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Incorporating cracking of concrete on chloride ingress and service life modeling of concrete structures

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ABSTRACT

Chloride induced reinforcement corrosion is the most common degradation mechanisms for reinforced concrete structures. The service life of concrete structures is normally predicted by estimating the rate of chloride ingress and the necessary time to initiate reinforcement corrosion. Normally, chloride ingress is modeled as a diffusive process in which concrete is considered as a semi-infinite continuous medium. This modelling approach disregards the influence of cracks on the rate of chloride ingress in concrete. However, experimental studies have shown that the influence of cracks on chloride ingress is significant and cannot be neglected.

In practice, cracks in concrete may originate due to different mechanisms. Recommendations on crack control in flexural members consider cracks in the range between 0.15 mm (0.006 in.) and 0.3 mm (0.011 in.) to be permissible in deicing and/or seawater exposure; with the same limit for both exposure classes in Europe.

The influence of cracks on service life prediction remains to be clarified. This paper presents describes a conceptual approach for incorporating the effect of flexural cracks on the calculation of the time-to-corrosion initiation of steel reinforcement due to chloride-ingress. The proposed approach consists of applying a correction factor to the chloride diffusion coefficient, which is dependent on the surface crack width.

Key words: cracks, chloride ingress, corrosion, reinforcing steel, service life modeling

INTRODUCTION

During fabrication and service, concrete structures are constantly subject to environmental actions and loading conditions that can result in the formation of cracks (i.e. drying or restrained shrinkage at young age; or mechanically induced cracks due to loading) as shown in Figure 1.[1] The origin of cracks in concrete stems from material and/or mechanical nature that results in numerous crack geometries. In general terms, cracks represent discontinuities in the porous medium that provide pathways for fast transport of moisture and ions depending on their saturation condition.[2-11] Although cracks in concrete cannot be considered as a homogeneous group, numerous investigations have shown an empirical relationship between crack width and chloride ingress and subsequent corrosion deterioration.[2,3,13] Nevertheless, the influence of cracks on service life predictions has not been explored to the same depth as the aforementioned topics.

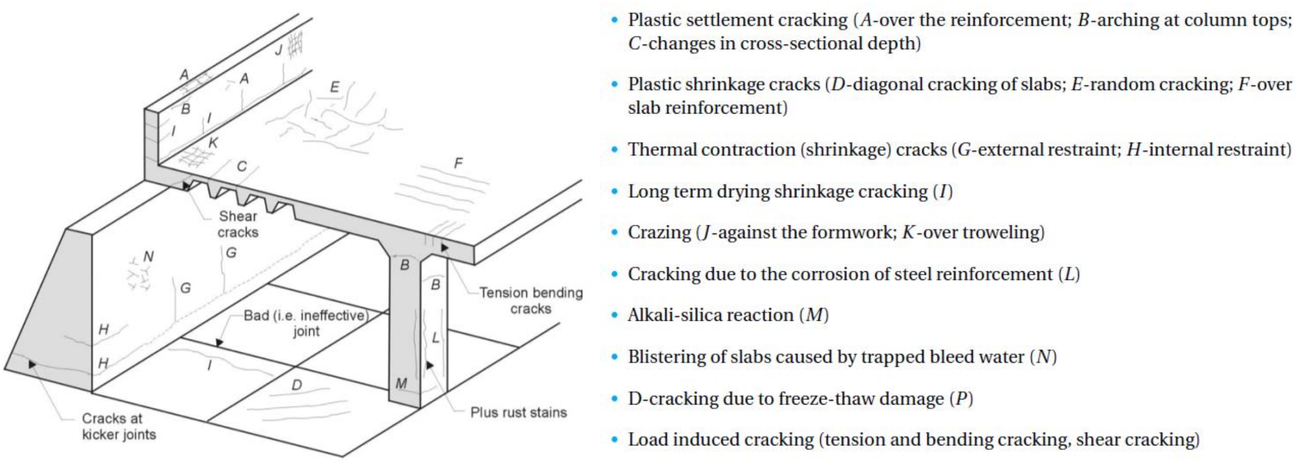

Figure 1: Types of cracks in concrete.

Structural regulations focused on durability control allowed crack widths based on exposure conditions. Eurocode 2 and ACI 224 permit 0.3 mm and 0.15 mm, respectively, as the maximum value for marine environment. However, the degree of protection conferred by controlling the crack width depends on more factors that are not considered in the codes, for example, concrete composition, concrete cover thickness, environmental conditions and curing. Table 1 presents the allowed crack width in concrete structures exposed to marine environment which are considered to have a negligible effect on the durability of concrete in accordance with different structural guidelines. These values seem to have been determined from empirical observations of the performance of cracked structures. With new, more detailed research and results on chloride transport in cracked concrete suggesting a pronounced effect of cracks on the chloride transport and corrosion initiation, this approach needs to be reconsidered.

Table 1
Maximum allowed crack width for reinforced concrete structures exposed to chloride contaminated environments

Guideline	Crack width, mm
ACI 224	0.15
FIB Model Code	0.30
BS-8110	0.30
Eurocode 2	0.30

Another important characteristic aspect that remains to be studied is the influence of secondary cracks (or internal cracks) on both chloride penetration and reinforcement corrosion. It has been found that internal cracks were present in reinforced concrete cylinders subject to tensile load, as shown in Figure 2.[14] Generally, the presence of these secondary cracks at the concrete-steel interface is generally undetected during the assessment of cracks at the concrete surface. The formation of these secondary cracks has been found to be dependent on the stress condition of the reinforcement. Under flexural loading, this means that the presence and amount of secondary cracks are directly related to surface crack width at the concrete surface. Understanding the impact that these secondary cracks may have on the time to corrosion initiation is therefore crucial.

