GUIDELINE FOR SERVICE LIFE DESIGN OF STRUCTURAL CONCRETE WITH REGARD TO CHLORIDE INDUCED CORROSION - THE APPROACH IN THE NETHERLANDS

Rob B. Polder (1,2), Gert van der Wegen (3), Klaas van Breugel (1)

(1) Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section Materials and Environment, Delft, The Netherlands
(2) TNO Built Environment and Geosciences, Department Civil Infrastructure, Delft, The Netherlands
(3) INTRON, Sittard, The Netherlands

Abstract
Nowadays the market calls for concrete structures with 80, 100 or 200 years life without major maintenance. To meet this call, CUR committee VC81 has developed a guideline for service life design based on initiation of corrosion due to chloride penetration for exposure classes XD and XS. A semi-probabilistic simplification of the DuraCrete methodology is introduced with a probability of failure of ≤10% for corrosion initiation, based on experience gained with two large tunnels and structures in the High Speed railway line.

The required concrete performance is the chloride diffusion resistance, measured as Rapid Chloride Migration (RCM). Its limit value depends on cover depth, required service life, exposure class and binder type (Portland, Blast furnace slag and Portland/fly ash). Model calculations were validated using data from marine and road structures. Three options are provided for specifying a maximum RCM value: (1) a range of concrete cover depths adapted to the binder type; (2) a semi-probabilistic approach using a safety margin for the concrete cover depth; (3) full probabilistic calculations based on specified input parameters. Quality control based on concrete resistivity measured using the Two Electrode Method is proposed. The guideline permits optimisation with respect to cover depth and concrete composition.

1. INTRODUCTION

Today owners frequently require service lives of 80, 100 or even 200 years for concrete infrastructure. Present design codes do not give quantified guidance for designing concrete structures for such long service lives. In the Dutch standards, for example, a service life of 50 years is only implicitly assumed. In 2003 an industry-wide committee was installed in The Netherlands to develop a probability-based guideline for designing durable civil engineering
structures with service lives up to 200 year. Due to limited experience it was stated that the requirements of the prevailing Dutch concrete standards should be met, which correspond to international regulations (e.g. EN 206, EuroCode 2). This implies the usual maximum water-to-cement ratios and minimum cement contents, depending on environmental class. Under these conditions chloride-induced rebar corrosion is likely to be the dominant mechanism determining the service life, whereas carbonation-induced corrosion can be ruled out safely.

The guideline is based on the DuraCrete methodology for Service Life Design (SLD) that was conceived in the 1980s by Siemes et al. [1] and developed in detail in the 1990s in European research project DURACRETE [2,3]. It follows structural limit state design philosophy by stating that the service life is the period in which the structure's resistance $R(t)$ can withstand the environmental load $S(t)$. $R(t)$ and $S(t)$ are time dependent, statistically distributed variables. A particular performance is predicted with a predetermined maximum probability of failure at the end of the design life, as shown schematically in Fig. 1.

![Figure 1: Schematic representation of probabilistic service life design [2,3]](image)

The limit state is initiation of reinforcement corrosion due to ingress of chloride ions. When the chloride content at the surface of the reinforcing bars exceeds the critical chloride threshold, the structure is considered to fail. The load is represented by the chloride content at the steel surface that increases with time due to chloride ions building up at the concrete surface and their subsequent transport into the bulk. The resistance is the critical corrosion initiating threshold for chloride at the steel surface. This property cannot reliably be influenced with present day knowledge [4]. As a practical approach, the critical chloride content is assumed constant and the concrete resistance to chloride penetration, expressed by its chloride diffusion coefficient, is taken as the model variable that, together with the chloride surface content, determines the service life. This diffusion coefficient changes with time due to hydration, binding of ions and drying out, which complicates the modelling. It is emphasized that the performance is considered in terms of absence of corrosion initiation, which is not an ultimate limit state, because no direct danger for human lives is at stake. It is a Maintenance Limit State (MLS), because corrosion means the upcoming need to repair, which is an economic threat rather than a safety issue, corresponding to a Serviceability Limit State (SLS). Target probabilities of failure for SLS are usually in the range of a few to 10 percent.
The DuraCrete approach has been tested in the field on six marine structures, from which chloride profiles were taken after 20 to 40 years [5,6], from which modifications of model parameters were deduced. This paper describes application of the DuraCrete approach for service life design of concrete structures in marine (exposure class XS) and de-icing salts environments (XD). Chloride migration test results are used in a semi-probabilistic concept, which was condensed into a set of tables specifying maximum values for chloride diffusion coefficients depending on cover depth, cement type, exposure class and required service life.

