

LONG-TERM PERFORMANCE OF CONCRETE STRUCTURES IN A MARINE ENVIRONMENT – MEASURED AND CALCULATED

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Abstract

This work deals with the long-term performance of concrete structures in a marine environment. Chloride profiles obtained from over 30 building elements of several German marine structures, in a wide range of ages from 25 to 55 years, and results of a long-term exposure test have been compiled. The validity of the measured chloride contents is discussed. The actual performance deduced from the experimental results is compared with a common chloride penetration model. The impact of binder type, chloride surface concentration and exposure conditions are considered and discussed.

Key Words: Concrete; Chloride; Corrosion; Long-term Performance; Diffusion; Modelling

1. INTRODUCTION

Concrete structures in a marine environment such as locks, dams, bridges and so on are affected by a wide range of degradation phenomena. Chloride-induced corrosion is the decisive aspect in the durability of these structures. Reinforcement corrosion is initiated when a critical chloride content at the surface of the rebars is reached. Chloride contents higher than the critical value can cause a disruption of the protective passive layer. Corrosion of rebars will be the consequence. The time required to initiate corrosion depends, apart from some environmental factors, on the properties of the concrete, in particular on its resistance to chloride diffusion.

The following period, the propagation period, refers to the evolution of different forms of deterioration after corrosion has been initiated (cracking, spalling, loss of bond between rebars and concrete and reduction in the rebar cross-section). Although the service life of structures is the sum of these two periods, in most cases the initiation period defines the service life because the propagation period may be very short.

To satisfy the durability of concrete structures one has to respect deemed-to-satisfy provisions which are based on field experience. These rules are given in current standards and guidelines. By contrast to this prescriptive methodology of standards, performance-based probabilistic design models are being developed. A full probabilistic concept has been developed for the purpose of assessing the initiation period of chloride-induced corrosion and has been published in “fib Model Code for Service Life Design” [1].

Germany borders the Baltic Sea and the North Sea in the north and has over 2,000 km coastal line with numerous marine structures. The Waterways and Shipping Administration of the Federal Government (WSV) is responsible for managing the marine structures, with the Federal Waterways Engineering and Research Institute (BAW) acting in an advisory capacity and providing technical expertise. The structures are controlled by monitoring and, more common, by regularly performed inspections. Numerous inspection reports and reports on the condition of the marine structures available at the BAW were considered when preparing this paper, with the aim of compiling chloride profiles for structural elements. The selection was limited to structural elements for which information on the concrete composition and age was available and to those parts of elements which appeared to be intact (without cracks, etc.).

After a brief introduction of the fib model [1], the chloride profiles will be compared with the results of the fib model calculations. Finally, the uncertainties in the chloride values obtained for structures will be discussed.

2. MATHEMATICAL DESCRIPTION OF CHLORIDE PENETRATION IN CONCRETE

Equation 1 constitutes the mathematical model used in the “fib Model Code for Service Life Design” [1] to estimate the time- and depth-dependent chloride concentration, $C(x,t)$, in

uncracked concrete. The equation is based on the error function solution of Fick's second law of diffusion in its one-dimensional form.

$$C(x, t) = C_0 + (C_{s,\Delta x} - C_0) \cdot \left[1 - \operatorname{erf} \frac{x - \Delta x}{2 \cdot \sqrt{D_{app,C}(t) \cdot t}} \right] \quad (1)$$

with:

C_0 : initial chloride content [wt.-%/c]

$C_{s,\Delta x}$: chloride content at the depth Δx and a certain point of time in relation to the environment [wt.-%/c]

Δx : depth of the convection zone (concrete layer up to which the process of chloride penetration differs from Fick's 2nd law of diffusion) [mm]

x : depth with a corresponding content of chlorides $C(x, t)$ [mm]

t : time [years]

$D_{app,C}(t)$: apparent chloride diffusion coefficient [m^2/s]

