Revista Ingeniería de Construcción RIC
Vol 38 Nº3 2023
www.ricuc.cl
DOI: 10.7764/RIC.00081.21

In situ measurements of carbonation rate with air permeability for the development of a proposal for a classification of exposure to carbonation.

Mediciones in-situ de la tasa de carbonatación y la permeabilidad al aire para el desarrollo de una propuesta de clasificación de exposición por carbonatación.

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Fecha de Recepción: 18/01/2023
Fecha de Aceptación: 20/01/2023
Fecha de Publicación: 30/12/2023
PAG: 419-436

Abstract

The ingress of carbon dioxide CO_2 into concrete is an issue that, unfortunately, does not have sufficient precedents at the national level for the execution of the Residual Service Life analysis of concrete structures. As a precursor element of steel corrosion, it is necessary to count on information on the behavior that concrete could have in Chile, according to the levels of aggressiveness expected for specific project locations. It was only in 2016 that the NCh170 Concrete Standard included this type of Exposure with Grade C1 as Mild Aggressiveness.

This work presents a review of background information collected from various third-party and own works, along with measurements of Carbonation Rates in 20-year-old concretes made in the city of Santiago, relating them to Air Permeability measured in a non-destructive way, which allowed generating a proposal for the Classification of the Degree of Exposure to Carbonation.

Keywords: *Concrete; Carbonation; Strength; Air Permeability; Service Life.*

Resumen

El ingreso del dióxido de carbono CO_2 al hormigón es un tema que lamentablemente no cuenta a nivel nacional con antecedentes suficientes para la ejecución de análisis de Vida Útil Residual de estructuras de hormigón. Como elemento precursor de la corrosión del acero, es necesario contar con información del comportamiento que podrían tener los hormigones confeccionados en Chile, según los niveles de agresividad esperados para ubicaciones específicas de los proyectos. Recién el año 2016 la norma NCh170 de Hormigones incluye este tipo de Exposición con el Grado C1 como Agresividad Leve, lo cual es insuficiente para pretender analizar este tema en forma debida.

Este trabajo presenta una revisión de antecedentes rescatados de diversos trabajos de terceros y propios, junto con mediciones de Tasas de Carbonatación en hormigones de una edad de 20 años, confeccionados en la ciudad de Santiago, relacionándolos con la Permeabilidad al Aire medida en forma no-destructiva, lo cual permitió generar una propuesta de Clasificación del Grado de Exposición por Carbonatación.

Palabras clave: Hormigón; Carbonatación; Permeabilidad al Aire; Vida Útil.

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1. Introducción

Although less aggressive than chloride-induced corrosion, carbonation-induced corrosion is a concern. Its incidence may be aggravated in the future by the gradual increase in the concentration of CO_2 in the air, especially in industrial and urban environments, by the continued use of fossil fuels and its consequence in the greenhouse effect, and by technical incidences such as the reduction of the clinker content in the cement and the alkaline capacity of the concrete. The hydration of the cement produces enough calcium hydroxide, $Ca(OH)_2$, forming an alkaline layer on the steel with a pH > 12.5 that protects against the onset of corrosion. Carbonation is defined as the process of the chemical combination of CO_2 with $Ca(OH)_2$ to create Calcium Carbonate $CaCO_3$, which generates a decrease in pH <9.0 that "depassivates" this protection, leaving the steel in "active" mode as Corrosion begins in the presence of moisture and oxygen, in addition to generating a denser and more resistant matrix. Carbonation progress is generally assumed according to (Equation 1):

$$x_c = TC * \sqrt{t} \tag{1}$$

Where:
- ***Xc**: Carbonation Depth (mm)*
- ***CR**: Carbonation Rate (mm/√year)*
- ***t**: Exposure time, Age (year)*

The carbonation front penetrates the interior of the concrete in parallel with the exterior face of the concrete, depending mainly on the resistance that the concrete cover presents when it enters. Various worldwide publications summarized by (Torrent et al., 2022) have demonstrated that this ingress resistance can be adequately represented by the permeability of the concrete cover. Permeability variations directly and proportionally affect the progress of carbonation.

The progress of the carbonation front depends on several factors, including:
a) Relative air humidity: high concrete humidity makes it difficult for CO_2 to ingress.
b) Permeability of concrete: resistance to the ingress of CO_2.
c) CO_2 concentration in the environment; higher levels speed up the ingress process.
d) Concrete curing conditions: formation of a dense, less porous matrix.
e) Type of cement: available alkaline potential.

In addition, corrosion will start once the carbonation front reaches the steel reinforcement, depending on the following:
a) Relative humidity of the air: the presence of humidity/water and oxygen is required for the occurrence of corrosion.

Part of these conditions are considered in the European standard (EN 206, 2013) when defining the following types of Exposure Classes that may induce corrosion due to the phenomenon of Carbonation (Table 1).

***Table 1.** Exposure Classes acc. to EN 206 associated with Carbonation*

EN 206			
Class	*****	**Exposure condition**	**Examples of concrete where it could occur**
XC1	a	Dry	• Concrete inside buildings with low air humidity
	b	Permanently wet	• Concrete permanently submerged in water
XC2		Wet, rarely dry	• Concrete surfaces subject to long-term water contact • Many foundations
XC3		Moderate humidity	• Concrete inside buildings with moderate to high air humidity levels • External concrete sheltered from rain
XC4		Cyclic wet and dry	• Concrete surfaces subject to water contact, not within exposure class XC2

* Subclass mentioned by some authors

The importance of moisture, or pore saturation, in the possibility of CO_2 ingress into the concrete, is evident. As saturation increases, ingress becomes negligible. On the other hand, when the corrosion process begins, the exact opposite effect will occur since humidity accelerates the corrosive process. This is shown in (Figure 1), which compares the two situations described:

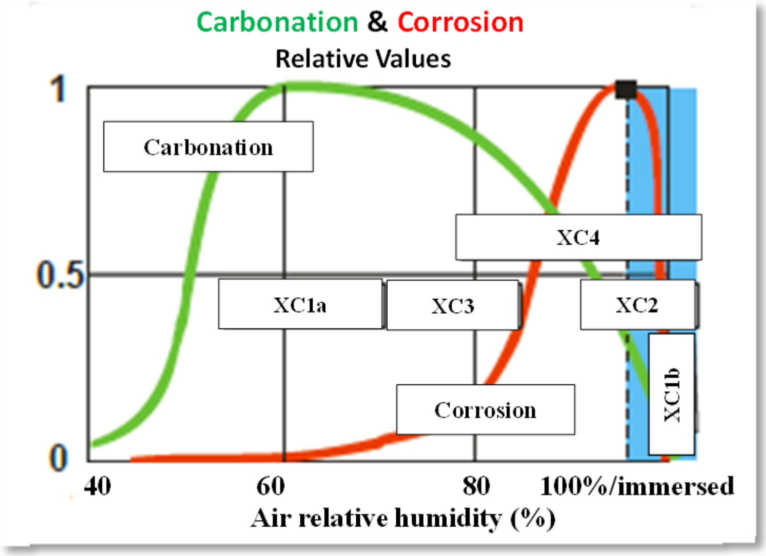

Figure 1. *Effect of humidity on the progress of ingress and corrosion induced by CO_2*

The carbonation depth Xc is measured in situ by spraying a pH level indicator solution (phenolphthalein) onto a fresh concrete face, typically from destructively removed cores. Once the age t of the structure is known, it is possible to estimate the Carbonation Rate CR using (Equation 1), which, in turn, allows predicting the moment when CO_2 will reach the steel reinforcement to initiate corrosion.

