

# Measuring critical chloride contents in structures and the influence on service life modeling

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**ABSTRACT:** While knowledge of mechanical properties of a specific structure is considered relevant for structural considerations, there exists currently no generally accepted method to assess the ability of a structure to withstand corrosion. An important parameter in this regard is the critical chloride content ( $C_{\text{crit}}$ ). Due to the lack of a reliable method to determine  $C_{\text{crit}}$ , this value is typically looked up in standards and text books. This paper presents a novel method that allows the determination of  $C_{\text{crit}}$  for individual engineering structures and reduces therefore current uncertainties in condition assessments. This is considered a particular advantage because of 1) the difficulties associated with mimicking real conditions in laboratory specimens, and 2) the lack of knowledge of the relevant parameters for corrosion initiation. First results from a structure are reported and their influence on the assessment of the remaining time to corrosion in existing structures is discussed.

## 1 INTRODUCTION

Being one of the major challenges in civil engineering, chloride-induced corrosion causes annually a high amount of repair cost (estimated for infrastructure: US\$ 22.6 billion (Koch et al., 2002)). Due to the continuous aging of infrastructure in the industrialized countries, these costs will continuously increase. This urges to develop methods to assess reliably the condition of corrosion.

The current established approach in engineering typically relies on a number of destructive and non-destructive tests, which aims at assessing e.g. cover depth, chloride profiles, transport coefficients (e.g. diffusion and migration tests). The chloride profiles are then compared to the so-called critical chloride content ( $C_{\text{crit}}$ ) to decide about maintenance strategies. This value defines, whether or not corrosion initiates and is given in standards and text books (SIA, 2011, fib, 2006), based on empirical experience. For instance, based on the results of Breit (Breit, 1997), the fib model code (fib, 2006) defined a statistical distribution function for  $C_{\text{crit}}$ .

Analogous to determining the compressive strength of concrete of a specific structure, also  $C_{\text{crit}}$  should be determined for a specific structure or part of it. In this paper we present the results of site-specific  $C_{\text{crit}}$  values. Based on these values the time to corrosion initiation can be determined more reliably compared to  $C_{\text{crit}}$  data in text books and codes. The significant influence of  $C_{\text{crit}}$  on service life pre-

diction was also shown in (Markeset and Kioumars, 2017).

This enables engineers to base their condition assessment on more applicable  $C_{\text{crit}}$  and leads therefore to less expensive maintenance strategies. This contribution highlights the main benefits for the remaining service life determination by measuring the  $C_{\text{crit}}$  for each structure.

## 2 MATERIALS & METHODS

### 2.1 General

A detailed description of the method including a video can be found in (Angst et al., 2017). For this work, a 35-year-old reinforced concrete tunnel structure in the Swiss Alps was investigated, shown in Figure 1. As it was common at this time in Switzerland, CEM I was used for construction. During winter season the structure is exposed heavily to de-icing salts (exposure class XD3). With its length of 391 m, the structure is divided in 16 elements that were cast in several phases. Two adjacent elements (labelled with A & B) of the sidewall were investigated. Due to the production and casting process on site the elements showed different properties, e.g. cover depth, concrete resistivity  $\rho$ , and carbonation depth. Table 1 lists details about the structure.

Table 1. Investigated structure (built in 1982).

Element	Cover [mm]		Resistivity $\rho$ [ $\Omega\text{m}$ ]		carb. depth [mm]	
	mean	SD	mean	SD	mean	SD
A	27	5	479	164	22	6
B	36	9	621	186	max. 18	7