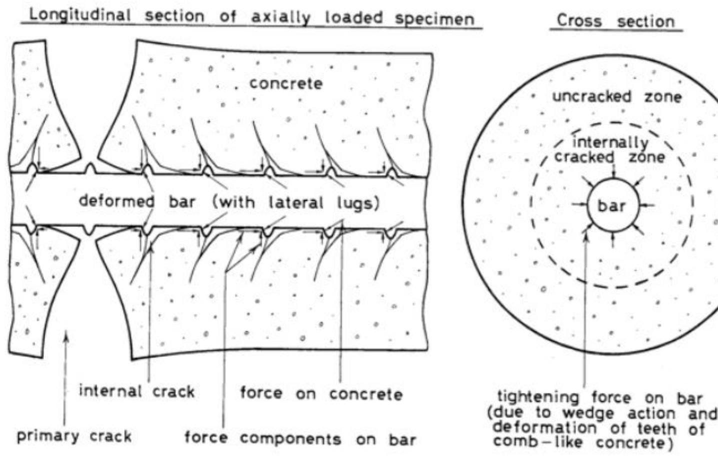

Figure 2: The formation of secondary cracks at the concrete-steel interface.

Cracks influence corrosion initiation because chloride penetration to the steel through cracks is fast, which may be expected to induce early corrosion initiation. In general terms, studies on the influence of cracks on chloride penetration have shown that chloride concentrations in concrete adjacent to cracks and overall penetration were higher. Figure 3 shows a schematic figure in which the penetration of chlorides is influenced by the presence of a transverse tensile crack. In this schematic figure, reinforcement corrosion is initiated at the intersection between the transversal crack and steel reinforcement. However, the location on which corrosion pits can nucleate is affected by several parameters. Oxygen availability along the steel reinforcement can be different than at the crack intersection if secondary cracks are present. In this sense, anodic regions (corrosion pits) could be prone to nucleate where oxygen availability is limited.

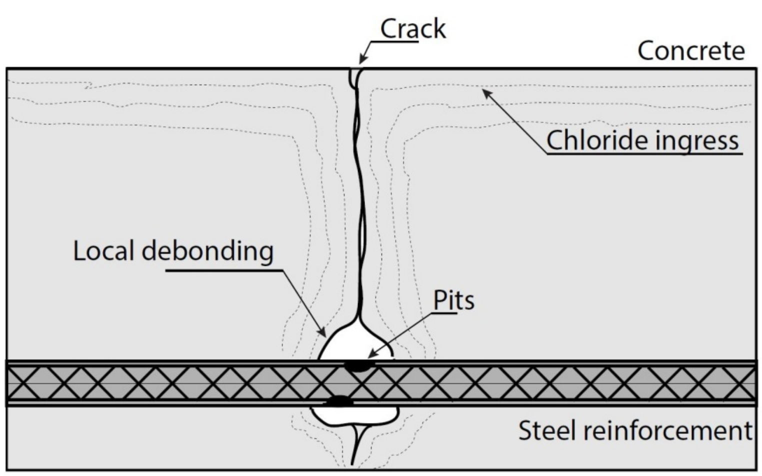

Figure 3: Schematic figure on the effect of cracks on reinforcement corrosion.

The repercussion of cracks on service life estimations of reinforced concrete is more controversial. Some researchers consider that cracks have an effect only on the initiation period by providing a fast route for chloride ingress.[4-11] In the propagation period, no direct relationship between crack width and corrosion rate was found. Other studies consider that the effect of cracks should be taken into account in both periods. Not only the crack width is relevant during the initiation phase, but also the crack spacing determines the rate of deterioration.[15-18] These studies have concluded that two important factors are related to the propagation of corrosion: crack width and crack spacing. For corrosion initiation in cracked concrete, the crack width at the concrete surface is the dominant parameter. In this paper, only the dependency of the time to corrosion initiation on the surface crack width will be considered.

Performance testing for service life predictions in sound concrete

One of the prominent challenges when attempting to incorporate cracks in service life predictions is the difficulty of providing sound estimations of the transport properties of cracked concrete. Service life prediction models have been developed based on performance tests of the concrete resistance to chloride ingress, i.e. the Rapid Chloride Migration test (NT BUILD 492) or natural diffusion (ASTM[1] C1556-11a). The transport mechanisms and principles for interpretation of results from these tests are, however, only valid for homogeneous, crack-free concrete. Therefore, employing these tests for assessing the performance of cracked concrete is questionable because of the influence of cracks on the resistance to chloride ingress.

Research studies on the effect of cracks on chloride ingress are limited to the characteristics of the studied cracks and materials. Incorporating the large number of parameters influencing this behavior into a specific performance test is unpractical for service life predictions. In order to overcome this challenge, a conceptual model that correlates the transport of chlorides in sound and cracked concrete is presented herein.