The purpose of this work is to obtain field results in 20-year-old concrete that should validate the application of the Air Permeability kT method to evaluate the Residual Service Life of reinforced concrete structures at risk of corrosion induced by carbonation. Finally, a proposal for Classification of Degrees of Exposure to Carbonation associated with the Risk of Occurrence of Steel Corrosion is presented, which considers a priori the concentration of CO_2 in the environment together with the degree of humidity present in the element, and values limits for Carbonation Rate and Air Permeability.

2. Background

Since the 90s, when the Air Permeability method was created, field investigations have been carried out to correlate the kT value to real Carbonation data in structures. Data obtained in the initial period (Torrent and Fernández, 2015) already showed an interesting relationship between the two methods, summarized in an average curve of all the data obtained, as shown in (Figure 2). It was determined that the Carbonation Rate is directly proportional to the Air Permeability of the concrete surface.

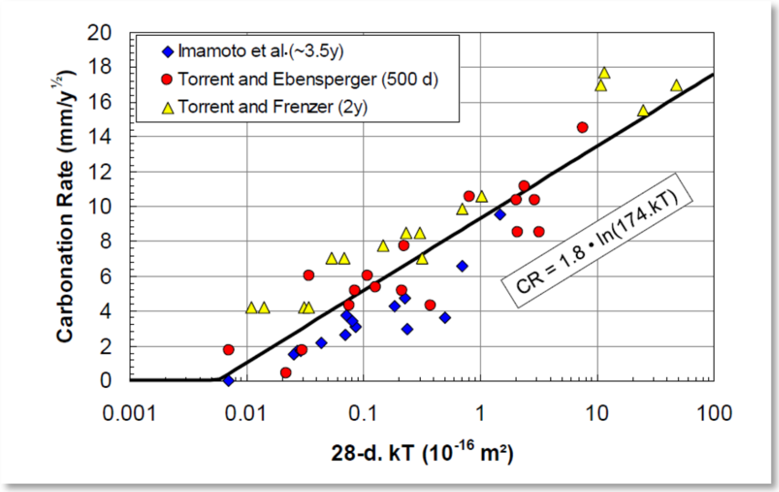

Figure 2. *Correlation between Carbonation Rate and Air Permeability*

Subsequent research around the world on existing structures showed the validity of the observed trend over time, but with a high range of results, depending on the age of the structure, environmental conditions, etc., as shown by the results of (Neves et al., 2018) with data from Portugal, Japan and Switzerland (see (Figure 3)).

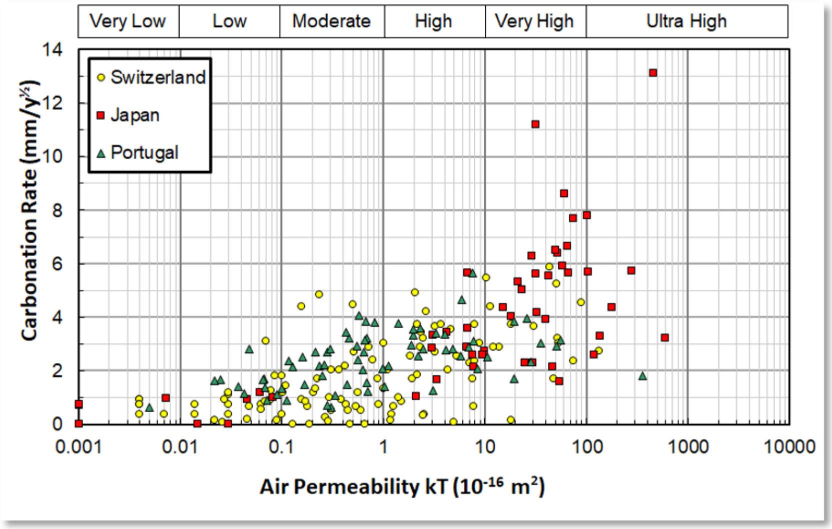

Figure 3. *Carbonation Rate and Air Permeability measured in 3 countries*

Studies on carbonation performed in Chile are limited. In (Rojas, 2006), the results of measurements on old structures in Chile are presented, all built with Portland cement in a humid coastal environment and an urban dry interior valley. The data analyzed indicate that for a humid coastal environment, the highest value measured was CR = 6.8 mm/√ year, while in the dry environment of the interior valley, it was CR = 10.3 mm/√year.

Another study carried out as part of a Fondef research project (Videla et al., 2012) showed the results of measurements of middle-aged (35 to 50 years) and current (5 to 15 years) structures, all built with Portland Pozzolanic Cement and located in two environments (marine and urban), and measurements on two faces of each building (west and south). The data analyzed indicate that the highest measured value for the humid coastal environment was CR = 7.0 mm/√ year, while in the dry environment of the interior valley it was CR = 8.8 mm/√year. The same study shows some measurements of Air Permeability carried out in a dry environment with kT values that varied from 2.1 to 57 x10-16m^2.

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In various assessments of concrete structures of different ages performed in Chile in recent years (Ebensperger, 2018), the results of Carbonation and Air Permeability obtained in the same measurement batches were compiled. (Table 2) presents the measurement results of both tests on structures built with Portland Cement (the first two) and the rest with Portland Pozzolanic Cement, located in different environments. The high Carbonation values coincide with the very high Permeability values, indicating the presence of a highly porous structure, which could be confirmed in the field.

Table 2. *Carbonation in Chilean structures*

Structure	Train Station			Río Colorado Bridge	Seminario Bridge	Highway Bridge			Foundation			Dock		Águila Norte Bridge	
Location	V-Region			Maipo River Valley	El Quisco Valparaiso	Santiago			Potrerillos			IV-Region		Santiago Central Valley	
Exposure condition	Dry interior valley			Dry interior valley	Humid coastal environment	Urban dry interior valley			Desert climate			Humid coastal environment		Dry interior valley	
Construction year	1930			1950	1964	1976			1991			2007		2009	
Measur. age (years)	88			70	55	46			30			10		10	
CO_2 max (mm)	180	115	65	36	30	35	45	48	7	16	13	20	7	0,5	17
***CR* (mm/√year)**	**19.2**	**12.3**	**6.9**	**4.3**	**4.0**	**5.2**	**6.6**	**7.1**	**1.3**	**2.9**	**2.4**	**6.3**	**2.2**	**0.2**	**5.4**
***kT* (10^{-16}m^2)**	**2692**	**1709**	**1182**	**366**	-	**73.2**	**29.3**	**95.3**	**10.4**	**256**	**73.6**	**1525**	**134**	**41**	-

(Figure 4) includes the data measured in Chile on in situ concrete where both CR and kT results are available. In general, the values are included in the ranges already shown in (Figure 3).