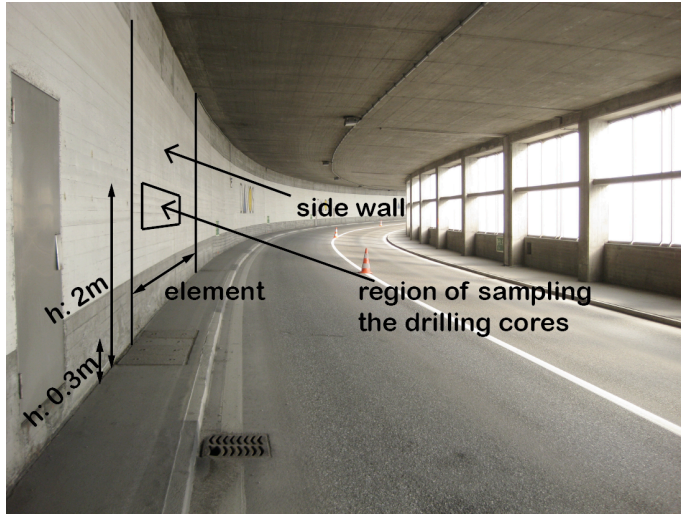


Figure 1. Road Tunnel on a cantonal road close to Davos (CH). The drilling cores were taken from a height of 1.5-2 m (not yet corroding). The time to corrosion initiation was calculated for the height of 0.3 and 2 m.

## 2.2 Sampling from structures

From the walls of two elements, six drilling cores (diameter = 150 mm), containing each one a centrally located reinforcement steel, were extracted from a height of 1.5 to 2 m. The reinforcement was not (yet) corroding in the region of sampling, which was previously tested with potential measurements.

## 2.3 Preparation of drilling cores for laboratory testing

To prepare the drilling cores, the cover depth was reduced to 15-20 mm. By removing partly the concrete at the steel bar ends and refilling this part with a highly alkaline and dense mortar, the steel was protected against corrosion on the side faces. Before covering the steel bar ends with this mortar, a durable connection to the steel was made by a self-tapping screw and cable-lug.

To guarantee uniaxial ingress of chlorides, the lateral faces were coated, as well as the end parts of the exposed surface. The exposed length was 60 mm (Fig. 2).

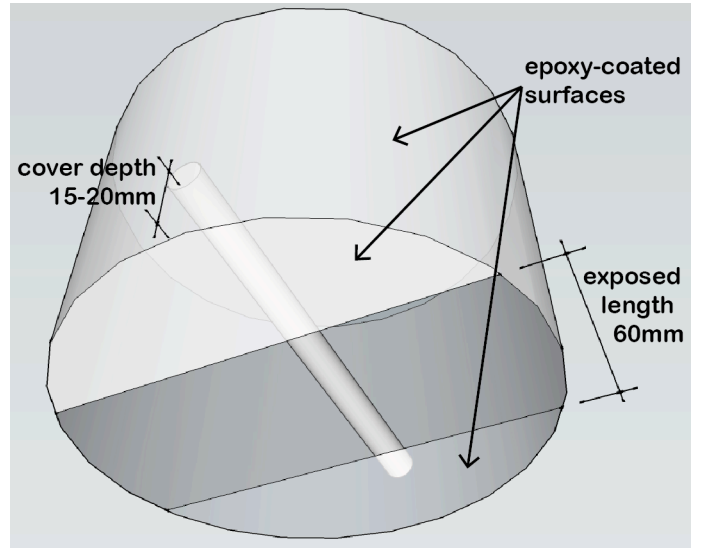


Figure 2. Prepared drilling core for lab exposure.

## 2.4 Corrosion test

Thereafter, the specimens were connected to a data logger to continuously measure the steel potential versus an external reference electrode ( $\text{Ag}/\text{AgCl}_{\text{sat}}$ ) and exposed to water for one week (Fig. 3). Subsequently, the chloride concentration in the exposure solution was increased to 3.5 M-% of NaCl. If corrosion had not initiated within two months, the chloride content was further increased (stepwise to max. 10 M-% NaCl).