The apparent chloride diffusion coefficient $D_{app,C}(t)$ is time-dependent and is to be determined by means of equation (2):

$$D_{app,C}(t) = \exp \left(b_e \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}} \right) \right) \cdot D_{RCM,0} \cdot k_t \cdot \left(\frac{t_0}{t} \right)^\alpha \quad (2)$$

with:

b_e : temperature coefficient [K]

T_{ref} : reference temperature (for laboratory tests) [K]

T_{real} : temperature of the structural element or the ambient air [K]

$D_{RCM,0}$: chloride migration coefficient [m^2/s]

k_t : transfer parameter (=1) [-]

t_0 : reference point of time [s]

α : ageing exponent [-]

This diffusion-controlled assessment of chloride ingress is only a simplification, since other transport mechanisms are involved in the chloride ingress in concrete, in particular, capillary absorption and permeation. However, in structures with concrete cover depths bigger than approx. 30 mm diffusion becomes the most effective and important mechanism related to the initiation of corrosion in concrete structures.

Due to the intermittent wetting and drying of the near-surface layer (approx. within the first 20 mm), particularly in tidal and splash zones, the transport mechanisms in this layer greatly differ from Fick's law of diffusion. Modelling is therefore conducted with a substitute surface chloride concentration, $C_{s,\Delta x}$, neglecting the data in the convection zone, Δx . Although

$C_{s,\Delta x}$ is theoretically a time-dependent variable, it will be considered as time-independent in order to satisfy the basic condition for solving the differential equation of Fick's second law of diffusion.

$D_{RCM,0}$ and the ageing exponent, α , are the governing parameters for the description of the material properties. While $D_{RCM,0}$ is simply determined by Rapid Chloride Migration (RCM) test methods [2, 3], the ageing exponent, which operates the decrease of $D_{app,C}(t)$ over time, is both material- (development of hydration) and exposure-dependent and cannot be determined by laboratory tests alone. To determine the ageing exponent the long-term behavior of $D_{app,C}(t)$ of existing structures has to be considered by processing the chloride profiles over time. Gehlen [4] quantified the statistical distribution of the ageing exponent of three different types of cement, considering both chloride profiling data of several existing structures and the RCM test results at the reference time (28 days), $D_{RCM,0}$.

In this probabilistic service life design concept all material and action parameters are to be considered and inserted as statistical distributions. Stochastic values are given in [1] by way of recommendations for the input parameters.

A description of the limit state of the model and how it is to be calculated by applying the reliability analysis in order to determine the service life of the structures have been dealt with in another paper in these proceedings [5]. This paper only examines the modelling of the chloride ingress in concrete.

3. MEASURED AND CALCULATED CHLORIDE CONTENTS OF MARINE STRUCTURES

The chloride values of over 30 different concrete structural elements of several structures on the German North Sea and Baltic Sea coasts are presented below and compared with the results of the model calculations.

The mean actual (measured) chloride values for several structural elements in a marine lock on the North Sea coast are shown in Figure 1, left. The elements were 35 years old at the time of the inspection in 1998. The composition of the concrete was one which was commonly used for the construction of marine structures at that time, with the cement containing ground granulated blast furnace slag and with a water/cement ratio of between 0.55 and 0.60 [6]. The samples were taken from all three sections within a XS3 exposure class: spray, splash and tidal zones. The tidal zone had the highest chloride values at each of the three depths at which measurements were taken, followed by the splash zone. The lowest values were to be found in the spray zone, as expected in view of its lower exposure to chlorides. No chlorides were detected in almost all of the sections at a depth of 50 mm, the greatest depth at which measurements were taken. For a mean concrete cover to reinforcement of $c = 60$ mm as specified in the German technical guideline "ZTV-W LB 215" [7] there is not yet any risk of corrosion in the structural elements after a period of 35 years.

The critical chloride content for the initiation of corrosion (C_{crit}) is taken to be 0.5 wt.-%/c on average in many standards and directives, such as RLiSIB [8].