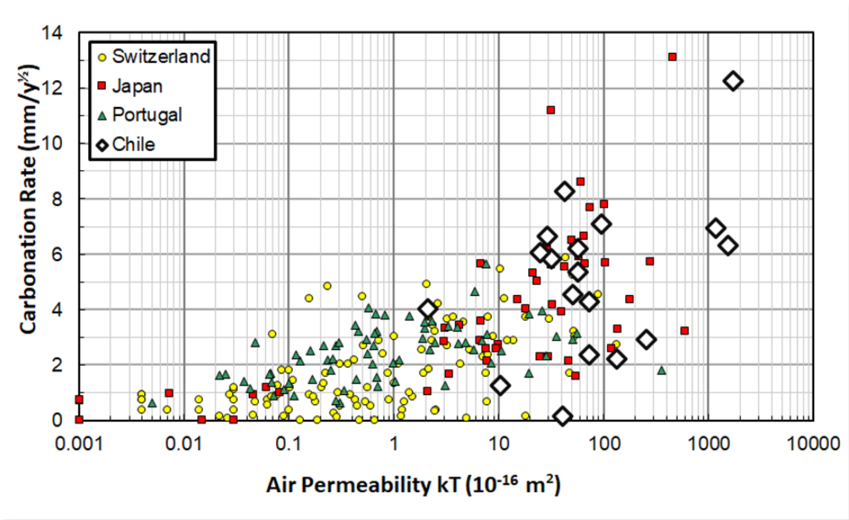

Figure 4. *Comparison of Carbonation Rates and Air Permeability measured in Chile*

The definition of Classification of the Degree of Aggressiveness of an environment by Carbonation differs according to the regulation that is studied. On the one hand, the Spanish regulations (EHE-08, 2008) make the CR depend mainly on the strength of the concrete and the type of cement (fcm, a, b) and on a factor cenv that depends on the environment (the case protected from rain is assigned a value of 1.0, which decreases by 50% when exposed), and another factor cair that depends on the content of air incorporated (in the case with air < 4.5%, it assigns a value of 1.0, which decreases by 30% when it is greater).

$$K_c = c_{env} * \ c_{air} * a * f_{cm}^{b} \qquad (2)$$

On the other hand, the European regulation (Eurocode 2, 1992) is under revision to incorporate the Exposure

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Resistance Classes (ERC) to classify concrete resistant to corrosion induced by carbonation (class XRC) to resist deterioration and protect against corrosion. For this purpose, it defines up to 8 levels of Carbonation Rate, from 0.5 to 7 mm/√year, and relates them to the four Exposure Classes (see (Table 3)) to deliver the required coating, either for a Service Life of 50 or 100 years, with a confidence level of 90%. The assumption for carbonation depth, through CR, is assumed to be obtained after 50 years under reference laboratory conditions of 400 ppm CO_2 and a constant environment of 65% r.h. at 20°C. For more aggressive environments, it proposes increasing the Safety Factor by increasing the minimum coating.

In addition, the Mexican regulation NMX C-530 (Castro et al., 2020) defines three Exposure Classes according to the level of humidity, as shown in the (Table 3).

Table 3. *Exposure Classes associated with Carbonation according to NMX C830*

Environment	Class	Condition	Environment Description	Humidity %
Rural Urban	**C1**	Concrete in contact with high humidity	Concrete in an environment with high humidity > 80%, independent of CO_2 and SO_2 pollution.	> 80
	C2	Concrete in contact with moderate humidity	Concrete in an environment with high humidity between 40% and 50%, independent of CO_2 and SO_2 pollution.	40 a 50
	C3	Concrete in contact with moderate humidity	Concrete in an environment with moderate humidity between 50% and 80%. with CO_2 and SO_2 pollution.	50 a 80

In the work carried out in Chile (Videla et al., 2012). the DuraSpec document presents a combination of levels of CO_2 concentration and humidity for rural, urban, and marine environments, defining three Degrees of Severity: Mild, Moderate and Severe considering four humidity levels (30, 50, 70, and 80%) and four CO_2 concentrations (250, 350, 450, and 650 ppm).

This proposal has not been applied in the country, and it has not been incorporated in the NCh170:2016 for Concrete, which only includes the Degree of Exposure by Carbonation as C1 as Mild Aggressiveness for wet concrete exposed to high concentrations of CO_2 which is insufficient to analyze the existence of an associated corrosion risk.

3. Experimental Program

3.1 Information on existing concretes

*A series of four concrete mixtures were prepared in 2001 in the RESMAT laboratory of Dictuc (Ferreira, 2004), on which fresh concrete and Compression Strength tests were conducted, and a total of eight walls with dimensions of 3.00*2.40*0.24 m were made. Half of them were cured for seven days, and the rest were left without curing for the later extraction of cores and the execution of various non-destructive tests.*

Two types of cement were used (Normal CC and High-Strength AR), and concretes with 2 Strength Grades were made (H20 and H35; current G15 and G30) for each one of them.

The contents of CC cement were 330 and 447 kg/m^3, and those of AR cement were 300 and 392 kg/m^3, and the respective w/c ratios were 0.74 – 0.49 – 0.63 – 0.56. The Compressive Strength at 28 days in 150x300mm cylindrical samples cured under standardized conditions reached values of 26.9, and 44.1 MPa, and 37.1 and 51.5 MPa, respectively. The strengths obtained from cores at the age of 28 days were 25.4 and 43.4 MPa. and 33.2 and 48.6 MPa, marking the difference between the types of cement.

3.1 Field Activities

The activities carried out were the following:

a) Choice of measurement side for each wall: a review of the eight walls according to the observed surface conditions, such as roughness and presence of microcracks.

b) Selection of measuring points:

• Four points for the END measurement of Air Permeability and later for the extraction of cores to measure the Carbonation on each face, and then the Compressive Strength.

• Four points for the measurement of the Rebound Hammer.

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• Four points for the measurement of the Rebound Hammer.

3.3 Execution of tests

The standards and equipment considered for the measurement were the following:
• Air permeability kT (SIA 262/1-E to be measured in situ)

Non-destructive measurement, performed with the PermeaTORR equipment directly on the surface of the concrete, with a previous polish to eliminate roughness that could affect the measurement due to the entry of unwanted air into the double-chamber measurement cell. A vacuum is generated on the concrete surface for 60s with a double chamber cell. The rate at which the pressure increases, while maintaining an air flow perpendicular to the surface is then measured in the inner cell for six minutes. Previously, it was verified with Tramex equipment that the surface humidity of the concrete was less than 5.5%.