Most service life design models consider corrosion initiation as the governing limit state for service life predictions. Figure 4 shows the time dependency of ingress of chlorides in sound concrete and the transition from the initiation period to the propagation period when the chloride concentration at 50 mm into the concrete exceeds the critical chloride content (C_{crit}) based on Tuutti's model.[19-20]

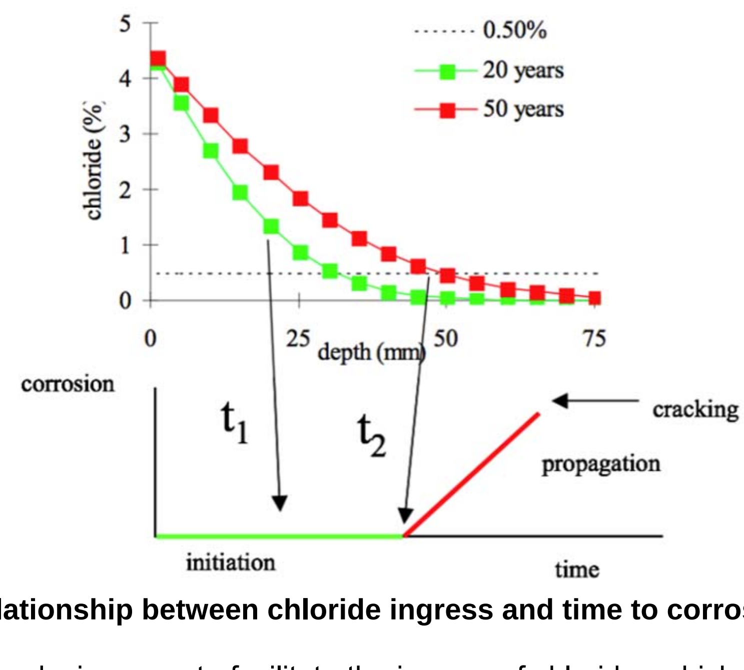

Figure 4: Relationship between chloride ingress and time to corrosion initiation

As described above, cracks in concrete facilitate the ingress of chlorides which can significantly reduce the duration of the initiation period. This behavior can be, therefore, related to an increase in the chloride diffusion coefficient compared to the reference diffusion coefficient (for uncracked concrete). Figure 5 shows a schematic of the conceptual model that relates the transport of chlorides in sound and

[1] ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA 19428-2959

cracked concrete. This Figure shows that in cracked concrete, the diffusion coefficient can be increased significantly compared to sound concrete for the same duration and exposure conditions.

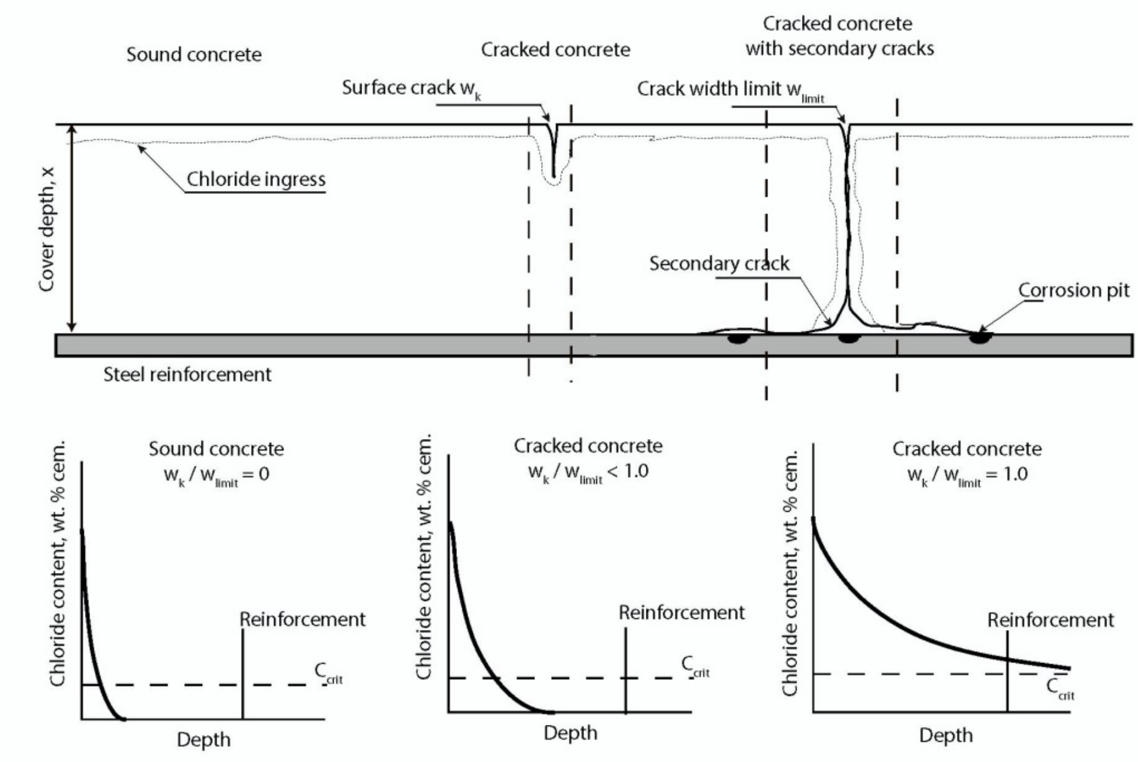

Figure 5: Conceptual model for estimating chloride ingress in cracked concrete.

