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Service Life Design of Reinforced Concrete Maritime Infrastructure: Holistic Approach with Experiences from Chilean Cases

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Abstract: The consideration of the useful life of reinforced concrete in the different stages of a structure's life cycle, as a distinguishing factor in the design process for performance under aggressive environmental conditions, has presented new challenges in construction. This includes the development of new regulations incorporating innovative engineering materials, performance tests and modeling processes to estimate concrete deterioration over time, and construction processes ensuring adequate Quality Control and Quality Assurance (QAQC). As a result, infrastructure projects have been able to exceed their intended lifespan, maintaining serviceability levels for more than 100 years. One such example is the Chacao Bridge project currently under construction in southern Chile. This paper provides an overview of project stages from a holistic approach, focusing on aspects inherent to planning including design and construction processes, control stages for monitoring deterioration levels through regular diagnostics and appropriate monitoring to support ongoing structural health management. Additionally, it presents real case design examples carried out with specific models created for each case.

Key words: concrete; durability; service life design; holistic approach

1. Introduction

Marine infrastructure, which refers to any structure in contact with seawater, is typically constructed using reinforced concrete and/or a combination of metal structures, such as piles and sheet piles. Given the high-level investment involved and its strategic importance in national logistics, the highest structural design standards are required. By implementing appropriate maintenance plans, the construction quality can be improved and the availability level can be maintained over time (Repetto et al., 2019). It is crucial to conduct preliminary research on possible diseases that may affect the structure when seeking to ensure the specified service life. In addition, it is necessary to consider the inconvenience and profit loss caused by the interruption or delay of port facility operation, which may be caused by construction defects and premature deterioration.

It is important to emphasize that dry or low saturation concrete structures are immune to physical and chemical degradation phenomena (alkali aggregate reaction, sulfate, freezing) or electrochemical phenomena (chloride or carbonization induced steel corrosion) that occur inside them. However, in terms of their nature, port facilities often or permanently come into contact with saltwater, as do other types of structures such as canals, locks, dams, pipelines, ponds, or desalination reservoirs and bridges. Both types of degradation can result in internal expansion or decomposition of cement hydration compounds, which, in combination with the corrosion process of steel, can cause the structure to lose its load-bearing capacity, as shown in the example in Figure 1.

Figure 1. Deterioration due to corrosion effect on port structures.

The accumulation and irreversible damage in cement slurry (bonding matrix) and steel reinforcement are inherent in the material, with the aim of using appropriate materials and delaying the entry of corrosive substances to such an extent as to ensure the usability of the structure within the specified service life.

Over the years, design methods that take into account all relevant factors have gradually improved, especially the models already used in most countries. However, as experts have emphasized, these advances have failed to ensure sustainable design. This is especially evident in the case of three bridges in Europe. These bridges, despite being designed for a service life of 100 years, have experienced issues within 20 to 25 years of operation, including premature corrosion of steel caused by chloride (Di Pace et al., 2019). The Morandi Bridge in Genoa deserves special attention. It collapsed unexpectedly in 2018, having been in service for just 21 years, causing a regrettable loss of life.

All of these clearly indicate that the material engineering profession, along with structural engineering, has not achieved success in ensuring durability, and this situation deserves further analysis. One explanation may be that designing for durability reflects a lack in physical, chemical, and electrochemical knowledge among many civil engineers. However, the main shortcoming in this area may be the mistaken belief that bridges in harsh environments can achieve a service life of 100 years merely by applying traditional design, materials, construction, and inspection practices. This erroneous belief arises from conceptual errors in standards and norms. For example, European Regulation 2 (EN, 2004) stipulates that merely by increasing the coating depth of steel by 10 mm compared to the 50-year service life requirement, a service life of 100 years can purportedly be achieved, despite the fact that the concrete specifications for both service lives are identical. This obviously insufficient combination of coating depth and concrete quality will not yield a long-lasting structure.

Achieving long-term service life for structures exposed to harsh environments is not an easy task and requires special efforts from all parties involved in their design, construction, inspection, and maintenance. Unless owners, designers, material suppliers, contractors, inspection and testing agencies, and consultants recognize this challenge and fulfill their tasks with great caution and responsibility, the expected durability performance will not be achieved.

The purpose of this work is to review the key aspects of each step of project development and emphasize the actions taken to achieve sustainable structures to meet the expectations of leaders and society. The focus is on the durability design of steel against chloride corrosion, showcasing Chile's experience. Given that our coastal and port infrastructure is aging, early defects in concrete can occur even in less than 5 years, which is a necessary experience (Oberreuter, 2022).