In this study, the result is the geometric average of four measurements of the Air Permeability kT [10-16m^2], carried out according to Recommendations issued by the Swiss Ministry of Roads (VSS, 2009). The quality of the concrete cover is classified according to (Table 9) (Materials Advanced Services, 2014):

***Table 4.** Classification of concrete cover according to Air Permeability*

Permeability Class	kT (10^{-16} m²)	Degree of Permeability
PK0	< 0.001	Negligible
PK1	< 0.01	Very Low
PK2	< 0.1	Low
PK3	< 1	Moderate
PK4	< 10	High
PK5	< 100	Very High
PK6	> 100	Ultra High

The Swiss standard (SIA 262/1, 2013) provides for the different levels of environmental aggressiveness (EN 206, 2013) the following admissible limits of Air Permeability measured in situ in a non-destructive way in the finished structure, as indicated in (Table 11) values defined to have structures resistant to the effect of carbonation.

***Table 5.** Admissible limits for Air Permeability kT (10-16 m²)*

Exposure combinations	Exposure Class	
	Severe	Strongly Severe
• Severe Carbonation	-	< 0.50
• Moderate Carbonation	< 2.0	-

• Measurement of the Rebound Hammer (NCh1565)

The non-destructive measurement, performed with the Schmidt Hammer, consists of measuring the energy generated when a plunger bounces off the surface of the concrete, generating an index known as N. This value is correlated with the Compressive Strength of the concrete through calibrated graphs for each type of Hammer Model.

Since Carbonation causes surface hardening by generating new calcium carbonate crystals, the N value must be corrected to represent an adequate value (Breccoloti et al., 2013). In this study, the result is the average of four surface measurements.

• *Taking Cores (NCh1171/1)*

*The extraction of Ø100*200mm cores is carried out with a core machine according to NCh1171/1 and evaluated according to NCh1171/2.*

• *Measurement of Carbonation Depth UNE-EN 14630*

The color change produced by spraying a phenolphthalein solution on a fresh concrete surface of the extracted core is measured. The maximum observed depth of the CO_2 penetration front is determined, which changes to purple in areas with pH > 9.5 (non-carbonated concrete). Carbonation depth is measured on both faces of four cores.

The Swiss standard (SIA 262/1, 2013) provides for the highest levels of aggressiveness due to Carbonation (EN 206, 2013) the following admissible limits of Carbonation Rate CR under natural concentration conditions (400 ppm), according to (Table 6) associating them with the Service Life required for the concrete structure.

***Table 6.** Admissible limits for the Carbonation Rate according to SIA 262/1*

Service Life (years)	**CR (mm/√year)**	
	Exposure Class	
	XC3	**XC4**
50	< 5.0	< 5.0
100	< 4.0	< 4.5

XC3: Moderate humidity – XC4: Cyclic wet and dry

• *Compressive Strength f´c (NCh1037)*

After any necessary specimen rectification, the compressive strength is measured in four cores. Conditioning entails immersing them in water for one day to ensure proper saturation. The result is the average of two measurements [MPa].

4. Result Analysis

4.1 Measurement of Carbonation Depth

(Table 7) and (Figure 5) compare the results of Carbonation Depth obtained at the age of 20 years in cores extracted from the wall, according to the measurement face.

***Table 7.** Carbonation Depth Results [mm]*

Wall Id	Meas. 1		Meas. 2		Meas. 3		Meas. 4		**Prom.**		STDEV		Var. Coef.	
	N	S	N	S	N	S	N	S	**N**	**S**	**N**	**S**	**N**	**S**
H20CC0d	34	33	34	30	39	39	39	30	**36.0**	**30.3**	**2.4**	**2.1**	6.8%	6.8%
H20CC7d	31	35	32	29	32	32	32	33	**32.8**	**32.8**	**2.2**	**2.6**	6.8%	8.0%
H35CC0d	16	16	16	12	16	16	16	13	**15.5**	**13.8**	**1.0**	**1.7**	6.5%	12.4%
H35CC7d	16	13	12	8	19	19	19	15	**16.0**	**13.3**	**2.9**	**3.9**	18.4%	29.1%
H20AR0d	21	22	24	23	26	26	26	25	**23.5**	**23.5**	**2.1**	**1.3**	8.9%	5.5%
H20AR7d	25	23	26	26	27	27	27	24	**25.3**	**23.8**	**1.7**	**1.7**	6.8%	7.2%
H35AR0d	6	0	13	0	12	12	12	0	**10.5**	**0.0**	**3.1**	**0.0**	29.6%	0.0%
H35AR7d	0	0	0	10	0	0	0	5	**0.0**	**3.8**	**0.0**	**4.8**	0.0%	127.7%

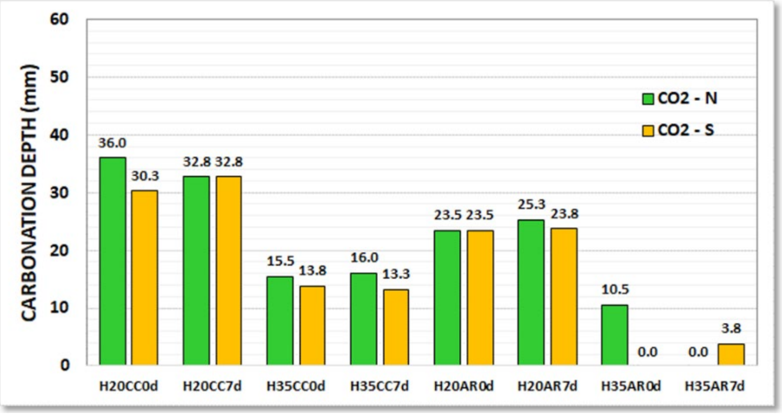

Figure 5. *Carbonation depth in walls after 20 years*

The calculation of the Carbonation Rate according to the square-root model (Equation 1) is shown in (Figure 6) according to the measurement face. It is noted that Grade H35 concrete would meet the Limit for a Design Service Life of 50 years, according to the criteria of the SIA 262/1 standard.

