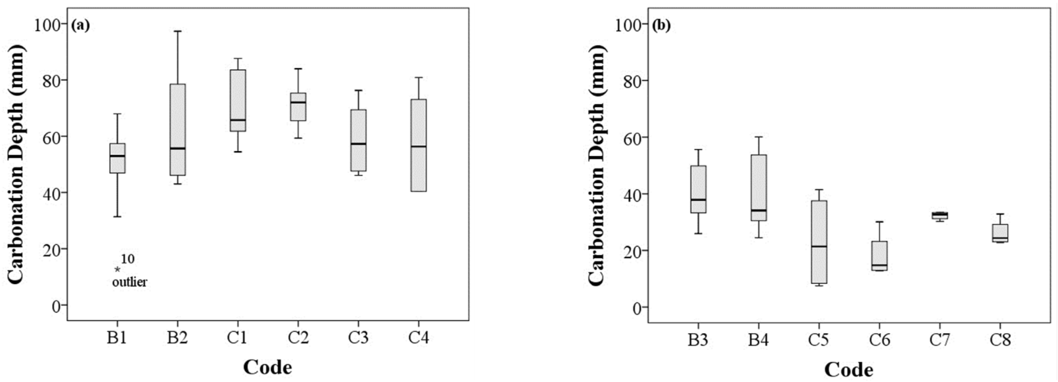


Fig. 7 Results of Kolmogorov-Smirnov's test - Average carbonation depth obtained on front face, B1

Table 2 Results of ANOVA's test - Combinations of front and bottom (or side) measurements

Code	Combinations	α	Null hypothesis
B1	Front and bottom measures	0.120	accepted
B2	Front and bottom measures	0.034	rejected
B3	Front and bottom measures	0.038	rejected
B4	Front and bottom measures	0.881	accepted
C1	Front and side measures	0.818	accepted
C2	Front and side measures	0.208	accepted
C3	Front and side measures	0.514	accepted
C4	Front and side measures	0.834	accepted
C5	Front and side measures	0.838	accepted
C6	Front and side measures	0.500	accepted
C7	Front and side measures	0.667	accepted
C8	Front and side measures	0.511	accepted



(a) Viaduct 1 (b) Viaduct 2

Fig. 8 Maximum carbonation depth

bottom face (or side) of the same structural element belong to the same group. Based on this criterion, the results of maximum carbonation depths in each one of the analyzed structural elements are shown in Fig. 8.

Fig. 8 shows a boxplot graphic where each box contains half (50%) of the data. The upper and lower edge indicates the percentile of 75% and 25% of data, respectively. The line in the box indicates the median value of the data. The extremes of the graphic indicate the maximum and minimum values, unless outlier values are presented. It has been noticed that the only outlier found in Fig. 8 was in beam B1 (= 10 mm). An advantage of using boxplot is to graphically observe the central position of data and its trend.

According to Fig. 8, it is possible to verify that beams of viaduct 1 had close median value (about 55 mm). However, the positioning of the median in beam B1 shows a symmetric behavior of data, unlike beam B2. The C3 and C4 columns (located in the same traffic direction) showed similar behavior, unlike the columns C1 and C2. On the other hand, the four columns of viaduct 2 (C5, C6, C7 and C8), visually, showed different behaviors between them.

However, the results discussed so far do not allow to state if the structural elements of a viaduct and between different viaducts, but inserted in a same microclimate, had results of maximum carbonation depth significantly different between each other. For this investigation, ANOVA test was applied for different combinations of these elements and the results are shown in Table 3.

According to Table 3, the beams of a viaduct when combined together confirm the null hypothesis of this study. However, when beam B2 of viaduct 1 was combined with beams of viaduct 2, the null hypothesis was rejected. This means that those measurements are different and do not have the same behavior. The null hypothesis was accepted when beams of viaduct 1 were combined among each other. However, when combined with beams of viaduct 2, the null hypothesis was rejected for all other cases. The columns of viaduct 2, even when combined among themselves, had combinations of rejected null hypothesis (ex.: C6 and C7; C7 and C8). That is, although they belong to the same viaduct and are made of the same material, columns positioned on opposite sides had significantly different results of carbonation depth among themselves.

When all structural elements of viaduct 1 were combined, it has been observed that the null hypothesis was accepted. However, the same cannot be said for the combination of all structural elements of viaduct 2, and also for the combination of all beams and columns of both viaducts.

Table 3 Results of ANOVA's test - Combinations of different structural elements

Combinations	α	Null hypothesis	Combinations	α	Null hypothesis
B1 and B2	0.126	accepted	C3 and C4	0.902	accepted
B1 and B3	0.192	accepted	C3 and C5	0.006	rejected
B1 and B4	0.194	accepted	C3 and C6	0.001	rejected
B2 and B3	0.006	rejected	C3 and C7	0.005	rejected
B2 and B4	0.008	rejected	C3 and C8	0.002	rejected
B3 and B4	0.896	accepted	C4 and C5	0.012	rejected
C1 and C2	0.812	accepted	C4 and C6	0.002	rejected
C1 and C3	0.188	accepted	C4 and C7	0.017	rejected
C1 and C4	0.198	accepted	C4 and C8	0.006	rejected
C1 and C5	0.001	rejected	C5 and C6	0.627	accepted
C1 and C6	0.000	rejected	C5 and C7	0.320	accepted
C1 and C7	0.001	rejected	C5 and C8	0.735	accepted
C1 and C8	0.000	rejected	C6 and C7	0.014	rejected
C2 and C3	0.085	accepted	C6 and C8	0.138	accepted
C2 and C4	0.107	accepted	C7 and C8	0.045	rejected
C2 and C5	0.000	rejected	B1, B2, C1, C2, C3, C4	0.073	accepted
C2 and C6	0.000	rejected	B3, B4, C5, C6, C7, C8	0.006	rejected
C2 and C7	0.000	rejected	B1, B2, B3, B4, C1, C2, C3, C4, C5, C6, C7, C8	0.000	rejected
C2 and C8	0.000	rejected			

Although both viaducts have the same age and are situated 2 km apart (inserted in a same macroclimate), the same evolution of the carbonation process for all structural elements combined has not been found.