2. Stages of a Project When Considering Its Life Cycle

2.1 Pre-project phase

At this stage, typically starting many years before construction begins, it is important to obtain accurate information about macro and micro climate conditions, as well as the expected level of aggression faced by the structure in each of its components and its potential impact on its durability. These pieces of information must be included in a report called "Durability Strategy". Figure 2 illustrates the varying degrees of erosion structures undergo in the marine environment, and this erosion ultimately influences the risk of corrosion in steel reinforcement

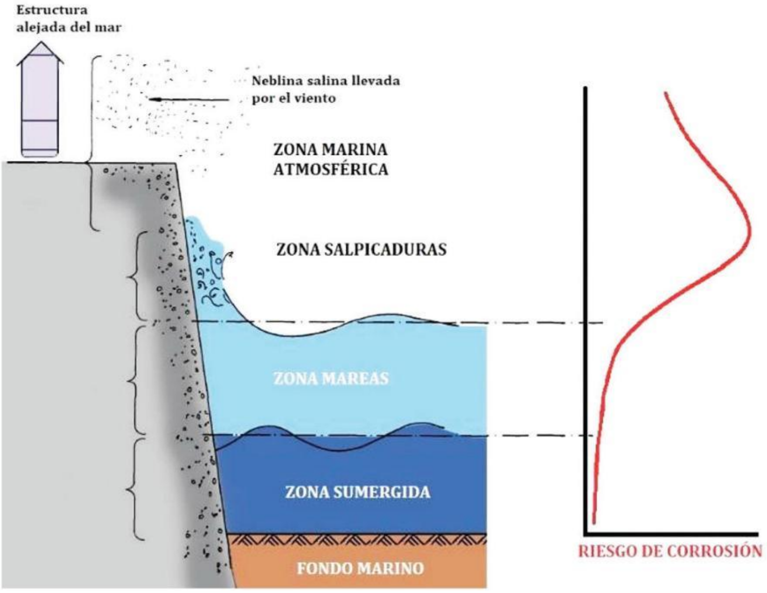


Figure 2. Corrosion risk in maritime structures according to their location.

It is recommended not only to use durable concrete, but also to use advanced building systems to build models. These models must be placed in environments similar to those experienced by the actual structural elements. Conduct comprehensive and advanced testing on the test mixture, and regularly monitor model elements, providing useful information on the long-term initial characteristics and behavior of the system. These pieces of information will help to calibrate more accurate models and predictions of chloride penetration and steel corrosion processes. A good example of this effort is the Hong Kong Zhuhai Macao Highway Connection Project launched in 2018, with a total of 55 km of different bridges and tunnel structures connecting three points at the the Pearl River Estuary in China (Li et al., 2015). Samples were installed and monitored 30 years prior to the start of construction, providing critical information for the design lifespan of the elements that make up the project. At this stage, the design life of the structure must be determined. The values shown in Table 1 are considered to indicate the service life (FIB, 2006).

Table 1. Reference service life values

Service life (years)	Description
10	Temporary structures (structures or parts of structures that can be dismantled with the objective of being reused, should not be considered as temporary).
10 – 25	Replaceable structural parts such as gantry beams, bearing supports, etc.
15 – 30	Agricultural and similar structures.
50	Buildings and other common structures.
100	Structures of monumental buildings, bridges and other major structures (infrastructure).

It is urgent to incorporate the concept of structural service life into national regulations as soon as possible, especially in offshore engineering, which will undoubtedly face a high risk of steel corrosion. According to Table 1, the design service life of reinforced concrete structures should be at least 50 years. The current concrete standard NCH170 (2016) incorporates durability concepts, such as exposure levels and minimum requirements for mixtures based on erosion levels. Research is underway on how to incorporate more detailed life analysis concepts from a material or structural design perspective.

2.2 Design phase

This is a critical stage of the project, where the main characteristics of concrete components expected to last for 50 years are defined, modeled, and transformed into the concrete technical specifications of the project.

2.3 Chloride ingress models by diffusion

The model of Tuutti (1982), applied to the corrosion of steel by chlorides or carbonation, schematically demonstrates the deterioration process that occurs in concrete. As shown in Figure 3, there is an initial period without considerable damage, referred to as Initiation Time T_i, which ends at the onset of corrosion. Within this period, chlorides penetrate the surface of the concrete until reaching the critical concentration C_{cr} in the reinforcing steel. If oxygen and moisture are present at this point, the steel is susceptible to initiating the corrosion process. The Initiation Time T_i is closely associated with the service life of the structural element, which may be linked to minor cracking, localized spalling, or loss of allowable section of the steel. Additionally, there is an ultimate limit state corresponding to the loss of bearing capacity of the structural element due to loss of bond and probable reduction of the steel and concrete section.

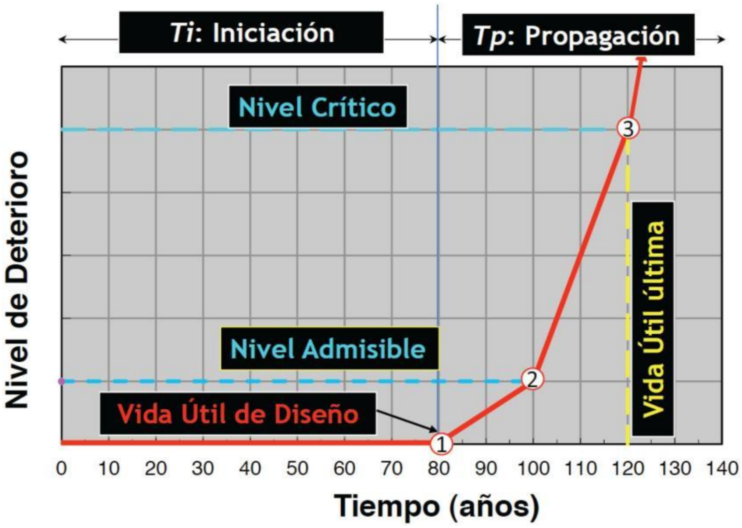


Figure 3. Tuutti's life cycle model (1982).