This conceptual model assumes that chloride diffusion is still the main controlling mechanism for chloride transport in cracked concrete, i.e. disregarding the influence of capillary suction or convection. The main advantage of this approach is it conservatively estimates the resistance to chloride ingress by utilizing test results determined by compliance tests without considering different crack geometries. At the same time, the influence of other parameters such as cement type, water/binder ratio, are still considered since these have been accounted for when determining the uncracked concrete's chloride diffusion coefficient D. The resistance to chloride ingress in cracked concrete is, therefore, considered to be a fraction of the resistance of sound concrete depending on the w_k/w_{limit} ratio as explained below.

Incorporating cracks in chloride transport in concrete

The transport of chlorides in sound concrete can be described by Fick's Second Law of diffusion:

$$C(x,t) = C_s \cdot \operatorname{erfc}\left(\frac{x}{2\sqrt{D \cdot t}}\right) \tag{1}$$

Where C_s is the chloride surface concentration, D is the diffusion coefficient of chlorides, x is the depth from the concrete surface, t is the time and erfc is the complementary Gaussian error function. In this equation, the concentration of chlorides at a particular depth and time is determined by the diffusion coefficient D and the surface concentration Cs. This modelling approach has been used extensively in the past decades. Newer models that consider time and chemical dependency of C_s and D are departing from this modelling approach and have not been considered in this paper.

Incorporating the effect of cracks in concrete is proposed as follows:

$$D_{cr} = \frac{D_0}{1 - \frac{w_k}{w_{limit}}} \tag{2}$$

where D_{cr} is the diffusion coefficient of cracked concrete, D_0 is the diffusion coefficient of sound concrete at the age of the compliance test (natural diffusion or RCM), w_k is the surface crack width in mm and w_{limit} is the crack width at which the concrete cover does not impose a resistance to chloride ingress, also in mm.

In the European Committee for Concrete (CEB) code, a value for w_{limit} of 0.30 mm is recommended in order to satisfy appearance and ductility regulations. A recent experimental work considered w_{limit} as the crack width at the concrete surface which results in the formation of secondary cracks at the concrete-steel interface. The formation of secondary cracks was observed when the surface crack width w_k was around 0.3 mm.[2] The value suggested in this publication pertains exclusively to that studied concrete mixtures, specimen geometry and loading conditions.

The occurrence of secondary cracks exposes a large portion of the reinforcing steel surface to be in direct contact with a chloride-rich solution. It is assumed that greater values of w_k yield w_k/w_{limit} ratios in which chlorides can reach the steel surface in a significantly shorter period. Figure 6 shows the proposed influence of cracks on the chloride diffusion coefficient for different w_k/w_{limit} ratios, from uncracked ($w_k/w_{limit} \sim 0$) to negligible resistance to chloride ingress ($w_k/w_{limit} \rightarrow 1$). For illustrative purposes, corrosion initiation is considered to occur when the chloride concentration at depth x exceeds C_{crit}.

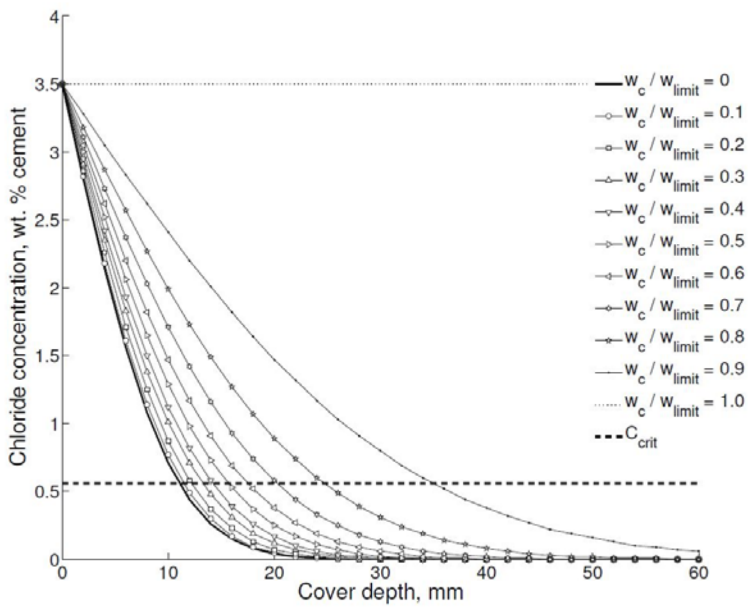

Figure 6: Proposed influence of cracks in concrete on chloride transport, i.e. t= 10 years.

Based on Figure 6, the chloride concentration in an uncracked concrete structure with reinforcing steel at 20 mm is very low after 10 years. However, if the w_k/w_{limit} ratio is 0.7 or higher, C_{crit} would have been reached at the same time of exposure (i.e. 10 years). Solving Eq. 1 for the time to corrosion initiation, $C(x,t) = C_{crit}$, results in:

$$t = \frac{1}{D}\left[\frac{x}{2 \cdot \mathrm{erfc}^{-1}\left(C_{(x,t)}/C_s\right)}\right] \tag{3}$$

The main advantage of this approach is it conservatively estimates the resistance to chloride ingress by utilizing test results determined by compliance tests without considering different crack geometries. At the same time, the influence of other parameters such as cement type, water/binder ratio, are still considered since these have been accounted for when determining the uncracked chloride diffusion coefficient D. The resistance to chloride ingress in cracked concrete is, therefore, considered to be a fraction of the resistance of sound concrete depending on the w_k/w_{limit} ratio.

