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Statistical investigation of different analysis methods for chloride profiles within a real structure in a marine environment

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ABSTRACT

Corrosion is a major problem for durability of reinforced concrete structures in a marine environment. To establish the best accurate planning for maintenance operations, assessing chloride ingress within concrete is essential. The present paper reports a study conducted to investigate a large amount of field chloride data collected from a 28-years old beam in a splash zone. The chloride profiles are examined based on Fick's second law to estimate the surface content C_s and the diffusion coefficient D. Firstly, three different cases considering the location of the maximum chloride content are tested: a reference case (individual analysis), a 15-mm discarded case and a 20-mm discarded case (generic treatments). The results highlight the importance of the individual analysis. C_s and D, indeed, appear to be significantly affected by the generic treatment, the relative error being around 50% for C_s and 100% for D. A focus is therefore placed on the individual analysis. The coefficients of variation are 44% and 61% for C_s and D, respectively. For the statistical distribution, both parameters show a clear dependence. They also follow a lognormal law with a mean value ranging between 0.0057 and 0.0085 $\mathrm{kg_{Cl^-}/kg_{concrete}}$ for C_s and equal to $1.3 \times 10^{-12}\ \mathrm{m^2/s}$ for D.

1. Introduction

Chloride penetration into concrete can cause irreversible damage within reinforced concrete structures, predominantly corrosion damage, when chloride content at the surface of reinforcement bars reaches a certain threshold level. Steel corrosion initiation is then a key indicator for the estimation of service life. The risk of corrosion damage is higher in a marine environment because of significant humidity and chloride contents in both seawater and air. Consequently, the corrosion of engineering structures is more severe in coastal areas than inland locations (Guo et al., 2015). Chloride profile analysis, is, therefore, an important tool for service life predictions of structures and inspection/maintenance/repair action scheduling (Bastidas-Arteaga et al., 2011; de Rincón et al., 2004). Recent studies have highlighted the spatial variability of chloride-induced reinforced concrete corrosion with an impact on infrastructure network maintenance optimization (O'Connor and Kenshel, 2013). In the following, the focus is on total chloride content because, firstly, measurement methodology is not subject to debate (Bonnet et al., 2017) and, secondly, because it is the key parameter for already available maintenance optimization methods.

Chloride profile analysis is therefore essential. Profiles are better assessed when different factors like concrete properties (Tadayon et al., 2016) and period of exposure (Mangat and Molloy, 1994; Tamimi et al., 2008) are taken into account. Exposure (above sea level: atmospheric and splashing zones, and under sea level: tidal and immersed zones) and environmental conditions (temperature, relative humidity, wind, orientation …) are also important factors in affecting the durability of concrete and in shortening the life span of structures. Many studies have shown that tidal and splash zones drive the most severe conditions as regards chloride ingress and steel corrosion of concrete in comparison with atmosphere and immersed zones (Valipour et al., 2013). Li and Shao (2014) conclude that immersed zones allow for a service life 1.6 to 3.9 times longer than splash zones, whatever the binding isotherm considered. Furthermore, in marine exposure conditions, chloride ions can penetrate into concrete through multiple mechanisms including diffusion, adsorption, permeation and surface deposit of airborne salts (Hilsdorf and Kropp, 2004). Although chloride ingress within concrete involves many mechanisms, it is widely accepted that diffusion is the primary mechanism (Pang and Li, 2016). Hence, chloride ingress can be modelled by the empirical Fick's diffusion model. Besides, The Fick's model is used by engineers and researchers to deal with in situ data (see references on Table 1) and recommended by codes like Fédération

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Table 1

Peak values of total[b] chloride content and diffusion coefficient of concrete structures and specimens exposed to a marine environment.

Reference	Structure	Exposure conditions	Construction period	Investigation period (year)	Number of samples	Peak position[a] (mm)	C_{peak} [a] kg/kg	D [a] 10^{-12} m^2/s
(de Rincón et al., 2004)	Bridge pier bridge	Above the sea level	1962–1963 1938 1986	33 64 11	–	Around 20-30 0	0.0028 0.0025 0.0018	–
(da Costa et al., 2013).	Offshore oil platform	Wetting drying cycles		25	35	Around 10-20	0.0029: 0.0051	0.27: 1.6
(Chalee et al., 2009)	Cube specimens (in sea water)	Two wet dry cycles of sea water daily	–	5	–	0 mm	0.013	1.65
(Pang and Li, 2016)	Pile wharf structure	splash zone	between 1971 and 2008	36	8/pile 14 piles tested	Between 0 and 10	0.0046	0.35
(Medeiros-Junior et al., 2015)	Offshore platform	splash zone	1976	29	3 layers/point of investigation	10	0.007	5.13
(Thomas and Matthews, 2004)	Cube specimens (in sea water)	Tidal zone	–	1, 2 and 10	–	around 7.5–10	0.0038: 0.006	–
(Pritzl et al., 2015)	Deck bridge	deicing salt environment	Between 1992 and 1995	16	4 locations	10	0.0059	2
(Tadayon et al., 2016)	Cube specimens (in sea water)	Tidal zone	–	4.17 (=50 months)	–	2.5	0.006:0.0091	2:4.2
(Cramer et al., 2002)	bridge	Marine breeze	–	40 to 60	–	–	0.0073: 0.003	0.41: 1.71
(Kenshel, 2009)	pier	Atmospheric zone	1980	27	45	Between 10 and 25 mm	0.0004: 0.0013	0.098: 0.72

[a] Peak position is the position within the sample where the maximum chloride content (C_{peak}) is measured. When information are missing to convert C and D into kg/kg and m^2/s, respectively, we considered Cement concentration = 350 kg/m^3 and concrete bulk density = 2500 kg/m^3.