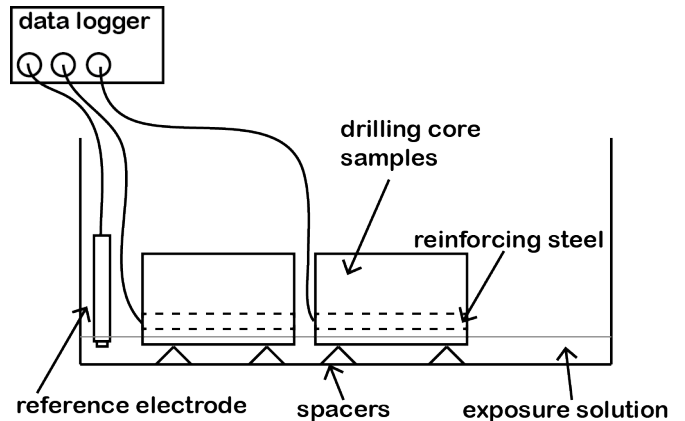


Figure 3. Lab exposure and connection to data logger.

The specimens were exposed until corrosion initiation was detected, which was defined according to the following two criteria: 1) the potential drops for at least 150 mV within 24 hours and 2) remains stable at this more negative value (or decreases further) for 7 d.

## 2.5 Sampling of chloride content

After corrosion initiation, the drilling cores were removed from the solution and split to extract concrete powder at the level of reinforcement to determine  $C_{\text{crit}}$ . Additionally, a visual inspection of the

steel-concrete interface (SCI) was conducted to identify possible defects at the SCI.

The chloride content in the concrete powder was determined according to the Swiss Standards (SIA, 2007), i.e. potentiometric titration with 0.1M silver nitrate-solution.

## 2.6 Calculations

The obtained  $C_{crit}$  were plotted as cumulative probability curves and fitted with the beta distribution. The probability density function (PDF) is equal to:

$$PDF = \frac{x^{\alpha-1} \times (1-x)^{\beta-1}}{\frac{\Gamma(\alpha) \times \Gamma(\beta)}{\Gamma(\alpha+\beta)}} \quad (3)$$

where  $\Gamma(z)$  is the gamma function.

For comparison, data from the literature was also considered, that is: (fib, 2006) and (Angst et al., 2016). The statistical distribution given in (Markeset, 2009), gained from a field study in Norway, are not depicted in Figure 4, as the lognormal distribution is similar to the fib model code (fib, 2006), with a slightly higher mean value. Additionally, the data by Markeset was not obtained on reinforcing steel bars, but on steel rings (machined surface) placed in drilling holes in existing structures, which leads to conditions at the steel-concrete interface different from rebars directly cast in concrete.

The remaining time to corrosion initiation was determined by modelling chloride ingress at a height of 0.3 m and 2 m respectively. The chloride ingress was calculated for each element by the error-function (solution of Fick's 2<sup>nd</sup> law):

$$C(x, t) = C_s \times \left( 1 - erf \left( \frac{x}{2 \times \sqrt{D \times t}} \right) \right) \quad (1)$$

where  $C_s$  is the chloride concentration at the surface,  $x$  the cover depth,  $D$  the diffusion coefficient, and  $t$  the time.

$C_s$  for both heights (0.3 and 2 m) was averaged and fitted (Tab. 2) with measured chloride profiles of the structure. All other parameters were assumed constant for both heights, but different for the two elements.

Table 2. Parameter  $C_s$  for two different heights.

Height	$C_s$
m	% by cem.wt.
0.3	1.1
2	0.3

The diffusion coefficient  $D$  was estimated from the measured concrete resistivity  $\rho$  (Tab. 1) with

$$D = \frac{k}{\rho} \quad (2)$$

The constant  $k$  is a material parameter (Tab. 3), which was here averaged over several studies (Liu et al., 2015, Sengul and Gjrrv, 2008, Andrade et al., 2014, Polder and Peelen, 2002, Torabian Isfahani et al., 2016). For the model calculations in this paper, the mean value was taken. These were found to be in agreement with  $k$  estimated based on profile fitting, i.e. fitting measured chloride profiles with eq. (1) and assuming  $D$  as time dependent.

Table 3. Parameter  $k$  (averaged over several studies) and calculated diffusion coefficient  $D$ .