Service life predictions of cracked concrete structures

In the DuraCrete model [21], predictions of the time to initiation of reinforcement corrosion t_i (for a specific reliability level) for new structures are determined by:

$$t_i^d = \left[\left(\frac{2}{x^c - \Delta x} \cdot erf^{-1}\left(1 - \frac{c_{cr}^c}{\gamma_{c_{cr}}} \cdot \frac{1}{A_{Cs,cl}^c \cdot w/b \cdot \gamma_{Cs,cl}}\right)\right)^{-2} \cdot \frac{R_{0,cl}^c}{k_{c,cl}^c \cdot k_{e,cl}^c \cdot t_0^n \cdot \gamma_{R,cl}}\right]^{\frac{1}{1-n}} \tag{4}$$

where c^c_{cr} is the characteristic value of the critical chloride content and γ_{cr} is the partial factor for C_{crit}. $A_{Cs,cl}$ is a regression parameter describing the relation between the chloride surface concentration and the water-binder ratio w/b. Then, $\gamma_{Cs,cl}$ is the partial factor for C_s. x_c and Δx are the concrete cover thickness and the variation for the cover thickness, respectively. Finally, $R^c_{0,cl}$ is the resistance to chloride ingress on the basis of compliance tests; $k^c_{c,cl}$ is the curing factor, $k^c_{e,cl}$ the environmental factor; t_0 is the age at which the compliance test was performed; n_{cl} is the age factor; and γR_{cl} is he partial factor for the resistance with respect to chloride ingress. The value of γ coefficients is determined from Tables given in DuraCrete for different reliability index β levels.

From Eq. 4, values attributed to C_{crit}.and $R^c_{0,cl}$ are crucial for the determination of the time to corrosion initiation. The effect of cracking of concrete on these parameters is described as follows:

- C_{crit}: Cracks are not considered to influence the values of C_{crit}. The effect of C_{crit} on service life estimations has been discussed extensively elsewhere and is not part of this paper.

- $R^c_{0,}$cl: The resistance to chloride ingress $R^c_{0,cl}$ represents the chloride transport properties of concrete. Normally, such transport properties are only dependent on the type of cement and water-to-binder ratio under the same environmental and experimental conditions. This parameter is considered to be affected by cracks due to a reduction of the resistance to chloride ingress.

For new structures, the design value of the time dependent chloride ingress resistance R^d_{cl} is described by:

$$R_{cl}^d(t) = \frac{R_{0,cl}^c}{k_{c,cl}^d \cdot k_{e,cl}^d \cdot \left(\frac{t_0}{t}\right)^{n_{cl}^d} \cdot \gamma R_{cl}} \tag{5}$$

where R^d_{cl} is the resistance to chloride ingress on the basis of compliance tests; $k^d_{c,cl}$ is the curing factor, $k^d_{e,cl}$ the environmental factor; t_0 is the age at which the compliance test was performed; n^d_{cl} is the age factor; and γR_{cl} is he partial factor for the resistance with respect to chloride ingress.

The initial resistance to chloride ingress $R_{0,cl}$ for sound concrete is:

$$R_{0,cl}^{c} = \frac{1}{D_{0,cl}} \tag{6}$$

where $D_{0,cl}$ is the diffusion coefficient obtained from compliance tests, i.e. NT Build 492.

In order to bridge the gap between the laboratory and field conditions, DuraCrete correlates the apparent diffusion coefficient, D_{app}, observed in field exposure conditions with the compliance test diffusion coefficient, $D_{RCM,0}$, obtained in laboratory conditions.

$$D_{app} = k_{e,cl} \cdot k_{c,cl} \cdot D_{RCM,0} \cdot \left(\frac{t_0}{t}\right)^{n_{cl}} \tag{7}$$

where $D_{RCM,0}$ is the chloride migration coefficient measured by e.g. the Nordtest method NT BUILD 492, at the age t_0 = 28 days, $k_{e,cl}$ and $k_{c,cl}$ are constants considering the influence of environment and curing, respectively, on chloride ingress, t_0 is the reference period (concrete age of 28 days) at which $D_{RCM,0}$ is measured and n_{cl} is the age factor describing the time dependency of the apparent diffusion coefficient.

Incorporating the conceptual model of the influence of cracks on chloride ingress for the DuraCrete equation is proposed as follows:

$$R_{0,cl} = \frac{1}{D_{0,RCM}}\left(1 - \frac{w_k}{w_{limit}}\right) \tag{8}$$

Similarly to Eq. 2, the resistance to chloride ingress is considered to decrease for increasing w_k/w_{limit} ratios as described by Eq. 8.

INCORPORATION OF CRACKS IN SERVICE LIFE PREDICTIONS

Project specifications for service life design of concrete structures normally define the minimum performance of concrete mixtures in specific durability tests, i.e. NT Build 492 or ASTM C1556-11a. As stated before, these provisions do not consider the effect of cracks on the transport of chlorides. Concrete mixtures that just comply with the specified D or D_{RCM} values can be subject to shorter service life in the presence of cracks.