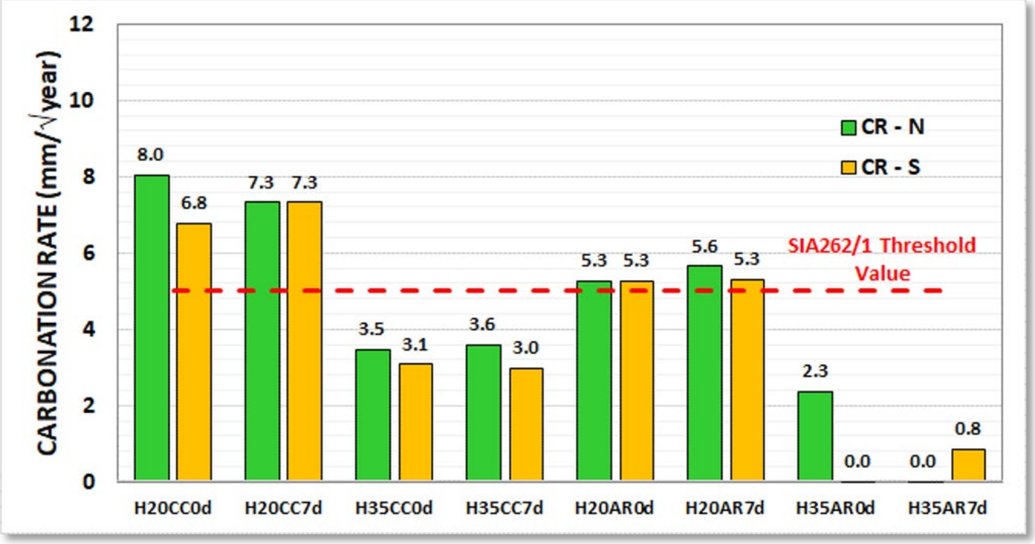

Figure 6. *Carbonation Rate in walls after 20 years*

4.2 Measurement of Compressive Strengths

(Table 8) shows the detail of the results measured in the four cores:

Table 8. *Core Compressive Strength Results [MPa]*

Wall Id	Meas. 1	Meas. 2	Meas. 3	Meas. 4	**Mean**	STDEV	Var. Coef.
H20CC0d	30.7	32.4	29.6	28.9	**30.4**	1.5	5.0%
H20CC7d	27.6	31.2	27.7	28.1	**28.7**	1.7	6.0%
H35CC0d	51.3	52.9	56.2	50.2	**52.7**	2.6	5.0%
H35CC7d	48.7	49.2	49.5	49.3	**49.2**	0.3	0.7%
H20AR0d	34.5	34.6	30.1	32.5	**32.9**	2.1	6.4%
H20AR7d	30.7	31.9	33.2	32.5	**32.1**	1.1	3.3%
H35AR0d	54.9	50.1	56.3	56.6	**54.5**	3.0	5.5%
H35AR7d	53.9	53.7	60.0	47.9	**53.9**	4.9	9.2%

Nomenclature: H20CC7d –20 MPa strength with common cement cured for seven days.

(Figure 7) compares the strengths results obtained at the age of 28 days in the standardized cured cylindrical samples and cores at that same age with the results obtained in cores extracted at the age of 20 years. After 20 years, the strength increased by an average of 15%.

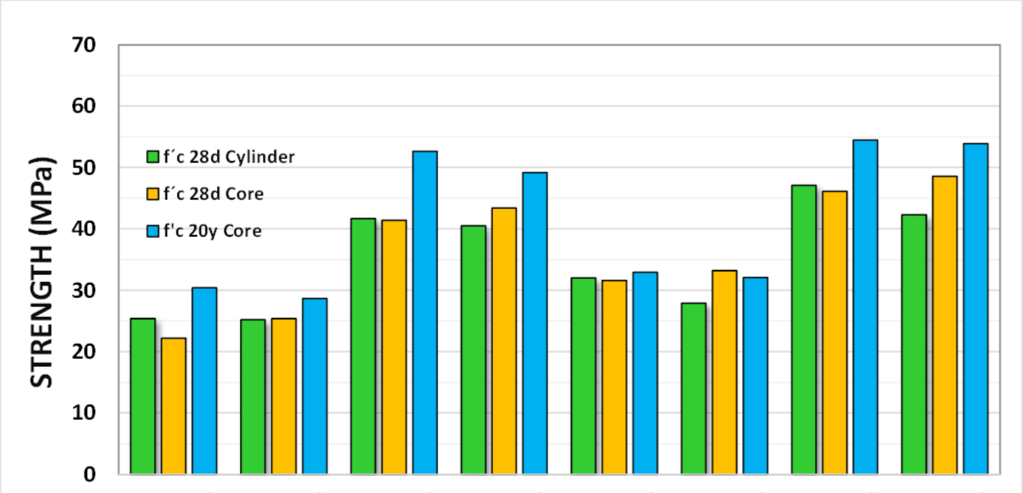

Figure 7. *Strength measured in walls after 28 days and 20 years*

4.3 Measurement of Rebound Hammer

The details of the results measured on the walls are shown in (Table 9) and (Figure 8). The N values and the estimated Strength f'c with the calibration curve of the equipment used are included, based on the measured data and those corrected by the carbonation effect. It is observed that the proposed correction gave strength estimation values like those obtained in the cores, except for the H35 mixture with AR cement.

Table 9. *Index Results N [-] and Strength [MPa]*

Wall Id	Meas. 1	Meas. 2	Meas. 3	Meas. 4	**N Mean**	STDEV	Var. Coef.	**f´c**	**N Correc. CO_2**	**f´c Correc. CO_2**
H20CC0d	51	50	50	50	**50**	0.5	1.0%	**59**	**35**	**31**
H20CC7d	51	50	52	49	**51**	1.3	2.6%	**59**	**35**	**31**
H35CC0d	55	56	53	59	**56**	2.5	4.5%	**71**	**39**	**37**
H35CC7d	59	56	56	54	**56**	2.1	3.7%	**72**	**39**	**38**
H20AR0d	56	53	53	50	**53**	2.4	4.6%	**65**	**37**	**34**
H20AR7d	51	52	50	51	**51**	0.8	1.6%	**60**	**36**	**32**
H35AR0d	61	61	62	62	**62**	0.6	0.9%	**84**	**49**	**55**
H35AR7d	61	61	59	61	**61**	1.0	1.7%	**81**	**55**	**70**

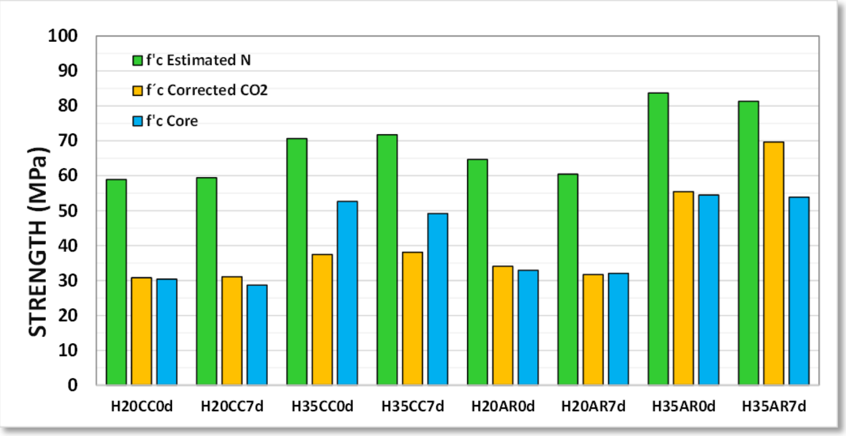

Figure 8. *Estimated and corrected strengths using N and measurements after 20 years*