Most of the models developed to predict the T_i of structures (fib, 2006; Life-365, 2012) are based on the simplified assumption that chloride penetration occurs exclusively by non-steady-state diffusion, which obeys Fick's second diffusion law defined in (1). The differential equation is complex, and its solution is possible only by considering constant the diffusion coefficient D_t and the chloride concentration at the concrete surface C_s. In this case, Fick's second law accepts an explicit solution. Assuming the boundary condition in (2), i.e., corrosion starts when the level of chlorides on the steel surface reaches a critical level Cc_r, the solution (3) of lifetime is obtained. The above requires the incorporation of the aging factor m to properly consider the variation of D_t in time according to (4). This factor depends on the type of cement used and the assumed time for cement hydration to continue to generate an increase in the impermeability of the concrete, known as T_{Hyd}.

$$\frac{\partial C_{(x,t)}}{\partial t} = \frac{\partial}{\partial x}\left(D_t \frac{\partial C_{(x,t)}}{\partial x}\right)$$

(1)

$$C_{(x,t)} = C_{Cr}$$

(2)

$$T_{\mathrm{i}} = \frac{x^2}{4D_t}\left(\frac{1}{\mathrm{erf}^{-1}\left(1 - \frac{C_{\mathrm{Cr}} - C_{\mathrm{o}}}{C_{\mathrm{S}} - C_{\mathrm{o}}}\right)}\right)^2$$

(3)

$$\begin{aligned} D_t &= D_o\left(\frac{t_o}{t}\right)^m \quad \text{para}\dagger \leq T_{\mathrm{Hyd}} \\ D_t &= D_o\left(\frac{t_o}{THyd}\right)^m \quad \text{para}\dagger > T_{\mathrm{Hyd}} \end{aligned}$$

(4)

where C (x, t) is the chloride concentration in depth and time, x is the coating thickness in mm, t is the time in years, t_o is the diffusion measurement time (28 days), D_o is the diffusion coefficient at 28 days (m^2/s), D_t is the diffusion coefficient in time (m^2/s), C_s is the surface concentration of chlorides, variable according to exposure severity condition, Cc_r is the critical concentration of chlorides (0.05% weight h) to initiate the corrosive process in steel, C_o is the initial concentration of chlorides contained in components, erf^{-1} is the inverse of the error function, m is the aging factor (reduction of diffusion over time) and T_{Hyd} is the duration of the aging effect on the reduction of diffusion (years).

Expressions (1) - (4) form the core of the best known models for predicting service life in cases of chloride-induced corrosion. While obtaining the specified pair of x and D_o values to achieve the design life T_i may seem trivial, the calculated values are extremely sensitive to the parameters C_s, C_{cr}, m, and T_{Hyd}. Determining the parameters C_s and C_{cr} is very difficult, and their relationship can affect T_i by a factor of 4. In addition, the validity of the diffusion decay function over time, as well as the proposed value for the exponent m, are subjects of much uncertainty and controversy. The effect of m on T_i can be dramatic, causing orders of magnitude changes in T_i and potentially resulting in unreasonably high values, especially when T_{Hyd} is not properly constrained.

Figure 4 shows the parameters involved in structural life design. Through their respective modeling, the distribution of chlorides at depth was calculated. In this example, from 10 to 120 years, it can be observed that, for a curve spanning approximately 100 years, it can be concluded that, at the depth of xc = 100 mm from the steel surface, the chloride concentration c (100, 100) is equal to the critical C_{cr}.

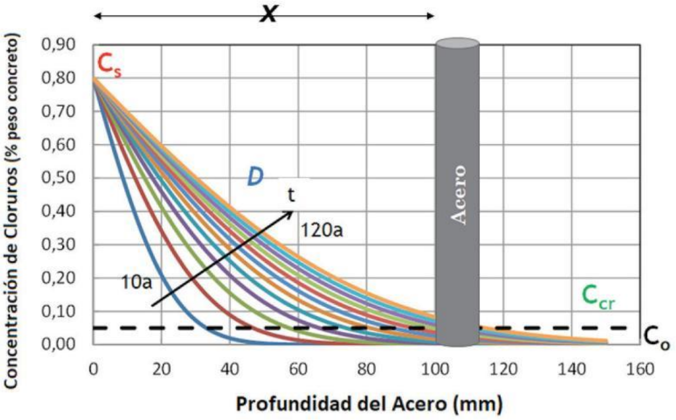
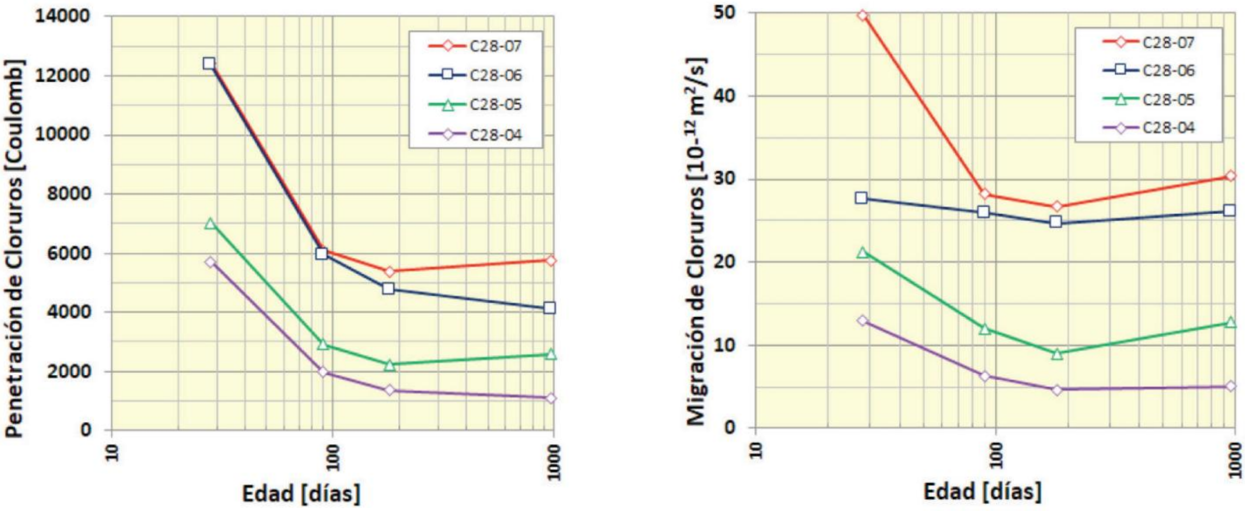


