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Proposal of a method for service life prediction of a concrete structure: a case study

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Abstract

This article presents a method for service life prediction of concrete structures. The proposed method aims to estimate the performance of a concrete structure through its permeability to carbon dioxide penetration, in order to verify its accordance to Brazilian standards. This case study is based on an inspection made in an educational building in the city of Porto Alegre, Rio Grande do Sul, Brazil. Through carbon dioxide penetration, non-destructive and partial destructive tests, an estimated service life design for the concrete structure was elaborated. These tests were carried out in the parking lot because there is a greater vulnerability of the structure in terms of concentration of vehicles and lack of finishing, such as mortars or paints. The tests carried out showed that the selected concrete pieces were carbonated from 2.9 to 4.4 mm deep, a situation whose prognosis suggests a superior performance in accordance with the parameters set in ABNT NBR 15575:2013.

Keywords: service life prediction, carbon dioxide penetration, Tutti law.

1. Introduction

Concrete is vulnerable due to its porosity within which various degradation agents can penetrate. Carbon dioxide (CO_2) in the atmosphere can penetrate it and react, in the presence of moisture, with calcium hydroxide (CH). This diffusion of CO_2 within the concrete porosity is one of the most common aggressive agents to structures in urban environments (Khunthongkeaw, Tangtermsirikul and Leelawat, 2006; Tan *et al*., 2008; Omikrine-Metalssi and Aït-Mokhtar, 2009; Tutikian e Helene, 2011; Omikrine-Metalssi *et al*., 2012; Benítez *et al*., 2019).

The carbonation of the cementitious matrix causes a decrease of pH, which may lead to corrosion of the steel reinforcement (Turcry *et al*., 2014; Pacheco *et al*., 2016; Pacheco *et al*., 2018; Bao *et al*., 2019), by changing the physical and chemical properties of the concrete, such as the destruction of the passivation film naturally created around the reinforcing steel. Once steel has corroded, it may cause cracks, rust stains and spalls of concrete cover. This means that reinforcement corrosion is considered a major factor for determining the service life of a concrete structure (Khunthongkeaw *et al*., 2006; Andrade e Tutikian, 2011; Mehta and

Monteiro, 2014; Shah and Bishnoi, 2018). However, the exposure to aggressive agents, volume changes, loading, frost, overload, abrasion, erosion and chemical actions may also deteriorate the concrete. (Taheri, 2019).

The diffusion of CO_2 through the surface of the concrete dissolutes $HCO3^-$ and $CO3^{2-}$ ions, which depends upon the pH of the pore solution. When CO_2 gets in contact with water (pH of 7), it forms bicarbonates. As an alkaline material, the concrete pH value of pore solution is around 12.5–13 (Tan *et al.*, 2008). The dissolution of $Ca(OH)_2$ leads to the presence of hydroxyl ions in the pore water. Thus, in the presence of calcium hydroxide, the high pH in the concrete bicarbonates dissociates into carbonate ions. The precipitation of the $CaCO_3$ is a result of the hydration products of cement; the dissolution of Ca^{2+} and hydroxyl ions which then react with the carbonate ions (Thiery *et al.*, 2007; Hussain *et al.*, 2017; Zhang *et al.*, 2020). The chemical equation of the hydration products of cement is shown in Equation 1.

$$2CaO.SiO_2{}^{(C2S)} + 3CaO.SiO_2{}^{(C3S)} + H_20 \rightarrow 3CaO\ .\ 2SiO_2\ .\ 3H_2O^{(CSH)} + Ca(OH)_2{}^{(CH)} \quad \text{Eq. (1)}$$