In these cases, a significant influence of the microclimate on concrete carbonation can observe. Several factors may have contributed to this behavior. Among those factors related with the microclimate are temperature and local humidity, incidence of heatstroke, cycles of wetting and drying, winds, superficial concentrations of CO_2 and rain shelf conditions (Houst and Wittmann 2002, Zayed and Halpin 2005). Additional factors are the stress state of the parts (Castel *et al.* 1999), intensity of traffic and speed limit. However, we recognize that it is necessary to perform measurements / verification of these environmental factors to assert more strongly that these variables are changing the process of carbonation. But, according to the results of this article, it is possible to realize that exposure condition of each structural part is a decisive factor in the degradation process of the structure.

Results of Fisher's method are shown in Table 4.

According to Table 4, it has been observed that for the viaducts in questions, 5 different groups of structural elements combination were formed, according to the data of maximum carbonation depth. Group A is restricted to elements of viaduct 1, however without the presence of beam B1. As noted in group B, beam B1 possess the same behavior of carbonation evolution of columns C3 and C4. So, probably by not being similar to columns C1 and C2, beam B1 is not present in group

Table 4 Results of Fisher's method - Combination of all beams and columns of viaducts 1 and 2

Group	Code
A	B2
	C1
	C2
	C3
	C4
B	B1
	C3
	C4
C	B1
	B3
	B4
D	B3
	B4
	C7
	C8
E	C5
	C6
	C7
	C8

A. Group C contains three of the four analyzed beams in this study. This group reveals that beam B2 does not have the same behavior from the other analyzed beams. Group D has the beams and two columns from viaduct 2. Finally, group E gathers all columns of viaduct 2.

Those results show that no group was formed with all elements of viaduct 1 or all elements of viaduct 2. Thus, once again, it has been proved the need to incorporate microclimate conditions on carbonation evaluations at a real structure. According to the achieved results, considering all elements of a concrete structure inserted in a same exposure condition ignoring the microclimate effect can lead to results with errors. This case is still aggravated when two structures, although close to each other, are projected in the same way, considering only aspects related to the macroclimate.

3.2 Practical relevance of the work

In Brazil, currently, the standard NBR 6118 (2014) is used to define important aspects of the design of a concrete structure, such as water/cement ratio and covering of reinforcement. This dimensioning is made according to a definition of environmental classes. However, the classes adopted by the standard do not incorporate important factors related to the microclimate, treating it in a much simpler way than what actually occurs in practice. This behavior is not exclusive to Brazil and can be extrapolated to the scientific community. However, it is admitted that there are still many points needed in order to advance the frontiers of knowledge in order to introduce in the standards a more realistically consideration of microclimates.

One point that makes the issue even more complex is the fact that some countries, such as Brazil, for example, have an extensive territory with very different environmental characteristics between them. As noted in the results of this study, methods based only in microclimatic aspects can be considered as not ideal and lead to generalized results that do not match the reality of the carbonation process occurring during service life.

Only phenolphthalein method was used to verify the carbonation process in concrete structures in this paper. This is a practical and quite usual method used in construction, especially in the field. However, other more accurate techniques may also be used as a diagnostic tool. For future work, the use of more advanced techniques such as the thermalgravimetric analysis (TGA), the X-ray diffraction analysis (XRDA), Fourier transformation infrared spectroscopy (FTIR) test, and the Nonlinear Resonant Ultrasound Spectroscopy (NRUS) technique are also encouraged.

We recognize that the lack of measures of environmental data related to microclimate in this paper makes it difficult to perform more precise statements. For future work on real structures, it is recommended to carefully observe and record the temperature and local humidity, incidence of heatstroke, cycles of wetting and drying, winds, and other environmental conditions in the carbonation test points.

This paper is important since there are few case studies like this in literature, precisely because of restricted access to these types of real structures. As discussed in the paper, some studies assessing the carbonation penetration in specimens, but analyzes in real structures are scarce. So, this study is relevant because it gives guidelines that there is some influence of microclimate on carbonation penetration, and therefore, opens an important field of study to draw attention to include these variables in models of service life. The aim of this article is not to show how to include these variables in the models, but to demonstrate, using data obtained in real structure, that the microclimate is important (change the carbonation process) and should be carefully studied and incorporated in models.

4. Conclusions

Based on carbonation testing in real construction works and after statistical treatment of the results, the following considerations are mentioned to be the key ones:

- The evolution of the advancement of carbonation can behave differently in different locations of the same structural piece and between different structural elements of a same work, as has been observed in viaduct 2.
- For both analyzed viaducts, located 2 km away, the maximum carbonation depths were statistically different, although the exposure time has been exactly the same.
- The behavior found can be mainly attributed to aspects related with the microclimate. Factors such as temperature and local humidity, wetting and drying cycles, superficial concentration of CO_2, rain shelf conditions, winds and heatstroke incidence can be different in the same structure.
- The model based on Fick's law used for predicting the carbonation of concrete structures does not consider all the aspects related to the microclimate mentioned in this study. Therefore, it is recommended to deepen the study of these variables so that they can be incorporated in models, standards and technical recommendations.

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