4.4 Measurement of Air Permeability

The results measured at four points on each wall are shown in (Table 10):

Table 10. *Air Permeability Results [10-16 m^2]*

Wall Id.	Face	Meas. 1	Meas. 2	Meas. 3	Meas. 4	**Geom. Mean**	STDEV (Log)	Var. Coef.
H20CC0d	N	222	1130	620	49	**295**	0.60	24.1%
H20CC7d	N	122	93	43	417	**119**	0.41	19.7%
H35CC0d	N	164	16	78	134	**72**	0.46	24.6%
H35CC7d	N	88	520	282	884	**327**	0.43	17.1%
H20AR0d	S	12	606	35	28	**52**	0.74	43.2%
H20AR7d	S	19	97	19	52	**37**	0.35	22.3%
H35AR0d	S	2.1	5.6	2.8	1.3	**2.6**	0.27	65.0%
H35AR7d	N	1.3	40	16	5.9	**8.4**	0.64	69.0%

*(Figure 9) compares the Air Permeability kT results obtained at the age of 20 years on the surface of the concrete walls. None of the wall concretes would reach the less demanding level of kT=2.0*10-16m2 of SIA 262/1, and only the two H35 mixes with AR cement are classified in Class PK4 of High Permeability.*

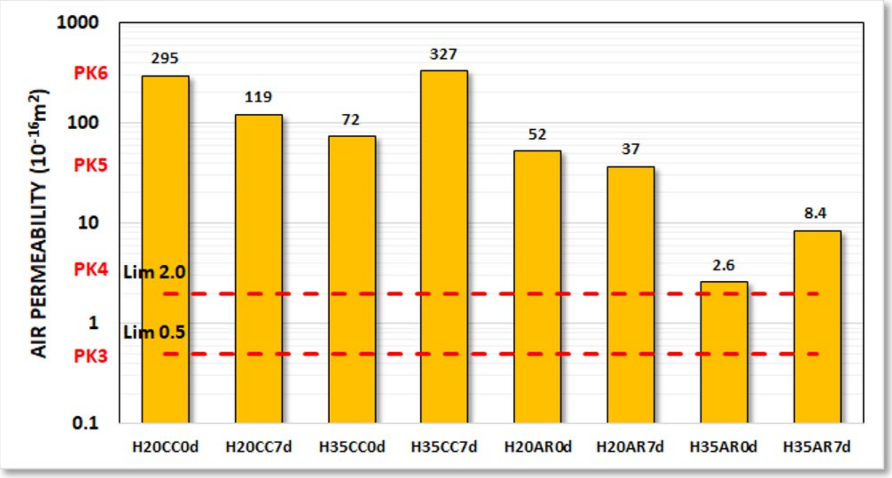

Figure 9. *Air Permeability measured in walls after 20 years*

5. Analysis of Results

5.1 Relationships between Carbonation and Performance Tests

(Figure 10) clearly shows the effect of increasing the Strength Grade of the concrete on the CR.
A similar situation is observed in (Figure 11) with the measured Rebound Hammer Index N. Neglecting the effect of carbonation on the Schmidt Hammer measurement leads to very high Strength estimations that alter the CR values estimated with this method.

(Figure 12) shows the eight measured Air Permeability kT results. In the case of the walls, is observed that for kT < 2.0 [10–16 m^2] values, almost zero CR would be expected.

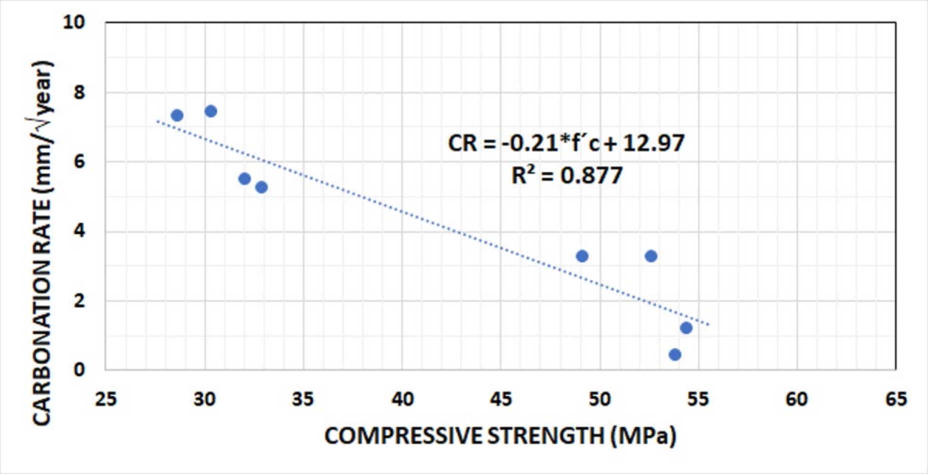

Figure 10. *Relationship between Carbonation Rate and Core Strength*

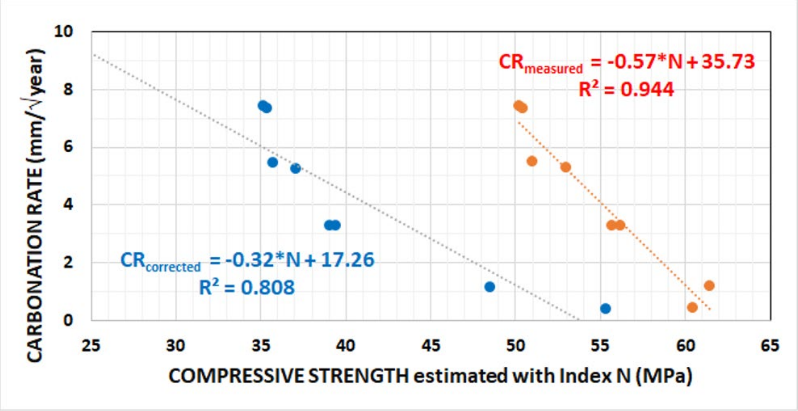

Figure 11. *Relationship between Carbonation Rate and Strength estimated with Index N*

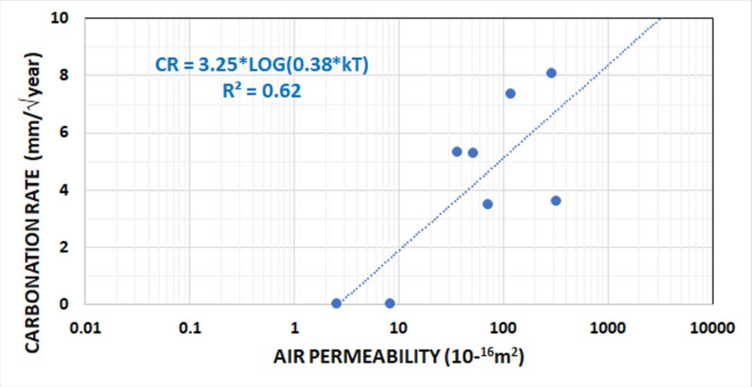

Figure 12. *Relationship between Carbonation Rate and Air Permeability*

(Figure 13) incorporates all the data measured in situ in existing structures in Chile, together with the results of this study, and it shows in red the enveloping curve of the Carbonation Rate in logarithmic trend. The results are compared with internationally measured data for existing structures. In the case of concrete measured in Chile, for values of kT < 0.1 [10-16m^2] almost zero CR is expected, which would only occur in the case of Europe at kT < 0.01 [10-16m^2]. This could be because most of the country's data corresponds to dry environments, which tend to measure higher kT values. The correlation obtained would allow estimates of Service Life to be made directly from the measurement of Air Permeability.