Example: the influence of cracks on D_{RCM}

In a recent guideline for service life design of concrete structures, limiting values of D_{RCM} are recommended for a design service life of 100 years (at 10% of probability of failure) depending on the cement type, concrete cover depth and exposure class.[22] Following Eq. 8, an increase in the value of D_{RCM} due to cracking ($D_{cr,RCM}$) could result in unacceptable values for a particular concrete cover or exposure class. For example, a design service life of 100 years for reinforced concrete structure with ordinary portland cement (CEM I) with 60 mm of concrete cover and exposed to airborne marine environment (XS1) requires a maximum D_{RCM} of 22.0 x 10^{-12} m^2 s^{-1}. The same structure fabricated with ground granulated blast furnace slag cement cement (CEM III/B) requires a maximum D_{RCM} of 6.5 x 10^{-12} m^2 s^{-1}. Increased values of $D_{cr,RCM}$ higher than the prescribed D_{RCM} values would determine the maximum w_k/w_{limit} for each concrete mixture. If $D_{cr,RCM}$ lies above the prescribed values, the design service life of that structure may not be guaranteed.

Two concrete mixtures with a water-to-cementitious ratio (w/cm) of 0.45 and 60 mm of concrete cover will be considered for this example. One concrete mixture is fabricated with ordinary portland cement (CEM I 52.5R - designated PC) exposed to airborne chloride ingress (XS1), and another fabricated with blast furnace slag cement (CEM III/B 42.5N - designated BFS) exposed to tidal marine exposure (XS3). The D_{RCM} determined in sound concrete specimens in accordance with NT Build 492 for each mixture is given in Table 2.[3] The critical chloride content and corrosion behavior of reinforced concrete specimens with these concrete mixtures is reported elsewhere.[2] Experimental and numerical modelling of chloride ingress in cracked concrete specimens is reported elsewhere.[3]

Table 2
Reference concrete mixtures and measured D_{RCM}.

Mixture	w/cm (-)	Concrete cover mm	D_{RCM} $\times 10^{-12}$ m^2 s^{-1}
PC	0.45	60	12.0
BFS	0.45	60	4.0

When considering a target design service life of 100 years for a reinforced concrete structure with 60 mm of concrete cover and these cement types, the specified maximum D_{RCM} values would be 22.0 x 10^{-12} m^2 s^{-1} for PC (exposure class XS1), and 6.5 x 10^{-12} m^2 s^{-1} for BFS (exposure class XS3), respectively.[22] By considering the proposed approach, $D_{cr,RCM}$ can be estimated as described by Eq. 8. Table 3 shows the effect w_k/w_{limit} ratio on estimated $D_{cr,RCM}$ values.

Table 3
Estimated $D_{cr,RCM}$ values per Eq. 8. Shaded cells show exceeding maximum D_{RCM} values.

PC mixture, Exposure Class XS1, D_{RCM} limit = 22 x 10^{-12} m^2 s^{-1}		***BFS mixture, Exposure Class XS3 D_{RCM} limit = 6.5 x 10^{-12} m^2 s^{-1}***	
w_k/w_{limit}	$D_{cr,RCM}$	w_k/w_{limit}	$D_{cr,RCM}$
Uncracked	12.0	Uncracked	4.0
0.1	13.3	0.1	4.4
0.2	15.0	0.2	5.0
0.3	17.1	0.3	5.7
0.4	20.0	0.4	6.6
0.5	24.0	0.5	8.0
0.6	30.0	0.6	10.0

These results show that the $D_{cr,RCM}$ exceeds $D_{RCM\ limit}$ when the w_k/w_{limit} ratio is between 0.4 and 0.5 or higher for PC and 0.4 or higher for BFS concrete, respectively. If 0.3 mm is considered as w_{limit}, the values of the surface crack w_k at which the D_{RCM} is higher than the specified D_{RCM} in Table 3 for PC and BFS concrete are 0.15 and 0.12 mm, respectively. So far, these guidelines only consider the crack width and exposure conditions when considering the limit for crack width values in concrete elements. The resistance to chloride ingress is, however, been neglected.

Contrary to the prescriptive approach of durability regulations, we propose that the maximum tolerable w_k values may not only be a function of the exposure class but *also* of the sound concrete transport properties. Table 4 shows the influence of initial D_{RCM} on tolerable w_k/w_{limit} ratios. Results presented in Table 4 show that when the initial (uncracked) D_{RCM} values are lowered, the maximum tolerable w_k/w_{limit} ratio that results in a $D_{cr,RCM}$ value that still complies with the specified $D_{RCM\ limit}$ is increased. For example, if PC concrete with a $D_{RCM\ limit}$ value of 8.0 x10^{-12} m^2 s^{-1} is used, the maximum allowable value of w_k/w_{limit} before $D_{cr,RCM}$ > $D_{RCM\ limit}$ is 0.7. For a w_{limit} of 0.3 mm, the maximum value of w_k at the concrete surface is 0.21 mm. In the case of BFS concrete, reducing the initial D_{RCM} to 2.0 x10^{-12} m^2 s^{-1} would allow a w_k value above 0.21 mm before $D_{cr,RCM}$ > D_{RCM} . On the other hand, concrete mixtures whose initial Drcm is closer to the specified $D_{RCM\ limit}$ are therefore more sensitive to the influence of cracks.