Figure 1, left, also shows the mean values and the 95 % quantiles of the chloride profiles calculated for this particular concrete composition and exposure. The input parameters for the model are shown in Figure 1, right. The input values were selected on the basis of [1, 4, 9] and the exposure conditions. The mean surface chloride concentration, $C_{s,\Delta x}$, was taken to be 4.0 wt.-%/c. The surface chloride concentration can be determined taking account of the chloride sorption isotherms of the binders according to Tang [10] where the chloride saturation concentration is calculated as a function of the chloride-binding capacity of the binder. Accordingly, a higher $C_{s,\Delta x}$ value is used for CEM III (ground-granulated blast-surface slag (GGBS cement)) concretes than for CEM I (Portland cement) concretes as the former have a greater ability to bind chlorides. However, this behaviour does not accord with the results in actual practice. This point will be dealt with later on when the exposure tests are discussed. In other pragmatic approaches, the surface chloride concentration is determined as a function of the concentration of the chloride source, the distance from the chloride source, the porosity of the concrete and the ambient temperature by means of the corresponding empirical factors, e.g. in LNEC E465 [11]. In this paper, the $C_{s,\Delta x}$ value is taken to be 4.0 wt.-%/c for a chloride content of around 19,900 mg/l for the North Sea and 3.0 wt.-%/c for a chloride content of around 9,000 mg/l for the Baltic Sea, irrespective of the concrete composition.

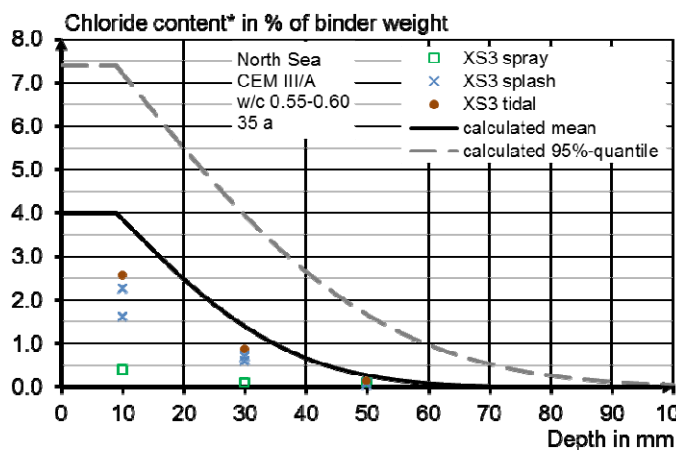
The calculated chloride profile (mean value) is slightly above the measured chloride values after 35 years of exposure. However, it should be noted that the chloride content was determined by hot water extraction. This method does not measure the total chloride content of concrete but the content of free chloride ions dissolved in the pore solution and some of the chemically and physically bonded ions instead. The total chloride content can only be measured by means of acid extraction (HNO_3) [15]. Although only the chloride ions dissolved in the pore solution of the concrete cause depassivation of the reinforcement, the total chloride content is considered in the model as it is difficult to determine the free chloride content of concrete. Furthermore, the initial chloride content of the concrete used was unknown and was thus disregarded in the model.

The reliability analysis shows that there is a probability of around $P_f = 23\%$ (reliability index $\beta = 0.75$) that corrosion of the reinforcement will occur in the structural element (concrete cover to reinforcement: 60 mm) after 35 years. In EN 1990 [12], ISO 2394 [17] and [18] there are recommendations for P_f for serviceability limit states in dependence of the necessary expenses to risk minimization from $P_f = 1\%$ to $P_f = 50\%$. (reliability index $\beta = 2.3$ to $\beta = 0$). The general condition of the structure was classified as “good” according to the results of the inspection, apart from small sections with damage due to execution errors or mechanical actions [6].

Figure 2 is a similar representation of the chloride content of other structural elements in the same marine lock after 40 years' exposure. In addition to XS3 exposure class (spray and tidal), the points at which the samples were taken also cover XS2 exposure class (submerged), figure 2, right. Compared with Figure 1, some sections of the spray zone exhibit higher chloride values than the tidal zone. The highest values were measured in the submerged zone. Generally, the XS3 exposure class is regarded as the most critical one as more chlorides are able to penetrate into the concrete owing to the greater degree of convection resulting from the intermittent wetting and drying. Furthermore, XS2 exposure class is regarded as less critical in practice and in codes in view of the long propagation period compared with XS3 exposure class owing to the low level of available oxygen and the lower potential difference (uniform moisture content) of the concrete.