2. A PROBABILITY-BASED PREDICTIVE MODEL

The basic components of the present concept are a transport model, a chloride transport coefficient, several model parameters and a semi-probabilistic approach. For the description of chloride ion transport into concrete a modification of Fick’s 2nd law of diffusion is adopted. Using Fick’s 2nd law and of the term diffusion coefficient does not imply, however, that the authors are not aware of other mechanisms that contribute to the transport of chloride ions into concrete. This discussion, however, is not the subject of this paper.

2.1 Chloride penetration (diffusion) coefficient

Since the diffusion model for chloride ingress in concrete was introduced by Collepardi et al. [7], several methods have been proposed for determining the resistance of concrete against chloride penetration. In the 1990s, two methods were standardised in the Nordic countries:

1. An immersion (pure diffusion) test, NT Build 443;
2. An accelerated (migration) test, NT Build 492, the Rapid Chloride Migration test (RCM).

The immersion test may be seen as a realistic representation of the natural diffusion process. A drawback is that it requires seven weeks exposure of specimens and involves chloride analysis of many samples. The migration test involves a different transport mechanism, but has a short execution time and is less laborious. In European research project CHLORTEST [8] both methods were studied and compared in a Round Robin Test. A good linear correlation was found between chloride diffusion coefficients from diffusion experiments and chloride migration coefficients from RCM tests. It was considered justified, therefore, to use the less time and labour consuming RCM test instead of the diffusion test [9].

In the past few years, RCM testing has been applied to many concrete mixtures in association with service life design of large infrastructural projects in the Netherlands. For the guideline, a total of 500 RCM-values from 153 different concrete compositions (prefab and ready mix) were obtained. The influence of the mix composition on the RCM-value was analysed. Cement types used were mainly Portland cement (CEM I 32.5R, 52.5N, 52.5R), blast furnace slag cement (CEM III/A 52.5 R, CEM III/B 42.5 LH HS), mixtures of these two cements and binders comprising powder coal fly ash and Portland or slag cement. Binder contents ranged from 300 to 450 kg/m³ and water/binder ratios (w/b) from 0.33 to 0.65. The age at testing ranged from 28 days to 3 years, with most data at an age around 28 days.

It was assumed that the RCM-value depends to a large extent on the type of binder (cement type and reactive additions), w/b and age. The data were first grouped with respect to binder type: Portland cement (CEM I); Slag cement (CEM III/A or III/B, 50 – 76% slag); Portland and slag mixtures (25 – 38% slag); Portland cement with fly ash (21 - 30% fly ash).

Within these groups, data of similar age were aggregated; ages of 28 to 35 days were considered as a single group. The influence of w/b on \( D_{RCM} \) was then analysed for each particular binder group at an age around 28 days. All fly ash present in the mixture was...
considered as cementitious material, so \( w/b = \text{water} / (\text{cement} + \text{fly ash}) \). This analysis showed that the \( D_{RCM} \)-value is linearly related to the water/binder ratio:

\[
D_{RCM}(28d) = A(w/b) + B
\]

with \( A \) and \( B \) constants for particular cement types, see Figure 2. It clearly shows that \( D_{RCM} \) strongly depends on binder type. For Portland cement \( D_{RCM} \) is strongly influenced by \( w/b \). For slag cement this influence turned out to be less pronounced. The regression coefficients \( (A, B) \) found for different binders are in good agreement with those reported by Gehlen [10]. The data suggest that in the range of practical \( w/b \) ratios between 0.35 and 0.55 (and present day concrete technology), minimum RCM-values apply that depend on binder type.

![Figure 2: Correlation between w/b and DRCM at about 28 days; all values * 10^{-12} \text{ m}^2/\text{s}](image)

Even though execution of the RCM-test is much faster than the diffusion test (NT Build 443), it is still labour intensive. For a quick impression of the resistance against chloride ingress also the Two Electrode Method (TEM) can be used. With that method the electrical resistivity of the concrete is determined. In [9] a good correlation was reported between these two methods. Particularly for production control the TEM test is suitable for a quick indication of the potential of a certain mixture to meet prescribed diffusion levels.