[b] Except for Medeiros-Junior et al., 2015 where only free chloride content is measured.

International du Béton (2006) for its simplicity and its capacity of being adapted to different exposure cases.

Indeed, a comparison of an oversimplified model to an improved model shows that both yields to similar results (Nguyen et al., 2017) and fairly well predict the chloride ingress in a Portland cement (up to 100 years) (Luping and Gulikers, 2007). Moreover, a long-term monitoring on real concrete structures exposed to environmental conditions makes the empirical Fick's model adapted for durability design (Li et al., 2015).

Then, many studies have been devoted to the measurement of chloride ingress within real structures like decks, piles, offshore platform or concrete specimens, in a marine environment with different exposure conditions (Table 1). The chloride profiles obtained (often) have the shape of a bell with a chloride content, which increases from the concrete surface to a certain depth where a maximum content, noted C_{peak} in Table 1, is reached and then decreases as depth increases. This is accounted for by (Andrade et al., 1997) as "concrete surface skin effect". In the studies reported in Table 1, the approach commonly used to estimate both surface content C_s and diffusion coefficient D come from the fitting of the Fick's second law to in-situ values of experimental chloride profiles. This regression beginning at C_{peak} provides C_s and D simultaneously.

It should be noted that the value of C_{peak} varies from 0.0014 $kg_{Cl-}/kg_{concrete}$ (Pang and Li, 2016) to 0.013 $kg_{Cl}/kg_{concrete}$ (Chalee et al., 2009). C_{peak} can also start at 0 mm (Chalee et al., 2009; de Rincón et al., 2004), around 10 mm (Medeiros-Junior et al., 2015; Pang and Li, 2016; Thomas and Matthews, 2004), and at 20 mm or 30 mm (de Rincón et al., 2004). The depth may vary in relation to concrete quality, exposure conditions and structure orientation. Some values of D obtained vary between 0.27×10^{-12} m^2/s (da Costa et al., 2013) and 5.13×10^{-12} m^2/s (Medeiros-Junior et al., 2015)

Among key parameters and phenomena (quality of concrete, exposure conditions and orientation) affecting structure service life, exposure conditions are the focus of this research. The present paper, indeed, reports the experimental investigation carried out on a 28-years old beam made from the same concrete composition and on which all the chloride profiles are measured on the same horizontal line (coring is performed on the same line along the beam). Moreover, the studied beam is located in a splash zone influenced by two local microclimates (both beam exposures are detailed in §2.1). The present study also provides a significant number of chloride profiles in accordance with (Medeiros-Junior et al., 2015), who underline the significance of the number of samples as a direct benefit to achieve precise statements. Furthermore, De Vera. et al. (2015) highlighted that to assign reliable values for C_S it is only possible on the basis of experimental chloride profiles obtained with the similar concrete composition and in similar locations. As for *D,* the sensitivity analysis realised by Li et al. (2009) shows that the achieved reliability of design is rather sensitive to the mean of D values as well as the cover thickness. It is thus necessary to evaluate D accurately.

These data form a substantial high value data base to improve the scientific documented knowledge library for concrete subject to XS3 class environmental exposure according to the NF EN 206-1 standard. The objective of this research is to address the problem of the determination of C_s that usually results from the chloride content reduction at the concrete surface (Song et al., 2008). So, the variation of the position where C_{peak} is measured appears to constitute a possible alternative route for study.

Thus, this paper provides an important data base of chloride measurements done on the same beam with reduced settings like concrete composition, location, marine environment and tidal height that were all the same for 30 core samples. Indeed, approximately 600 chloride measurements were carried out to highlight the observations and comments done hereafter. On a comparable data, it is possible, on the one hand, to underline the variability of the raw data of chloride profiles and, on the other hand, the variability of C_s and D along the beam once the raw data was processed by Fick's second law solution. This work, as far as we know, has never been done on so many data.

Since very numerous comparable data are available it led us to review the generic treatment used by some authors to deal with chloride profiles to determine C_s and D (Chalee et al., 2009; da Costa et al., 2013; Pang and Li, 2016). This treatment was compared to the individual treatment called reference case in this paper which is more time consuming than the previous treatment.

Accordingly, the paper is structured as follows:

- Experimental investigation of the studied structure.
- Experimental chloride profile fitting methodology based on three sets of analyses depending on the chloride maximum content position and using Fick's second law to assess C_s and D.