Table 4
The influence of initial D_{RCM} on $D_{cr,RCM}$ estimations as a function of w_k/w_{limit}

Mixture	D_{RCM} x10^{-12} m^2 s^{-1}	w_k/w_{limit} 0.1	0.2	0.3	0.4	0.5	0.6	0.7
		$D_{cr,RCM}$						
PC	12.0	13.3	15.0	17.1	20.0	24.0	30.0	40.0
	11.0	12.2	13.8	15.7	18.3	22.0	27.5	36.7
	10.0	11.1	12.5	14.3	16.7	20.0	25.5	33.3
	9.0	10.0	11.3	12.9	15.0	18.0	22.5	30.0
	8.0	8.9	10.0	11.4	13.3	16.0	20.0	26.7
BFS	4.0	4.4	5.0	5.7	6.7	8.0	10.0	13.3
	3.0	3.3	3.8	5.0	5.0	6.0	7.5	10.0
	2.0	2.2	2.5	3.3	3.3	4.0	5.0	6.7
	1.0	1.1	1.3	1.7	1.7	2.0	2.5	3.3

Service life predictions of cracked concrete structures

A deterministic exercise on service life predictions of cracked concrete using the concrete mixtures is presented below. The input parameters for predictions of t_i in accordance with Eq. 4 are listed in Table 5. Note that this is a deterministic calculation, i.e. γ values are considered to be 1.0 and Δx is equal to zero. Predictions of the time to corrosion initiation given here pertain to mean times-to- corrosion. DuraCrete provides both a full-probabilistic approach as well as partial factors for a LRFD based approach for calculating probabilities of failure.[21] This is outside the present scope, however.

Table 5
Parameters for service life predictions of cracked concrete

Parameter	PC	BFS	Units
Exposure class	XS1	XS3	(-)
C_{cr}	0.56	0.56*	wt. % of cement
$A_{Cs,cl}$	2.57	6.77	wt. % of cement
w/b	0.45	0.45	(-)
X	60	60	mm
Δx	0	0	mm
$R_{0,cl}$	0.0026	0.0048	year/mm^2
$k_{e,cl}$	0.68	2.70	(-)
$k_{c,cl}$	0.79	0.79	(-)
t_0	0.0767	0.0767	year
n_{cl}	0.4	0.5	(-)

* *assumed to be the same as for PC* [23]

Table 6 shows the predictions of t_i for the PC and BFS concrete mixtures for exposure classes of XS1 and XS3, respectively. Results show than in un-cracked conditions, predicted t_i for PC and BFS is 108 and 186 years, respectively. For both concrete compositions, the predicted t_i values decrease significantly as the w_k/w_{limit} ratio increases. In the case of a crack width that is considered to be negligible by durability guidelines presented in Table 1 (0.2 mm, equal to a w_k/w_{limit} ratio of about 0.7) the predicted service life is reduced dramatically. In the case of the BFS concrete, a decrease in t_i due to cracking suggests that the design service life requirement of 100 years can be fulfilled if the maximum w_k/w_{limi} ratio is limited to 0.25 or lower (w_k ~ 0.075 mm). When considering an allowable crack width of 0.2 mm (w_k/w_{limit} of 0.7) the time to corrosion initiation for both PC and BFS concrete is quite short, i.e. about 15 years.

Table 6
Predicted t_i (in years) for concrete structures as a function of w_k/w_{limit}

w_k, mm	w_k/w_{limit}	PC (XS1)	BFS (XS3)
0	0	108	186
0.03	0.1	90	151
0.06	0.2	75	120
0.09	0.3	60	91
0.12	0.4	46	67
0.15	0.5	35	47
0.18	0.6	24	30
0.21	0.7	15	17

Predictions of the time to corrosion initiation following the proposed model show that the presence of cracks results in a serious reduction. Compared to the previous section in which cracks of up to 0.15 mm in width were acceptable considering the specified D_{RCM}, the service predictions of cracked concrete elements were reduced by more than 50%. Therefore, in order to provide a design service life of 100 years, the D_{RCM} in sound concrete of both PC and BFS concrete would need to be lower than the initial values 12 x 10^{-12} m^2 s^{-1} and 4 x 10^{-12} m^2 s^{-1}, respectively. This supports the premise that concrete's resistance to chloride ingress should be taken into account when determining the maximum allowable crack width limits.

An aspect that needs to be considered is the influence of the correction on R_{cl} in the DuraCrete model of the parameters $k_{e,cl}$ and $k_{c,cl}$. The values of both $k_{e,cl}$ and $k_{c,cl}$ have been determined from correlating field and laboratory observations of concrete elements exposed to chloride ingress. Although not mentioned explicitly, it could be possible that the present values of $k_{e,cl}$ and $k_{c,cl}$ already take into account the effect of cracks from field observations. Therefore, it is suggested that possible influence of a modification in the DuraCrete design equation on the rest of the parameters is considered.

CONCLUSIONS

In concrete Codes, cracks in concrete are considered to have a negligible impact on concrete durability if their width is limited to a specific value depending on the exposure conditions. These values, however, do not account for concrete resistance to chloride ingress which is dependent on concrete composition and the nature of cracks. Recent research into the influence of cracks on transport properties of concrete has shown that chloride ingress is dependent on crack width, cement type, water-binder ratio and concrete cover values. However, the effect of cracks has not been considered explicitly in service life predictions of concrete structures.

Performance testing is required for service life predictions. Current performance tests are carried out in sound concrete. In un-cracked conditions, the resistance to chloride ingress is crucial for estimations of the time to corrosion initiation. In this paper, a conceptual model was presented for the incorporation of the effect of bending cracks on chloride ingress and service life predictions.