### 2.2 Modelling chloride ingress

In the DuraCrete model the evolution of chloride profiles is approximated with:

\[
C(x,t) = C_s - (C_s - C_i) \text{erf} \left[ \frac{x}{\sqrt{4kD(t)t}} \right]
\]

where \( C(x,t) \) is the chloride content (all chloride contents are expressed in % by mass of binder) at depth \( x \) at time \( t \), \( C_s \) is the surface chloride content, \( C_i \) the initial chloride content in the concrete, \( k \) a correction factor and \( D(t) \) the apparent diffusion coefficient as a function of time. The surface chloride content was assumed to be independent of mix composition for
reasons of simplicity: 3.0% for marine structures [5,6] and 1.5% for land based structures [11]. The initial chloride content was taken equal to 0.1%.

The apparent diffusion coefficient \( D(t) \) is multiplied by a correction factor \( k \) to obtain the chloride diffusivity of concrete in a real structure. This correction factor depends on binder type, environment and length of wet curing. The \( k \)-values were taken from DuraCrete [2]. The critical chloride content was taken equal to 0.6% by mass of cement, see a.o. [10,11,12].

2.3 Time dependency of chloride penetration coefficient \( D(t) \)

The rate at which chloride ions penetrate into concrete decreases with time. This is due to hydration of the binder, which causes narrowing of capillary pores (especially in binders with slag or fly ash); and drying, which reduces the amount of liquid in the pores. A decreasing rate of chloride penetration can be described with a time-dependent diffusion coefficient [13]:

\[
D(t) = D_0 \left( t_0 / t \right)^n
\]  

where \( D_0 \) is the \( D_{RCM} \)-value at reference time \( t_0 \) (usually 28 days) and \( n \) is the ageing coefficient \((0<n<1)\). The value of \( n \) for a particular binder in a particular environment depends on the rate of hydration and on the extent of drying. Ageing coefficients for different binders without the effect of drying were determined from \( D_{RCM} \)-values that had been cured at 20°C for different periods from 28 days up to three years. Structures in the field will dry out to some extent and hydration may occur slower than under water. In DuraCrete ageing coefficient values under field conditions were determined from profiles taken from structures and exposure tests, combined with \( k \) values (Equation 2) for different environments and lengths of wet curing. Based on those data, the present analysis and additional work [5,6], \( n \)-values were chosen for the Guideline in two groups of environmental classes: very wet (XD2/XS3) and moderately wet (XD1/XD3/XS1) [7,15], see Table 1.

The time needed to reach the critical chloride content at a certain depth can now be calculated for any given mix (within the available data collection) in exposure classes XS and XD, using Equation (1) indicatively. For a specific service life design calculation, \( D_{RCM} \) of a particular mix should be measured and used for the calculation.

Table 1: Ageing coefficients \( n \) for different binders in two groups of environmental classes

<table>
<thead>
<tr>
<th>Environmental classes</th>
<th>Underground, splash zone</th>
<th>Above ground, marine atmospheric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of binder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEM I</td>
<td>XD2, XS3</td>
<td>XD1, XD3, XS1</td>
</tr>
<tr>
<td>CEM I, 25-50% slag, II/B-S; III/A, &lt;50% slag</td>
<td>0.45</td>
<td>0.65</td>
</tr>
<tr>
<td>CEM III 50-80% slag</td>
<td>0.50</td>
<td>0.70</td>
</tr>
<tr>
<td>CEM I with 21-30% fly ash</td>
<td>0.70</td>
<td>0.80</td>
</tr>
<tr>
<td>CEM V/A with c. 25% slag and 25% fly ash</td>
<td>0.60</td>
<td>0.70</td>
</tr>
</tbody>
</table>
2.4 Reliability considerations and semi-probabilistic approach

For a given concrete cover depth, Equation (2) can be used for calculating the time needed for the critical chloride content to reach the reinforcement. Such a calculation, however, is deterministic and yields a mean value. This means that the probability of corrosion initiation at that point in time and space is 50%. In practice such a high probability is unacceptable. An acceptable probability of failure for an MLS may be 10% [14] for reinforcing steel.

To obtain such a lower probability of failure than 50%, either the cover depth can be increased or the maximum \( D_0 \) can be decreased. If the former option is chosen, the required amount of additional cover can be calculated for each individual case using probabilistic calculations. In the guideline, however, it was chosen to add a fixed amount to the (deterministically determined) cover depth as a safety margin. This is a semi-probabilistic approach, comparable to using a safety factor for a materials property or a load.

An increase of the cover depth by 20 mm will reduce the probability of corrosion from 50% to about 10% [9]. This procedure has been followed in the guideline. Calculations using TNO's probabilistic software Prob2B™ have shown that a safety margin of 20 mm results in a probability of failure of 10%; a safety margin of 30 mm produces a probability of 5%. Such probabilities are considered appropriate for reinforcing and prestressing steel, respectively.