Value	$k$	$D$ (El. A)	$D$ (El. B)
	$10^{-9} \Omega m^3/s$	$10^{-12} m^2/s$	$10^{-12} m^2/s$
MIN	0.2	0.3	0.2
MAX	2.1	4.4	3.4
MEAN	1.0	2.0	1.6

## 3 RESULTS

### 3.1 Critical chloride contents for structures

The obtained distribution of  $C_{crit}$  for each element is given in Figure 4, revealing a strong dependency on the element. For element A it has to be considered, that the three lowest  $C_{crit}$  values were obtained on cores where the concrete already was carbonated at the level of reinforcement (determine with phenolphthalein spray test).

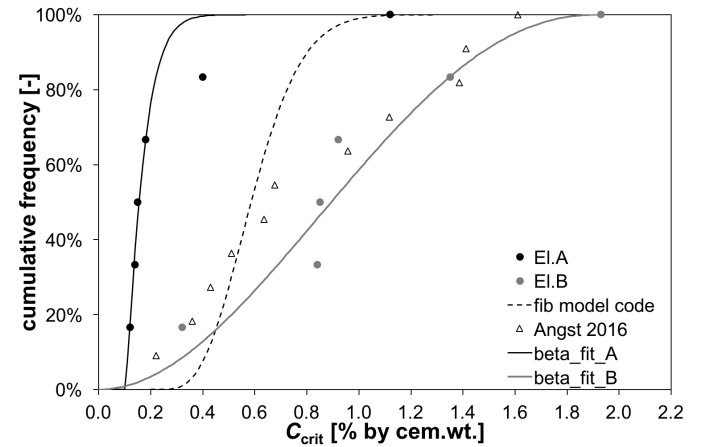


Figure 4.  $C_{crit}$  distribution of the investigated structure, compared to  $C_{crit}$ -distribution of (fib, 2006) and (Angst et al., 2016).

The fitted parameters of the beta-distribution are given in Table 4.

Table 4. Beta-distribution parameter.

Parameter	fib	El. A	El. B
$\alpha$	5.3	1.1	2.1
$\beta$	18.6	28.0	2.3
a (low. lim.)	0.2	0.1	0.0
b (up. lim.)	2.0	2.1	1.9
mean	0.6	0.2	0.9
SD	0.15	0.1	0.4

From Figure 4 it is apparent, that the  $C_{crit}$ -distribution is clearly dependent on the specific element under test. Factors such as concrete quality, cover depth, and carbonation depth might influence  $C_{crit}$ . The distribution of the fib model code (fib, 2006) lies in between both elements and tends to overestimate the lower  $C_{crit}$  of all elements and to underestimate the higher  $C_{crit}$  of element B. The standard deviation (Tab. 4) for element A is much smaller (and similar to (fib, 2006)) than for element B, but the mean (Tab. 4) is also much lower than element B or (fib, 2006).

### 3.2 Remaining time to corrosion

Figure 5 depicts the chloride content vs. time as calculated with equation 1. The parameters cover depth  $x$  and diffusion coefficient  $D$  are taken identical for both heights 0.3 m and 2 m, but different for elements A and B (Tab. 1, Tab. 3). The chloride concentration at the surface  $C_s$  was taken identical for both elements A and B but different for the height 0.3 m and 2 m (Tab. 2). The results show high chloride contents at the height 0.3 m, at a height of 2 m the chloride content reaches about 0.2% after 100 years. Assuming a constant  $C_{crit}$  of 0.4% by cement weight according to the Swiss Standard (SIA, 2011), both elements start corroding early (<20 y) at a height of 0.3 m, whereas at a height of 2 m the  $C_{crit}$  will not be reached for both elements within the next 100 years.

Note that no age factor has been applied to the apparent diffusion coefficient as usually done for long-term service life predictions (Bertolini et al., 2013, Markeset, 2009). An age factor of 0.5 has been shown to markedly reduce the probability of corrosion compared to a constant  $D$  (Markeset and Kioumarsi, 2017). However, introducing an age factor will not affect the conclusions that can be drawn from this study.