Ca^{2+} ions are consumed by this process and by the dissolution of the calcium hydroxide. The solubility of $Ca(OH)_2$ is higher than that $CaCO_3$. Therefore, the $Ca(OH)_2$ will be dissolved, while the $CaCO_3$ is formed until the $Ca(OH)_2$ is consumed (Lagerblad, 2005; Gil *et al.*, 2017; Zhang *et al.*, 2020). So, the reaction of the carbonation is resulted from the released hydroxide calcium in contact with the atmosphere, generating the basic chemical reaction of carbonation (Equation 2).

$$Ca(OH)_2{}^{(CH)} + CO_2 \rightarrow CaCO_3 + H_20 \quad \text{Eq. (2)}$$

Concrete structures are vulnerable to carbonation, in many situations; however, the main issue is when the process will initiate. Several authors (Chi *et al.*, 2002; Turcry *et al.*, 2014; Hussain *et al.*, 2017) tend to use accelerated tests because the natural carbonation is a slow phenomenon from a practical perspective. Therefore, the need to predict when the carbonation reaches the embedded reinforcing steel bars is relevant (Khunthongkeaw *et al.*, 2006; Neves *et al.*, 2013).

There are several methods to detect the carbonation front, and the ones that involve phenolphthalein indicator tend to be easiest to use, with a good efficiency. It is the main method in the fields to locate the depth of the penetration of the carbon dioxide. This indicator will change the color of the concrete sample to purple, when the pH value of the pore solution is above 9, which indicates alkalinity of the element, and therefore, a non-carbonated compound. Because of the heterogeneity of the concrete and its densified carbonated zone, the penetration of the CO_2 does not occur at a constant rate and prevents further propagation into concrete (Parrot and Killoh, 1989; Roper and Baweja, 1991; Veleva *et al.*, 1998; Zhang and Shao, 2016; Shah *et al.*, 2018).

According to ABNT NBR 15575:2013, the service life design of a reinforced concrete structure must perform within three ranges, the minimum (50 years of service), intermediate (63 years of service) and superior (75 years of service). According to Roper and Baweja (1991) and Veleva *et al.* (1998), there are several factors that either individually or combined, influence the propagation of carbonation into the concrete, such as the permeability of concrete, the pozzolanic material, the moisture in concrete, the CO_2 concentration, the duration of exposure, and the covering of the structure.

2. Scope of the study

This case study concerns a building inspection of a precast concrete structure of an educational building. Non-destructive and partial destructive tests were performed to predict the design service life of the parts of the structure that were analyzed. Figure 1a shows the building under study, while Figure 1b indicates the inspected area (where the tests were performed).

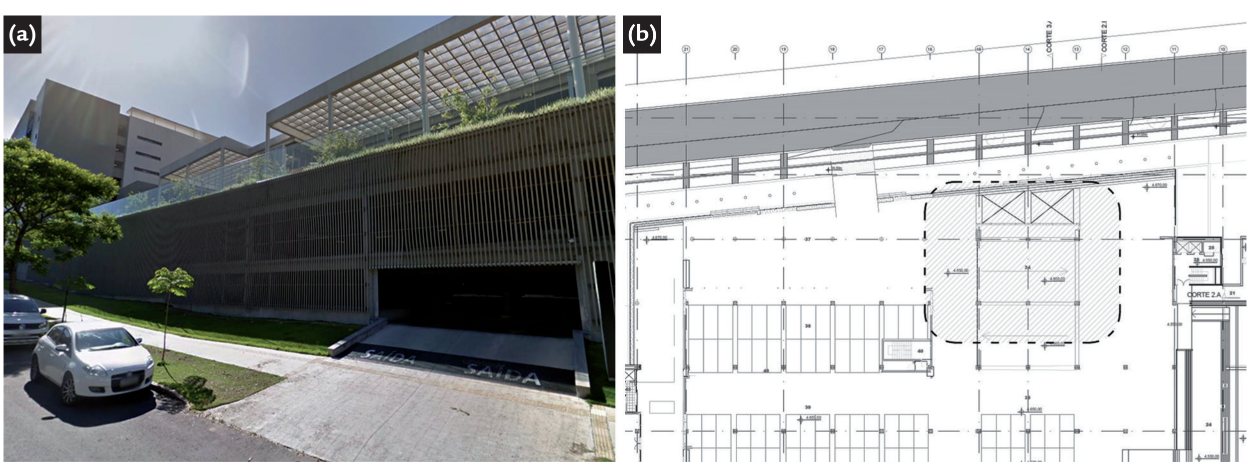

Figure 1 - (a) Building of study, (b) Inspected area.