Figure 4. Schematic diagram showing the parameters for analysis of chloride ingress into concrete.

Recommendations vary widely. Life-365 (2012) proposes a T_{Hyd} value of 25 years, while the fib model (2006) extends T_{Hyd} to the entire T_i of the structure. Some experts more reasonably suggest a value of no more than 10 years and others recommend limiting it to one year or less. In the latter cases, the recommendation is based on the observation that after an appropriate curing period, there will be no substantial decrease in chloride permeability under in site conditions.

Due to the long-term nature of the index, the experimental determination of m is difficult. Therefore, it is impossible to use representative values of m and T_{Hyd} for calculation in the design life. Here, you can see the importance of conducting long-term testing in the aforementioned model elements. Li et al. (2015) provided a good example of how to use the information collected from these elements for evidence-based lifespan design. In Chile, there is limited experience on this topic. Ebensperger and Olivares (2019) demonstrated the experience of measuring chlorine diffusion through chlorine permeation Q and chlorine migration M tests, which lasted for up to 3 years. For different water contents and initial solidification, these two values remained unchanged from 180 days onwards, as shown in Figures 5a and 5b.



(a) Chloride penetration Q (b) Chloride migration M

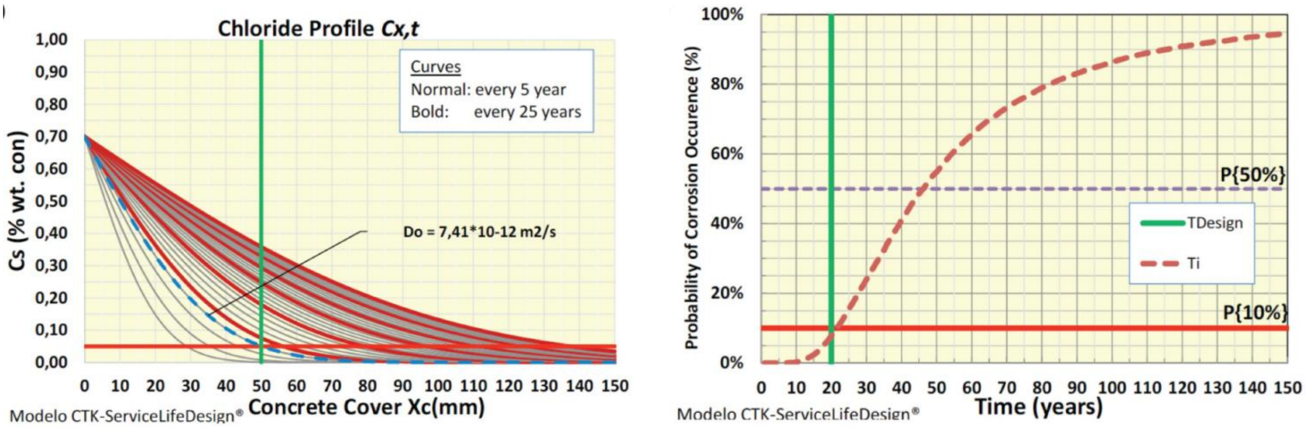
Figure 5. Decrease of Q and M values (increase of resistance to chloride ingress) with time.

In fact, when accurate information about the parameters of the equation shown cannot be obtained, designers must rely on the values proposed by the model, many of which are not results of experimental data, but mainly based on expert opinions. The selection of these parameters makes predictions very weak and makes subjective judgments easy to make.

To avoid time-consuming (12 weeks) immersion tests for D_o determination (ASTM C1556, 2016), the current trend is to replace them with one-day rapid chloride migration M tests (NT Build 492, 1999). In this test, an electrical differential is established between the faces of a concrete specimen, one of which is in contact with a NaCl solution. Due to this electric field, which greatly accelerates the process, chloride ions migrate from the cathode to the anode through the concrete specimen. This method conservatively assumes that the chloride migration coefficient $M = D_o$ (fib, 2006), although for some authors $M = 2D_o$ (Li et al., 2015).

One method to strengthen correlation analysis is to attribute certain statistical distributions to each factor in the equation. These distributions are also questionable speculations, as the central values of the distributions are uncertain, but through Monte Carlo simulation, they can provide a probability curve for corrosion to occur.