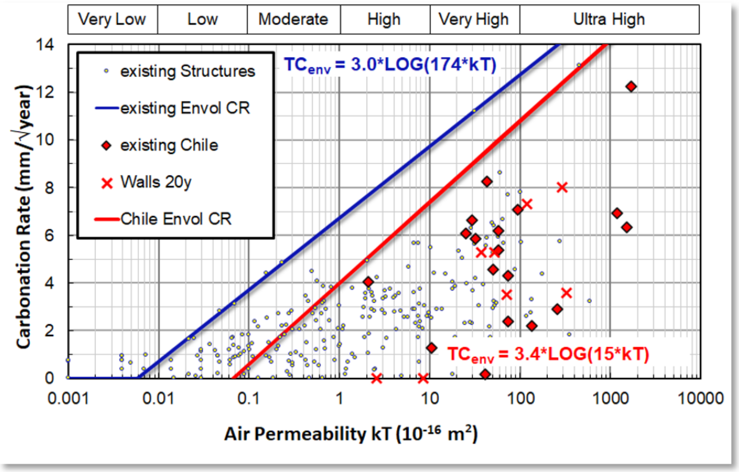

Figure 13. *Summary of relationships between CR and kT*

5.2 Proposal for a Classification of Exposure to Carbonation

The objective is to define a Classification that includes the aggressive conditions of the environment and the Performance requirements for each defined Grade. In the first place, the limits for the CO^2 concentration in the environment must be defined by considering the simultaneous effect of the presence of humidity.

The European Cement Committee (CEB, 1997) defines four humidity levels, and the current "normal" CO^2 concentration is considered to be 400 ppm, and above 650 ppm is considered to be high. These limits, associated with rural, urban, and Industrial environmental conditions, allow the proposal of the following classification. as shown in (Figure 14).

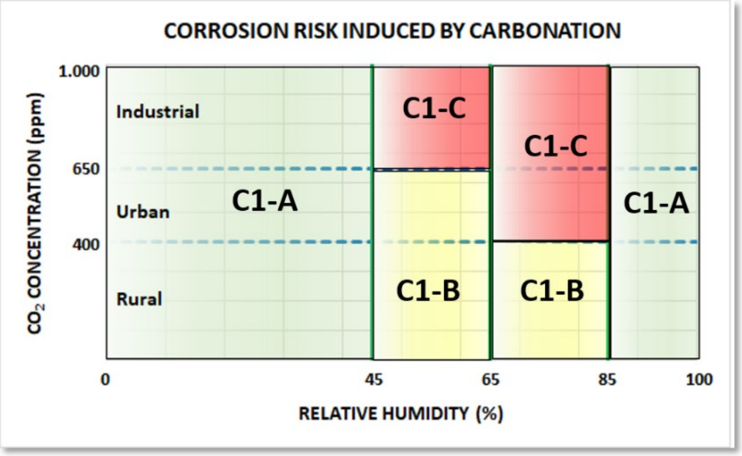

Figure 14. *Proposal for Carbonation Exposure Degrees*

While low humidity favors the ingress of CO^2, high humidity favors corrosion. The range in which CO^2 ingress more easily (see (Figure 1)) corresponds to humidity between 45% and 85%. In the case of corrosion, it increases as humidity increases and is negligible at low and high humidity due to the absence of oxygen. On the other hand, the risk of corrosion increases as the CO^2 concentration increases.

(Table 11) summarizes the proposal and the requirements to be determined in situ of CR and kT, taken from international experience ((Table 4) and (Table 5)) and the results presented in (Figure 13).

Table 11. *Proposal for a Classification of the Degree of Exposure to Carbonation*

Exposure Class	Risk	Description	CO_2 Concentration (ppm)	Relative Humidity (%)	CR (mm/√year)	kT (10^{-16} m²)
C1-A	**MILD**	Environment with low humidity or continuously wet	-	< 45	< 5	< 2
				> 85		
C1-B	**MODERATE**	Environment with dry/wet cycles	< 650	45 to 65	3 a 5	0.5 a 2
			< 400	65 to 85		
C1-C	**SEVERE**	Environment with dry/wet cycles	> 650	45 to 65	< 3	< 0.5
			> 400	65 to 85		

The incorporation of the kT requirement will support the previous mix design at the laboratory level following the guidelines of the Argentine standard (IRAM, 2022) and the Integral Methodology of Design and Control of Concrete by Service Life (Ebensperger, 2018), which transfers the potential laboratory results to the in-situ condition through the correction factor γ_{ccc} which considers the effect of pouring, compaction, and curing executed on site.

5.3 Analysis of Service Life and Residual Life

Performing non-destructive measurements of Air Permeability kT on the surface of the concrete, it is possible to estimate the Carbonation Rate CR of the concrete, using the relationship already identified in (Figure 13) and presented as (Equation (2)). The value of the expected Service Life SL can be obtained through this CR value by using (Equation (3)) as the model of the root of the time of the Carbonation Rate CR and incorporating the value of the cover thickness Xc.

$$\boldsymbol{CR} = 3.4 * LOG(15 * \boldsymbol{kT}) \tag{2}$$

$$\boldsymbol{SL} = \left(\boldsymbol{Xc}/\boldsymbol{CR}\right)^2 \tag{3}$$

If the estimated Service Life is greater than the age of the concrete, it is considered that:

$$Residual\ Service\ Life = Service\ Life - \ Age \tag{4}$$

(Figure 15) shows the chart for the estimation of SL as a function of the Carbonation Rate CR and the cover Thickness Xc. For a CR of 3 mm/√year and a concrete cover of 30mm, the expected SL is approximately 50 years, similarly for a TC of 5 mm/√year and a cover thickness of 35mm. Increasing the coating thickness to 50 mm leads to doubling the SL, at 100 years. As the age of the concrete of the walls is already 20 years, the Residual Life, considering the moment in which the CO_2 reaches the steel, would be, for this example, 30 and 80 years, respectively.