Thus, this study begins with an inspection in situ, followed by collection of the information available of the construction, and then the development of the tests. Four structural elements, two beams and two columns, were randomly chosen to perform the tests. These tests were carried out in the parking lot because there is a great structural vulnerability due to vehicle concentration and lack of finishing, such as mortars or paints. This case study is similar to the Bueno *et al.*, (2019) investigation.

3. Building pathology

3.1 Surface hardness of the structure

The compressive strength of the concrete estimated by non-destructive tests, generates additional information about the quality of the material during its service life. Therefore, due the highly variable materials used in construction, the results can lead to unreliable information regarding the concrete. Thus, information such age, concrete compounds, construction quality, curing method, and concrete mechanical properties may gain importance (Hassan and Jones, 2012).

The inspections were developed in all the parking pavements. Figure 2 presents the application of the test on the concrete column with the equipment used to perform the surface compressive strength test. These tests were performed in accordance with the guidelines of ABNT NBR 7584:2012, and according to El Mir and Nehme (2017), it is one of the most used techniques. Thus, the equipment used was a Schmidt hammer, whose specifications are shown in Table 1.

Figure 2 - Surface hardness test.

Table 1 – Specifications of the Schmidt hammer used in the study.

Model	SilverSchimidt
Company	Proceq
Impact energy	2.207 Nm (N), 0.735 Nm (L)
Compressive strength range	10 to 100 N/mm² (1'450 to 14'500 psi)

This procedure was also performed in three other concrete structural elements. All the four elements tested are presented in Figures 3a and 3b.

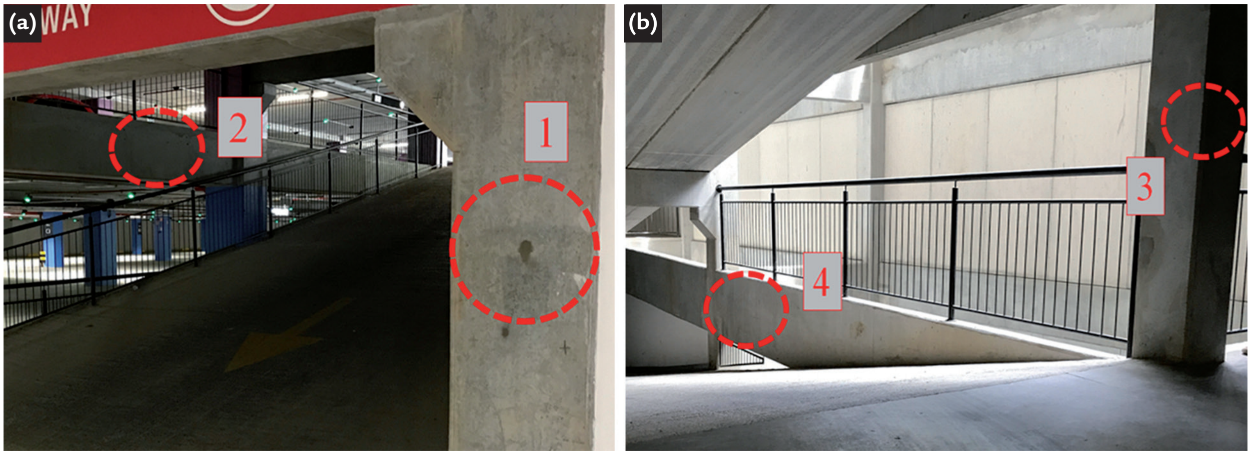

Figure 3 - (a) View of the areas where the samples 1 (column) and 2 (beam) were collected, (b) View of the areas where the samples 3 (column) and 4 (beam) were collected.