The CTK-Service Life Design® model developed in Chile for application in offshore structures is based on these concepts (construtechnik.cl), additionally incorporating the temperature parameter, based on the Duracon model (Gjørv, 2013; PIANC, 2016). Figure 6 shows an example of service life estimation using this model. This case involves submerged concrete structures located in the waters of the Strait of Magellan, with an average annual temperature of T = 7.4°C. The parameters used to obtain a useful life of VU = 20 years, apart from temperature, were taken from international experiences. These include C_s = 0.70% of concrete weight, C_{cr} = 0.05% of concrete weight, C_o = 0%, m = 0.45 for pozzolanic type cement, T_{Hyd} = 10 years, and x_c = 50 mm. In all cases, a normal distribution of the parameters was used, with a standard deviation of 10%



(a) Chloride concentration versus surface concrete thickness

(b) Corrosion probability versus time

Figure 6. Service life design for submerged concrete according to the CTK-Service Life Design® model.

Under these conditions, a concrete with a resistance to chloride ingress of $D_o = 7.4 \times 10^{-12}$ m^2/s, determined according to Fick's second law, is required (see Figure 6a). In this case, although the structure is located in a cold climate zone, it is not affected by freeze/thaw cycles due to being submerged. Figure 6b presents a probability analysis based on the Duracette model's recommendations (fib, 2006), estimating the likelihood of corrosion initiation (start time T_i) at the age of 20 to be 10%, with a reliability index of $\beta = 1.30$.

On the other hand, due to the need to consider various phenomena such as corrosion rate, electrical resistivity, O_2 supply function, and the occurrence and growth process of cracks in concrete, the modeling problem of T_P propagation time is more complex than the modeling problem of T_i.

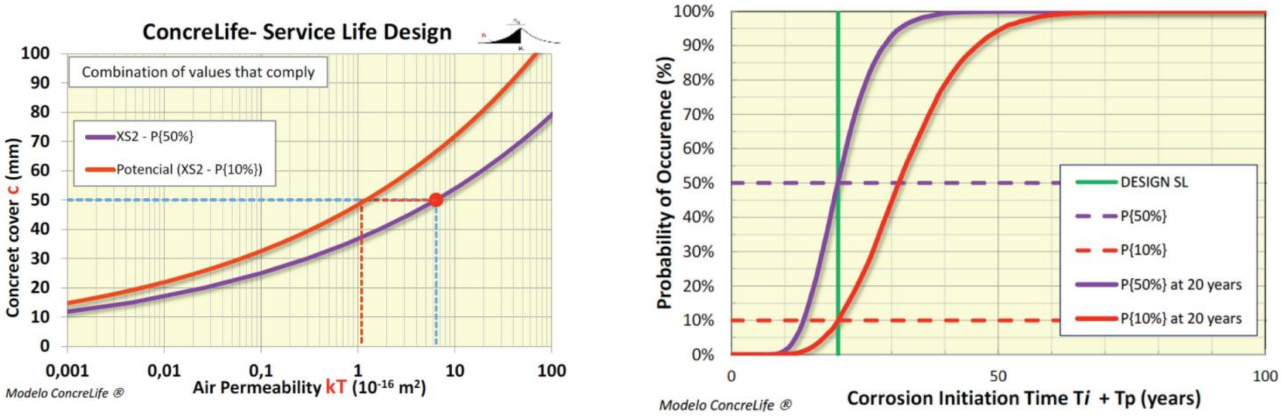
For structures affected by harsh environments such as tides and splash zones, it is acceptable to associate their lifespan with T_i, where T_P is relatively short: according to Life-365 (2012), 6 years. This is because the alternating wet and dry conditions ensure sufficient oxygen (O_2) and humidity supply to promote electrochemical reactions through concrete coatings. For less severe environments, especially corrosion caused by carbonization, the standard of Vu = T_i is too conservative, and the propagation time T_P must be considered.

2.4 Reference model based on air permeability

In the early 1990s, through two remote studies conducted by Torrent and Ebensperger (1993) and Torrent and Frenzer (1994), the development and first application of an END testing method capable of measuring air permeability coefficients on-site began. This innovative method has been incorporated into the Swiss standard SIA262/1 (2013) as a standardized on-site testing method and updated 10 years later, specifically aimed at providing recommendations and specifications for its on-site control.

The new reference method based on the Exp-Ref method described by Torrent et al. (2022) is simple but robust, and is based on correlations obtained from worldwide research results that have correlated chloride diffusion and CO_2 ingress to air permeability results. By considering the level of aggressiveness of the acting exposure, which is influenced by the thickness of the coating and the required design life, the required air permeability value of the surface concrete in as-built conditions is specified.

By analyzing the statistical distribution of different parameters mentioned above, including the actual concrete mixing conditions in the laboratory and on site, a more realistic service life value can be calculated using the CTK-ConcreLife® model (construtechnik.cl). The design module allows for analysis of different aggressive conditions exposed to the actuator, presenting results in graphical form. Additionally, it offers the possibility of predicting when the steel will start to corrode over time under different combinations of permeability and coating thickness (see Figures 7a and 7b).



(a) Surface concrete thickness versus air permeability

(b) Corrosion probability versus corrosion onset time

Figure 7. Design life for a submerged concrete according to the CTK-ConcreLife® model.