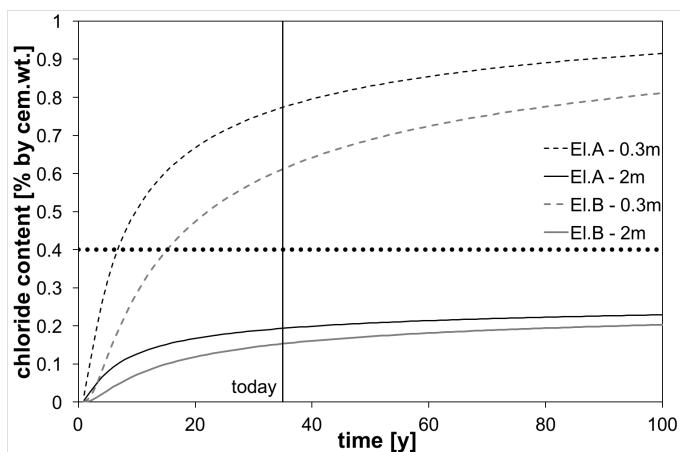


Figure 5. Modelling chloride content over time for both elements (Black: El. A, Gray: El. B) at two different heights (Dashed: 0.3 m, solid: 2 m). The dotted line depicts the lower limit of  $C_{crit}$  according to (SIA, 2011).

From Figure 5 the chloride content as a function of time,  $Cl(t)$ , is obtained for both elements A and B and heights 0.3 m and 2 m. With  $Cl(t)$  as x-value in the distribution of  $C_{crit}$  (Fig. 4) that is markedly different for element A and B, the probability to initiation of corrosion can be calculated (Fig. 6). It is obvious that the time to corrosion initiation of element A (at both heights) is much shorter. Even at a height of 2 m, element A has today (35 years) a probability for corrosion initiation of approx. 70%.

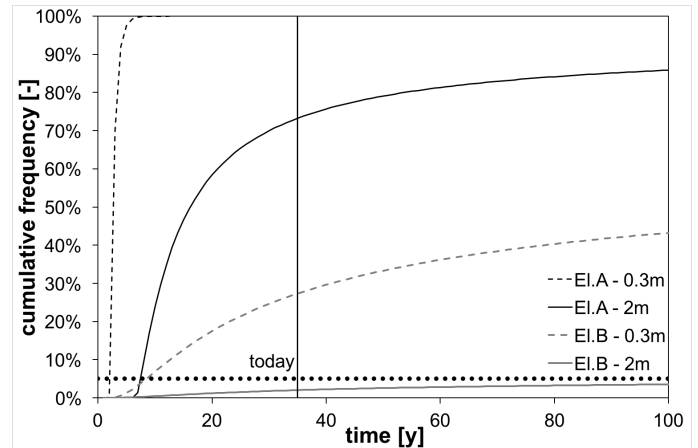


Figure 6. Probability of corrosion initiation for both elements (Black: El. A, Gray: El. B) at two different heights (Dashed: 0.3 m, solid: 2 m). The dotted line depicts the 5% probability of corrosion initiation.

In contrast, element B has a low probability for corrosion initiation at 0.3 m (ca. 25%) and will not initiate at a height of 2 m within the next 100 years (not even when choosing a low probability of 5% for corrosion initiation). This calculated remaining time to corrosion initiation is in line with the detected time to corrosion initiation in the laboratory experiment: in element A with calculated time to initiation of less than 10 years (Fig. 6), 5 out of 6 drilling cores initiated immediately after placing them in water. In element B with a calculated time to initiation at height of 2 m of more than 100 years, 5 out of 6 drilling cores from that height were not initiating with the chloride content already present in the drilling cores (approx. 0.3% by cem.wt.).