The influence of cracks on the resistance to chloride ingress has been presented by considering the relationship between the crack width at the concrete surface (w_k) and the crack width at the concrete surface that results in the formation of secondary cracks at the concrete-steel interface (w_{limit}). The proposed w_k/w_{limit} ratio is used to estimate the diffusion coefficient of cracked concrete D_{cr} which is a function of the un-cracked diffusion coefficient D determined by compliance tests, i.e. natural diffusion (D_{cl}) or rapid chloride migration (D_{RCM}).

Incorporating cracks in calculations of the time-to-corrosion initiation of concrete structures was presented with a deterministic prediction for chloride ingress in cracked concrete elements. Estimations of t_i showed that cracks may have a severe effect on the reduction of the time to corrosion initiation t_i. Further research is required for determining the influence of $D_{cr,RCM}$ on other parameters such as $k_{e,cl}$ and $k_{c,cl}$.

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REFERENCES

1. *Non-structural cracks in concrete.* Report of a Concrete Society Working Party (Concrete Society London, 1992).

2. J. Pacheco, *"Corrosion of steel in cracked concrete: chloride microanalysis and service life predictions"*, Ph.D. dissertation, Delft University of Technology, 2015.

3. B. Šavija, *"Experimental and numerical investigation of chloride ingress in cracked concrete,"* Ph.D. dissertation, Delft University of Technology, 2014.

4. B. Pease, *"Influence of concrete cracking on ingress and reinforcement corrosion,"* Ph.D. dissertation, Denmark Technical University, DTU, Dec. 2010.

5. L. Pel, P.A.J. Donkers, K. Kopinga, and J. J. Noijen. "1H, 23Na and 35Cl Imaging in Cementitious Materials with NMR." *Applied Magnetic Resonance* 47, no. 3 (2016): 265-276.

6. A. Djerbi, S. Bonnet, A. Khelidj, and V. Baroghel- Bouny, "Influence of traversing crack on chloride diffusion into concrete," *Cement and Concrete Research*, vol. 38, no. 6, pp. 877–883, Jun. 2008.

7. M. Boulfiza, K. Sakai, and N. Banthia, "Prediction of chloride ions ingress in uncracked and cracked concrete," *ACI Materials Journal*, vol. 100, pp. 38–48, 2003.

8. P. Win, M. Watanabe, and A. Machida, "Penetration profile of chloride ion in cracked reinforced concrete," *Cement and Concrete Research*, vol. 34, no. 7, pp. 1073–1079, Jul. 2004.

9. A. Konin and R. François, "Penetration of chlorides in relation to the microcracking state into reinforced ordinary and high strength concrete," *Materials and Structures*, 1998.

10. N. Gowripalan and V. Sirivivatnanon, "Chloride diffusivity of concrete cracked in flexure," *Cement and Concrete Research*, 2000.

11. L. Marsavina, K. Audenaert, G. De Schutter, N. Faur, and D. Marsavina, "Experimental and numerical determination of the chloride penetration in cracked concrete," *Construction and Building Materials*, vol. 23, no. 1, pp. 264–274, Jan. 2009.

12. A. Michel, *“Reinforcement Corrosion: Numerical Simulation and Service Life Prediction,”* Ph.D. dissertation, Denmark Technical University, Oct. 2012.

13. M. B. Otieno, *“The development of empirical chloride-induced corrosion rate prediction models for cracked and uncracked steel reinforced concrete structures in the marine tidal zone,”* Ph.D. dissertation, University of Cape Town, 2014.

14. Y. Goto, “Cracks formed in concrete around de- formed tension bars,” *ACI Journal Proceedings*, vol. 68, no. 4, 1971

15. N. Otsuki, S. Miyazato, N. Diola, and H. Suzuki, “Influences of Bending Crack and Water-Cement Ratio on Chloride-Induced Corrosion of Main Reinforcing Bars and Stirrups ,” *ACI Materials Journal*, vol. 97, no. 53, pp. 454–464, 2000.

16. A. W. Beeby, “Cover to reinforcement and corrosion protection,” in *International Symposium on the Behaviour of Offshore Concrete Structures*, Brest, FR, 1980, pp. 8–10.

17. C. Arya and F. Ofori-Darko, “Influence of crack frequency on reinforcement corrosion in concrete,” *Cement and Concrete Research*, vol. 26, pp. 345–353, 1996.

18. P. Schießl, “Laboratory studies and calculations on the influence of crack width on chloride- induced corrosion of steel in concrete,” *ACI Materials Journal*, 1997.

19. R. Polder, M. de Rooij, H. de Vries, and J. Gulikers, “Observed Chloride Penetration in Eastern Scheldt Storm Surge Barrier, The Netherlands, after 20 years in North Sea Environment ,” in *Risk based maintenance of Structures*, 2007.

20. K. Tuutti. Corrosion of Steel in Concrete. Technical report, *CIB*, July 1982.

21. DuraCrete. DuraCrete - General Guidelines for Durability Design and Redesign. Technical report, The European Union - Brite EuRam III BE95-1347/R17, May 2000.

22. G. van der Wegen, R.B. Polder, and K. van Breugel. Guideline for service life design of structural concrete -A performance based approach with regard to chloride induced corrosion. *HERON*, 57(3):1–16, August 2013.

23. J. Pacheco and R. B. Polder, “Critical chloride concentrations in reinforced concrete specimens with ordinary Portland and blast furnace slag cement”, HERON, In Preparation.