According to ABNT NBR 7584:2012, the evaluation of surface hardness by reflection, provides information about the surface compressive strength of the concrete about 20 mm depth when operating with percussion energy sclerometers around 2.25 Nm. It must be highlighted that these tests do not substitute other methods, but only as a comparison issue in order to investigate the magnitude of each structural element across its surface compressive strength. The results of the performed tests are shown in Table 2.

Table 2 – Results of the surface compressive strength.

n	Beam 01	Column 01	Beam 02	Column 02
1	69.00	60.50	68.00	64.00
2	64.50	59.00	62.50	61.00
3	69.50	67.00	61.50	64.00
4	67.50	63.00	60.00	62.50
5	73.50	65.50	60.50	55.50
6	73.00	71.50	59.00	61.50
7	60.50	66.50	65.00	60.00
8	69.00	58.50	66.00	60.00
9	70.00	61.00	67.00	59.00
10	72.00	60.00	65.00	63.00
11	66.00	61.00	70.00	63.00
12	65.50	61.50	63.00	64.00
13	70.50	63.00	58.50	67.00
14	68.50	61.50	64.50	66.00
15	67.00	57.00	64.00	63.00
16	60.50	63.00	64.50	60.00
Average	68.75	61.50	64.25	62.75
Standard deviation	3.85	3.67	3.26	2.84
Conversion of the obtained values according to the equipment graphic	55 MPa	51 MPa	52 MPa	51.50 MPa

It is possible to verify through the results presented in Table 2, that the compressive strength of the surface of the precast element indicates values over 50 MPa, which initially suggest some characteristics of the analyzed structure. According to Bueno *et al.* (2019), the results presented above are between an intermediate and a high average of compressive strength and a lower deviation was obtained, since the structure elements in that study were not precasted.

3.2 Service life design of the structure

According to Tuuti (1982), it is possible to estimate the service life of a concrete structure through a relationship with the carbon dioxide penetration. In Equation 3, the cover thickness of the structural element is used to establish the service life design of the structure through its correlation with the carbon dioxide penetration in within a certain time period.

$$C = k.\sqrt{t} \qquad \text{Eq. (3)}$$

Where: C = Concrete cover thickness, in millimeters, k = carbonatation ratio, t = time, in years.

The penetration test was performed at the places shown in Figures 3a and 3b. In accordance with the managers of the building, the educational building had two years of service; time period used in the application of Equation 3. Therefore, initially, the concrete cover thickness was determined using the wall scanner shown in Figure 4. The equipment characteristics are shown in Table 3.

Figure 4. View of wall scanner.

Table 3 – Specifications of the wall scanner used in the study.

Model	D-tect 150 Professional
Company	Bosch
Impact energy	150mm
Compressive strength range	4 x 1.5 V LR6 (AA)

Posteriorly, the structure was drilled following the assigned marks (Figures 5a and 5b). A pachymeter was also used to verify the depth of the hole. Once the target depth was obtained, the phenolphthalein indicator was applied. These procedures made it possible for the naked eye to verify if the sample of the concrete was carbonated or not. In the case of Figure 5b, an uncarbonated concrete powder is verified, which is determined by the apparent purple color. This means that the pH of the sample is above 9. However, in less deeper samples, the gray color was obtained, which suggested that the dioxide diffusion had occurred, and that the structure is carbonated until that measured depth. The procedure was performed several times until it reached an uncarbonated sample.