At this stage, it is necessary to develop a comprehensive experimental plan that includes guidelines on the characteristics of the mixture and the required durability performance, to be carried out by qualified testing laboratories. Ideally, mixtures proposed by interested concrete producers and materials planned for use during project construction, especially aggregate types, should be used. The suggestion proposed by the author was carried out by the Chilean Chagao Bridge Consortium, in which 24 concrete test mixtures were comprehensively characterized, including mechanical, rheological, thermal properties, and durability (including long-term testing), to improve the structural and durability design of the bridge structure that will cross the same named seawater channel.

2.5 Construction phase

During the construction phase, a strict concrete testing plan must be developed, which includes not only mechanical testing but also testing to provide durability performance indicators. The testing may last for a few minutes (resistivity and permeability), several hours (chloride penetration and migration), several weeks (pressure water penetration), or a few months (chloride immersion or diffusion test and resistance to ice/melt cycles). The correlation between short-term, medium-term, and long-term experiments established during the complete characterization of the mixture (design phase) can verify whether the concrete production process is controlled. Through this method, the concrete produced and delivered for pouring meets the specified requirements.

Quality control is mainly carried out on specimens made under laboratory conditions, and the quality of these specimens is usually higher than the quality obtained on site. Durability largely depends on the permeability of concrete coatings, which are coatings that protect steel. Poor concrete pouring behavior has been identified as an important factor in poor structural durability performance, as the harmful effects of such behavior on concrete coatings far outweigh their impact on the core of concrete components.

In fact, poor placement and compaction techniques, combined with a lack of curing (usually leading to larger microcracks), may result in air permeability 50 times higher than measured values in the same batch of cast samples and curing under laboratory conditions (Ebensperger and Olivares, 2017). Other factors include the variability of the conditions for handling concrete on the ground and the high variability of coating depth.

The only practical way to have a realistic assessment of the variability of the penetrability and thickness of the concrete coating is by non-destructive measurements (NDT) performed in site on the finished structure (Figure 8). It is therefore recommended that regular and extensive investigation of both the air permeability kT (SIA262/1, 2013) and the coating thickness Xc of concrete on the exposed surfaces of the various elements of a structure should be carried out. These measurements are incorporated in the in-site control module of the CTK-ConcreLife® model. Based on the results of this quality control (laboratory and on-site), compliance with breathability requirements and service life prediction was reviewed.

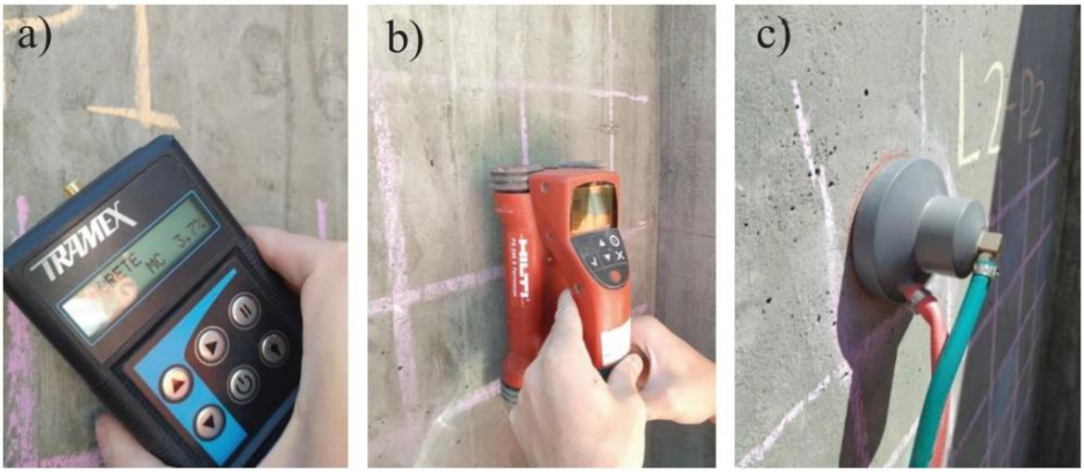


Figure 8. Examples of application of nondestructive testing for service life control with the CTK-ConcreLife® model (construtechnik.cl), a) concrete moisture, b) reinforcement verification and c) air permeability of concrete.

On the other hand, there are electromagnetic instruments or GPR technology (radar-type wave penetration) capable of non-destructively and accurately assessing the depth of the coating in accordance with current standards (BS1881, 1988).

2.6 Commissioning and delivery phase

All information collected during the design and construction phases should be compiled in a maintenance report and manual. An important aspect in this phase is the generation of a Birth Certificate which, according to the model code (fib, 2010), should provide specific details on parameters important for the durability and service life of the reinforced concrete structure, either as a consequence of its degree of exposure (poorly considered assumptions) or its characteristics and properties (steel coating, concrete permeability and quality of workmanship achieved).

The areas of the structure detected as most vulnerable, i.e. those showing higher in-site air permeability and/or lower overburden depths, should be identified in the report, focusing the attention of the engineers responsible for the maintenance plans.

The results of the expected service life analysis calculated using the CTK-ConcreLife® method can facilitate maintenance planning, which should be incorporated in the maintenance manual. This manual details the actions to be carried out during the service life of the structure in order to prevent deterioration as early as possible and to remedy it in a timely manner. Both documents are of vital importance for successive generations of engineers in charge of the surveillance and maintenance of structures that must last for several decades.