## 4 DISCUSSION

The results obtained from this field study show that the crucial parameter to calculate the remaining service life of a reinforced concrete structure is the critical chloride content  $C_{crit}$ . The concrete quality (in terms of the diffusion coefficient  $D$ ), the cover depth  $x$  and the surface chloride concentration  $C_s$  (eq. 1) are less important, as was shown in earlier discussions (Boubitsas and Tang, 2015, Glass, 2006, Mohammed et al., 2002).

#### 4.1 Influence of transport parameters

As the elements A and B of the tunnel under study were cast in two different phases, the concrete quality (Tab. 3) and cover depth (Tab. 1) are different. The diffusion coefficient for element A is higher, resulting in faster chloride ingress in element A at both heights (Fig. 5). As also the cover depth  $x$  for element A is lower, corrosion will initiate earlier in element A. The lower concrete quality in element A leads (at least at height 2 m where the concrete is often dry) to a carbonation front closer to the reinforcement level in element A than in element B (Tab. 1).

#### 4.2 Influence of the critical chloride content

$C_{crit}$  is influenced by the conditions at the SCI and by the pH of the pore solution at the reinforcement (Angst et al., 2009). Both, the SCI and the pH might change with concrete quality, thus be different for element A and B. Indeed, the experimentally determined  $C_{crit}$ -distribution (Fig. 4) is very different. As a consequence, the calculated time to corrosion initiation for element A and B are very different (Fig. 6). The very low  $C_{crit}$  leads to a very high probability of corrosion initiation in element A even at a height of 2 m – in contrast to assuming a constant value of  $C_{crit}$  of 0.4%.

#### 4.3 Consequences

As the decision for maintenance strategies is often based on a comparison between measured chloride profiles (chloride content at the cover depth) and the value of  $C_{crit}$ , the knowledge of  $C_{crit}$  is essential. The facts that a)  $C_{crit}$  is not a constant value, and b)  $C_{crit}$  can differ markedly among elements of the same structure, have to be highlighted. If the measured  $C_{crit}$  is higher than 0.4% (from standards), repair work might be planned too early which means unnecessarily high repair costs. If instead the actual  $C_{crit}$  is much lower than the one given in the codes, repair work is planned too late and gets more expensive. Additionally, corrosion degradation could be severely underestimated. Note that in the present case, no corrosion damage was detected during condition assessment of element A (neither visually, nor by potential measurements). However, very little additional chloride was needed to initiate corrosion during the laboratory test.

It may be worth noting that the  $C_{crit}$ -values were here obtained in completely saturated conditions, whereas on-site the exposure conditions are changing with seasons and are not always saturated. Therefore, the calculated remaining service life is on the safe side (conservative), because the model essentially only considers the time during which the concrete is saturated; dry periods, occurring in reali-

ty, can be regarded as a safety time margin in these models.

If for a structure, two structural members show completely different concrete quality, their  $C_{crit}$  should be not averaged for both elements. As depicted in Figure 4, the  $C_{crit}$ -distribution can deviate considerably, an averaged value would not give reasonable results.

Differences for the  $C_{crit}$  when investigating different structures are expected to be even higher than for two different elements. When investigating different structures, not only the concrete quality and cover depth are changing, but also the used materials (different steels, concrete mixes, etc.), and the exposure conditions. Therefore, the influence of the varying  $C_{crit}$  is expected to be even more crucial for condition assessment.

## 5 CONCLUSION

The following conclusions can be drawn from this work:

- The shown method to determine  $C_{crit}$  individually for different elements of the tunnel gives reasonable results. The service life predictions, calculated with model-parameters measured on the specific structure, find good agreement with the actual observations.
- Based on specific values of  $C_{crit}$  per element, the time to corrosion initiation can be predicted more accurately. Using tabulated or general input data ( $C_{crit}$ ), will significantly overestimate or underestimate the actual corrosion probability in a certain structural element.
- Condition assessment and maintenance strategies will benefit using this method with reduced costs for repair work and/or enhanced service life of infrastructure objects exposed to chloride environment.

## 6 ACKNOWLEDGEMENT

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