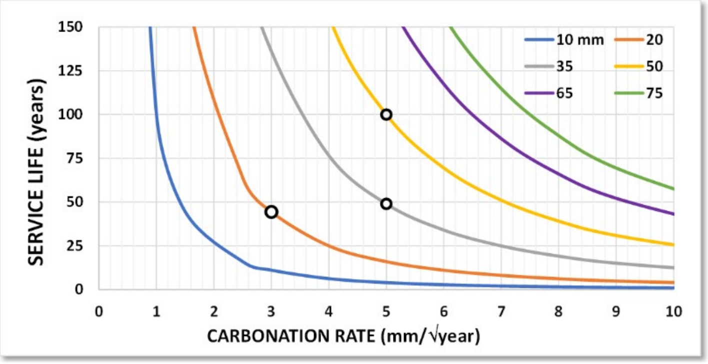

***Figure 15.** SL estimation as a function of CR and Xc*

*(Figure 16) shows the chart for the estimation of SL as a function of the Air Permeability kT and the cover Thickness Xc. For an Air Permeability of kT = 0.5*10-16 m^2 and a cover thickness of 20mm, the expected SL is approximately 50 years, a situation that is maintained if the coating thickness increases to 35mm and the Air Permeability increases to kT = 2*10-16 m^2. If kT is kept fixed and Xc increases to 50mm the SL increases to 100 years.*

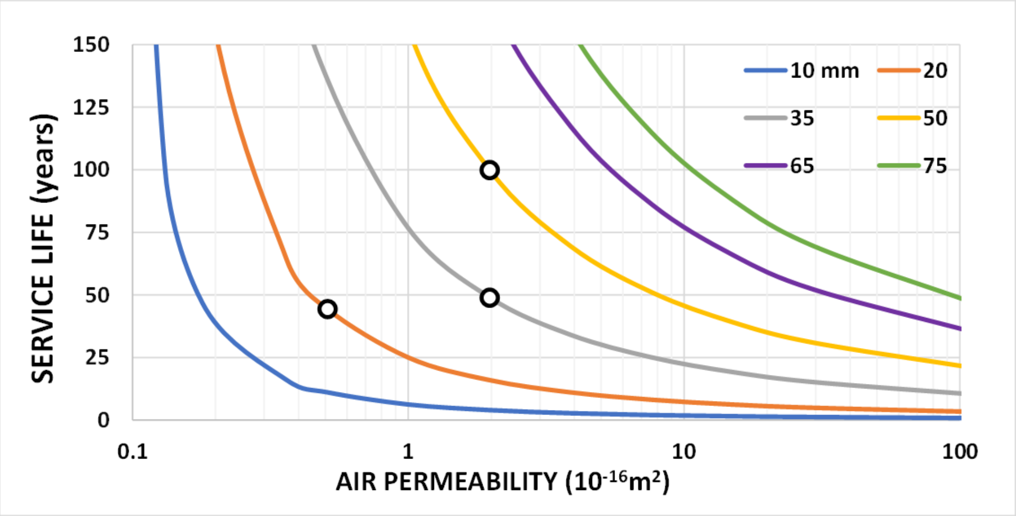

Figure 16. *SL estimation as a function of kT and Xc*

A detailed Service Life analysis is presented in the CTK-ConcreLife® Model (Ebensperger, 2018), which considers the variations that can occur on site by measuring both the concrete cover thickness and the Air Permeability. This model generates a probabilistic analysis, which allows assigning a Reliability Index to the SL assessment, which is defined at √=1.30, equivalent to a Confidence Level
of 90% (10% defective fraction). In addition, it considers the Type of Exposure by Carbonation to which the concrete will be subjected, according to (Table 1).

*(Figure 17) shows the result obtained if the exposure of the walls is Exposure Type XC3 (moderate humidity), with an assumed standard deviation of the data measured in the field of 10% and 20% for the concrete cover thickness and Air Permeability, respectively. For a Service Life SL =50 years, a Permeability of kT = 5.4*10-16m^2 means that the probability of corrosion initiation at this age will be 60%, which is reduced to 10% (ideal design condition) if kT is 1.4*10-16m^2.*

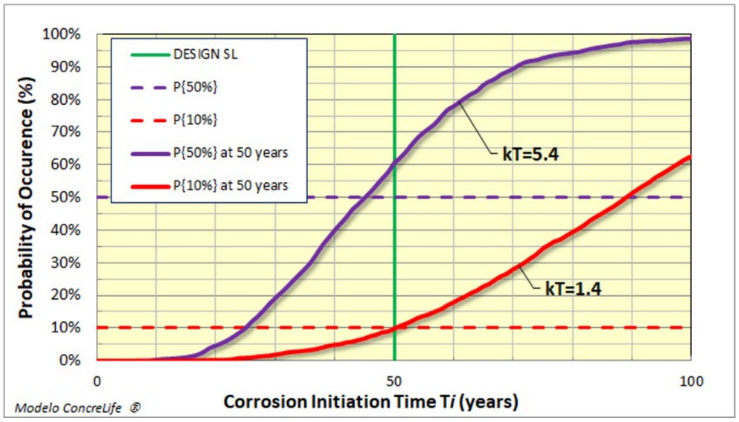

Figure 17. *Corrosion initiation probability (Design SL) as a function of kT*

5. Conclusions

The investigation carried out in the field on some 20-year-old concrete walls with two levels of strength allowed the collection of relevant information on Carbonation in Chilean concretes. The tests performed on the walls were classified according to their mode of application: non-destructive on the concrete surface (Air Permeability and Schmidt Hammer) and others on extracted cores (Carbonation Depth and Compressive Strength).

Determining the Carbonation Rate allowed for obtaining differences according to the type of cement and Strength Grade, with a decrease on CR when using high-strength cement and when increasing the level of Strength. It was shown that *the estimation of the strength by means of the Rebound Hammer overestimates the real value of the strength of the concrete unless a correction is made for the effect of carbonation on the surface of the concrete.*

*Regarding the Air Permeability Method, a correlation has been identified for Chilean concretes, which would indicate that for permeabilities kT < 0.1*10-16m^2, the occurrence of Carbonation would be almost null, and that for other higher values the correlation found would make it possible to count with a non-destructive in-situ method for estimating the Carbonation Rate, making it easier to estimate the real situation on site.*

An innovative Classification of the Degree of Exposure to Carbonation is proposed, which is associated not only with the concentration of CO_2 in the atmosphere but also with the environmental conditions that generate the Risk of Corrosion of the reinforcement (humidity), in addition to incorporating requirements of a performance test, such as Air Permeability.

Apart from that, the incorporation of Air Permeability as a methodology to determine the Carbonation Rate of the concrete allows a simple way to determine the estimated Service Life of a structure when of incorporating the data of the coating thickness, either by design phase or determined in situ, in the CTK-ConcreLife® Model. Using a model such as the one proposed provides a probabilistic result of the start of corrosion according to the data that are measured in the field in finished structures. This model has already been used successfully in various designs for Service Life and in the estimation of the Residual Service Life of existing structures.

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