2.7 Operational phase

The maintenance plan should include monitoring the long-term performance of engineering structural elements and models, which are carried out under the same conditions as the structural elements. The monitoring system can include integrated sensors, application of ND diagnostic testing, and obtaining chloride profiles from signals extracted from the model.

These measures are crucial for assessing and improving the accuracy of the predictive models used in the design process, as they serve as calibration reference points. These measurements can be used to evaluate the future performance of actual structures and estimate their remaining lifespan.

The study of structural temporal behavior can be reflected in Figure 9, which is an adaptation of ISO16311 (2014). For natural aging conditions, they gradually deteriorate with age, leading to a decrease in expected performance levels (central red curve). Based on the observed aggressiveness or degree of damage on the structure, diagnosis after a reasonable time will help determine whether the actual performance of the structure is consistent with the design performance: the yellow curve on the left indicates lower performance.

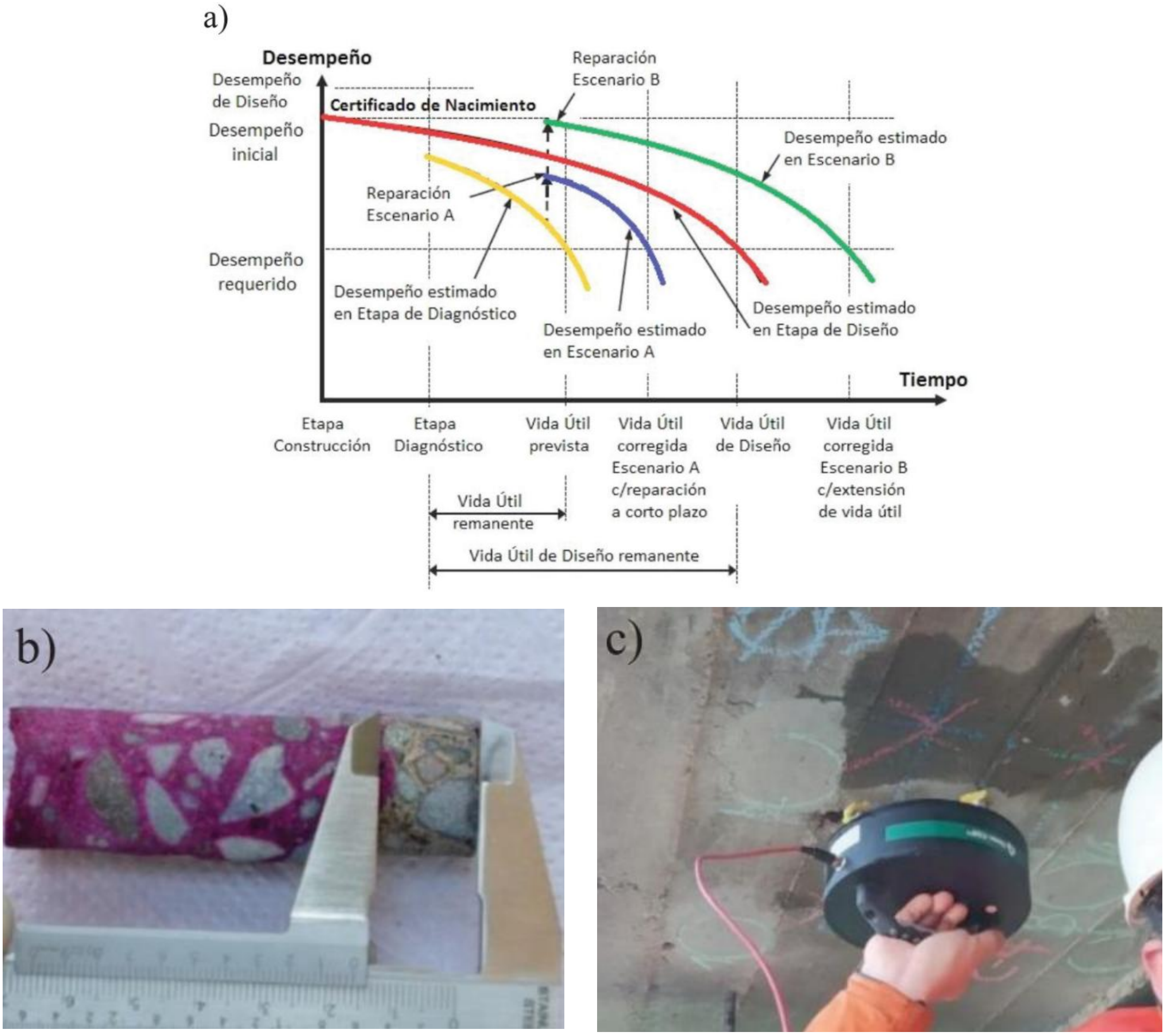


Figure 9. a) Definitions of serviceability level (performance) of a structure over time (ISO16311, 2014), b) NDT measurements of carbonation and chloride ingress and c) level of reinforcement corrosion.

If no action is taken, the remaining useful life is drastically reduced (crossing of the red and yellow curves with the required performance level) and it is necessary to carry out maintenance work, which can be partial (scenario A blue curve) or exhaustive (scenario B green curve, with higher cost). In the first case, the remaining useful life is increased, but remains below the design life. Scenario B, on the other hand, even allows extending the original design life. The initial performance condition can be determined by performing tests on the finished work, which are included in the birth certificate of the structure.