Table 2: Maximum \( D_{RCM,28} \) for various cover depths as a function of binder type and environmental class for a design service life 100 years. Note: Boldface values are practically achievable by present-day concrete technology with currently used w/b.

<table>
<thead>
<tr>
<th>Mean cover [mm]</th>
<th>Maximum value ( D_{RCM,28} ) [(10^{-12} \text{ m}^2/\text{s})]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reinforcing steel</strong></td>
<td>CEM I</td>
</tr>
<tr>
<td>XD1/2, XS1</td>
<td>25-50% S</td>
</tr>
<tr>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>55</td>
<td>65</td>
</tr>
<tr>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

3. SERVICE LIFE DESIGN IN PRACTICE – EXAMPLES

Following the method described above, including a safety margin to the cover depth of 20 mm for reinforcing steel or 30 mm for prestressing steel, combinations of required cover depth and maximum \( D_{RCM} \)-values were calculated for service lives of 80, 100 or 200 years. Curing was assumed to last for three days (XD) or seven days (XS). Values for 100 years are presented in the Table 2. Two examples may illustrate using it for service life design.
Example I concerns a reinforced concrete structure in XD1-3/XS1 environment. For the type of cement a CEM III/B with 70% slag was chosen. The required service life is 100 years. From Table 2 it can be seen that with a cover depth of 45 mm (reinforcing steel), a maximum DRCM,28 is required of 6.0 \( \times 10^{-12} \) m²/s. With this cement and a w/b of 0.45, a DRCM-value of 4.0 \( \times 10^{-12} \) m²/s can be obtained rather easily (Fig. 2). Going back to Table 2 it can be seen that with a DRCM-value of 4.0 \( \times 10^{-12} \) m²/s the cover depth could be reduced to 40 mm.

Example II concerns the same structure as Example I. The cover depth is 45 mm, but now CEM I is used. For CEM I and a cover depth of 45 mm, Table 2 gives a maximum DRCM,28 of 8.5 \( \times 10^{-12} \) m²/s. Even though DRCM is higher than in case I, such a value might be hard to achieve with CEM I (see Fig. 2). It would require quite a low w/b, probably below 0.4, which may cause workability problems. Increasing the cover to 50 mm will allow an increase of DRCM,28 to 12 \( \times 10^{-12} \) m²/s, which can be readily achieved with a w/b of about 0.45.

Navigating through all possible options in the Tables, the designer can find the economic optimum, while he can demonstrate to the client that the required service life is achieved.

4. CONCLUDING REMARKS

In many cases obtaining a long service life for structural concrete (bridges, harbour quays, tunnels, parking garages) is mainly a matter of postponing the onset of rebar corrosion. The most important parameters in a model based approach are:

- chloride load from sea water or de-icing salt environments
- chloride transport by diffusion
- time dependent diffusion coefficients
- coefficients taking into account environmental, curing and materials influences
- determining the Rapid Chloride Migration coefficient of the intended concrete.

This paper presents a probability-based design procedure for determining combinations of cover depth and 28-day chloride diffusion coefficients that are required to guarantee a specified service life. Target probabilities of failure are 10% and 5%, respectively, for reinforcing steel and prestressing steel. Based on a semi-probabilistic simplification, the required combinations of cement type, cover depth and diffusion coefficient are brought together in simple design tables. The tables give limiting values for chloride diffusion coefficients obtained with the RCM test for service lives of 80 to 200 years in marine (XS) or de-icing salt (XD) environments. From analysis of a large number of test results, the dependency of the DRCM-value on w/b and cement type was determined and an indication was obtained which values are possible using present-day concrete technology.

Similar tables as proposed here have recently been presented by Li et al. [15]. In their tables, however, the compressive strength is still considered one of the durability parameters. Instead of the strength, here an explicit transport parameter is chosen, i.e. the RCM-value, to indicate the concrete's susceptibility to chloride ingress. A similar probability-based approach to various degradation mechanisms has been presented by fib [16], using a slightly different model for chloride induced corrosion.

With this Guideline [17], the Dutch concrete industry now has rules for practical service life design. All parties involved have agreed to collect their experience using the Guideline, with the intention to evaluate it and if necessary, to improve it in the near future. At the same time, however, it was realised that many items used in the calculations still contain large uncertainties. Further research should contribute to reducing them.
ACKNOWLEDGEMENT

This paper is based on ideas and results from the DuraCrete consortium, researchers at TNO and INTRON and CUR-committees B82 and VC81. The financial and in kind support of Rijkswaterstaat and other participating organisations are gratefully acknowledged.

REFERENCES