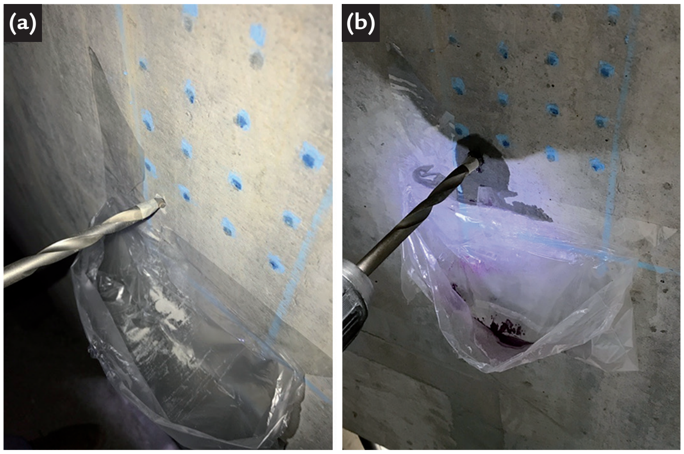

Figure 5 - (a) Dioxide carbon penetration test before the application of pH indicator, (b) Dioxide carbon penetration test after the application of pH indicator (purple – uncarbonated).

The performed test shows the average diffusion of carbon dioxide which establishes the variable "C" in Equation 3. With the information obtained for service time (t), that is two years, the carbonation ratio (k) can be calculated. Furthermore, with the same obtained coefficient (k), and with the aim to predict the remaining service life, Equation 3 is used again considering the new variables. Thus, the results obtained are shown in Table 4.

Table 4 – Results of the proposed methodology with carbon dioxide penetration tests.

-	Sample		1	2	3	4
-	-	Unit	Beam 01	Column 01	Beam 02	Column 02
-	Surface compressive strength	MPa	55	51	52	51.5
-	Concrete cover thickness	mm	20	20	19	28.5
-	Carbonated depth	mm	3	3.1	2.9	4.4
A	Structure's life in service	years	2			
-	k (Eq. 3)	mm/√year	2.12	2.19	2.05	3.11
B	t (Eq. 3)	years	88.89	83.25	85.85	83.91
C (B – A)	Remaining service life	years	86.89	81.25	83.85	81.91

For precast concrete structures, applicable at the time of the execution of this construction, determines that this type of structure must have a cover thickness of reinforced concrete of at least 20mm, considering a 5mm admissible range (ABNT NBR 9062:2017). From Table 4, it becomes possible to affirm that the concrete cover thickness of this precast structure is in accordance with such standard. Thus, with the performance ranges mentioned above, it is verified that the service life design resulting from the analyzed elements, suggests superior performance according to ABNT NBR 6118:2014 guidelines. Additionally, the surface compressive strength tests (Tables 2 and 4) are satisfactory and corroborated the information found.

4. Conclusion

It is important to highlight that the results are related to the concrete quality, although it is known that industrialized precast elements tend to have a superior quality control compared to those traditionally cast during the construction process. From the symptoms verified in the collected samples and additional information, it can be concluded that:

1) The proposed methodology leads to coherent conclusions;

2) The higher the surface compressive strength of the concrete, the less tends to be the capillary porosity and consequently the structure will be less permeable or vulnerable to aggressive agents, which will result in a longer service life for the structural elements;

3) The surface compressive strength of the concrete obtained indicates values over 50MPa;

4) The higher the effective concrete cover thickness, the longer the structure service life tends to be;

5) The greater the carbon dioxide diffusion in the structure cover, the shorter the structure service life and consequently its performance tends to be;

6) The concrete cover thickness obtained on the survey are in accordance with the guidelines of ABNT NBR 9062:2017 and oscillates between 19 a 28.5mm;

7) Although the guidelines of ABNT NBR 15575:2013 are not applied to the extent that the object of this study relates (educational building), it can be said, that similar remaining service lives were obtained, and that they were ranked as superior performance;

8) That the service life of the analyzed elements is between 83.25 and 88.89 years, which indicates that the remaining service life is between 81.25 and 86.89 years.

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