The execution of diagnostics to determine the real condition of existing structures is essential to support the decision making process regarding their conservation and maintenance over time, and also to determine their residual or remaining life. It is worth mentioning in this aspect the SIDDE® methodology based on a series of non-destructive tests that allow the estimation of residual life according to in site measurements of air permeability, coating thickness, corrosion levels (speed and potential together with electrical resistivity), colorimetric entry of carbonation and chlorides, and resistance estimations (construtechnik.cl).

3. Concluding Comments

Traditional specification based durability design methods have been proven to be insufficient to ensure the expected lifespan of structures exposed to corrosion. The application of existing models is difficult for civil engineers because it requires defining key parameters, which is difficult even for experts to determine. Most models are based on laboratory test results of specimens, which do not reflect the actual durability of engineering structures. Only when everyone involved in the concrete construction chain recognizes the challenges and strives to build high-quality structures, can projects exposed to corrosive environments have a longer service life. A comprehensive approach has been proposed, including measures to be taken before, during, and after structural construction. It emphasizes the quality of the final product, the quality of concrete mixtures, and on-site practices, all of which must be appropriately controlled. This includes experience in designing and controlling using models developed by the country on the durability of reinforced concrete.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] ASTM C1556. 2016. Standard test method for determining the apparent chloride diffusion coefficient of cementitious mixtures by bulk diffusion. ASTM International, West Conshohocken, PA, USA.

[2] BS1881. 1988. Testing concrete. Part 204 - Recommendations on the use of electromagnetic covermeters. British Standards Institutions, Milton Keynes, UK.

[3] Di Pace, G., Ebensperger, L., Torrent, R. and Bueno, V. 2019. From cradle to maturity: a holistic service-life approach for concrete bridges. *Concrete International*, 41(4): 47-54.

[4] Ebensperger, L. y Olivares, M. 2019. Envejecimiento a mediano plazo de probetas: factor incidente en las estimaciones de vida útil. XV Congreso Latinoamericano de Patología de la Construcción y XVII Congreso de Control de Calidad en la Construcción, CONPAT 2019, Chiapas, México.

[5] Ebensperger, L. y Olivares, M. 2017. Especificación y control de durabilidad del hormigón in site con ensayos no-destructivos: metodología integral de estimación de vida útil con mediciones de permeabilidad al aire y espesor de recubrimiento. Presentación en el Segundo Congreso Internacional de Puentes, Dirección de Vialidad, Santiago, Chile.

[6] EN. 2004. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. European Standard EN 1992-1-1, Brussels, Belgium.

[7] fib. 2010. Model code 2010 - Final draft, v.1. Féderation Internationale du Béton, Lausanne, Switzerland.

[8] fib. 2006. Modelo duracrete. fib Bulletin 34. Féderation Internationale du Béton, Lausanne, Switzerland.

[9] Gjørv, O.E. 2013. Durability design of concrete structures in severe environments. CRC Press, USA.

[10] ISO16311. 2014. Maintenance and repair of concrete structures - Part 1: General principles. Geneva, Switzerland.

[11] Li, Q., Li, K., Zhou, X., Zhang, Q. and Fan, Z. 2015. Model-based durability design of concrete structures in Hong Kong-Zhuhai-Macau sea link project. *Structural Safety*, 53: 1-12.

[12] Life-365. 2012. Service life prediction model TM and computer program for predicting the service life and life-cycle cost of reinforced concrete exposed to chlorides. Life-365 Consortium II.

[13] NCh170. 2016. Hormigón - requisitos generales. Instituto Nacional de Normalización INN, Santiago, Chile.

[14] NTBuild492. 1999. Concrete, mortar and cement-based repair materials: chloride migration coefficient from non-steady-state migration experiments. Nordtest, Espoo, Finland.

[15] Oberreuter, R. 2022. Infraestructura costera y portuaria en Chile: desafíos para su desarrollo. *Hormigón al Día*, 78: 30-33.

[16] PIANC. 2016. Recommendations for increased durability and service life of new marine concrete infrastructure. Report N°162, Brussels, Belgium.

[17] Repetto, F., Boré, G., Eliceiry, M., Sabaini, S. and Covarrubias, M. 2019. An innovative approach for corrosion control to enable asset management of steel elements in coastal infrastructure. *Obras y Proyectos*, 26: 37-42.

[18] SIA 262/1. 2013. Betonbau - Ergänzende Festlegungen (Concrete structures - supplementary specifications). Swiss Society of Engineers and Architects SIA, Zurich, Switzerland.

[19] Torrent, R. and Frenzer, G. 1995. Study on methods to measure and evaluate the characteristics of the cover concrete on site - Part II. Report N° 516, Swiss Federal Highways Office, Bern, Switzerland.

[20] Torrent, R. and Ebensperger, L. 1993. Study on methods to measure and evaluate the characteristics of the cover concrete on site. Report N° 506, Swiss Federal Highways Office, Bern, Switzerland.

[21] Torrent, R.J., Neves, R.D. and Imamoto, K. 2022. Concrete permeability and durability performance: from theory to field applications. CRC Press, USA.

[22] Tuutti, K. 1982. Corrosion of steel in concrete. Research Report 4.82, Swedish Cement and Concrete Research Institute CBI, Stockholm, Sweden.