While the calculated chloride profile (mean value) reproduces the actual chloride values for the spray and tidal zones relatively well, particularly in the lower depths (figure 2, left), some of the chloride values measured in the submerged zone are far above the calculated mean value profile (figure 2, right). For the submerged zone, a lower degree of scatter was assumed for $C_{s,\Delta x}$ (LND (4.0 / 1.0) than for the XS3 exposure class (LND (4.0 / 1.8) and a convection zone was not taken into account ($\Delta x = 0$).

Figure 3, left, shows that the model calculation confirms the measured chloride values for the 55-year-old structural elements. The actual chloride values for several structural elements (with an age of approximately 25 years) in four different marine structures on the Baltic Sea coast are compiled in figure 3, right. The figure shows that, apart from the individual values for depths of 50 mm and 70 mm, the measured and calculated chloride profiles correspond quite well. The high chloride values at a depth of 70 mm after only 25 years' exposure do not seem plausible.



* determined by hot water extraction

input parameters for the model based calculation, eq. (1):

Parameter	distribution & values
D_{RCM} [$10^{-12}m^2/s$]	ND (5.0/1.0)
t_0 [s]	constant 2,419,200 (28 d)
ageing factor α [-]	BetaD (0.40/0.18/0/1)
T_{ref} [K]	constant 273
T_{real} [K]	ND (282/6)
b_0 [K]	ND (4800/700)
$C_{s,\Delta x}$ [wt.-%/c]	LND (4.0/1.8)
Δx [mm]	BetaD (8.9/5.6/0/50)
k_1 [-]	constant 1
C_0 [wt.-%/c]	constant 0

Figure 1: Measured and calculated chloride values of several elements of a 35-year-old marine lock (left), input parameters for modelling (right)

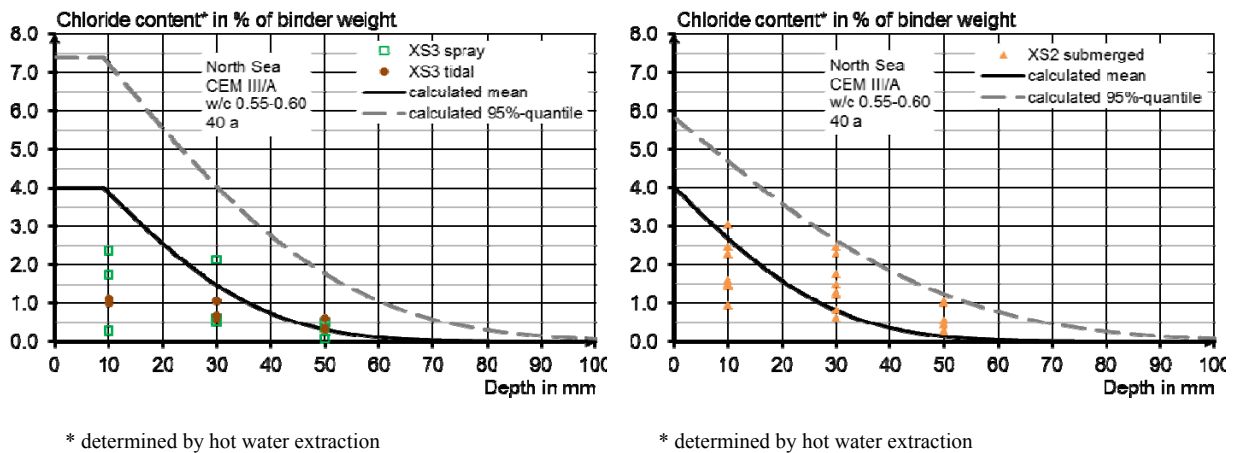


Figure 2: Measured and calculated chloride values of several elements of a 40-year-old marine lock; left: spray and tidal zone; right: submerged zone

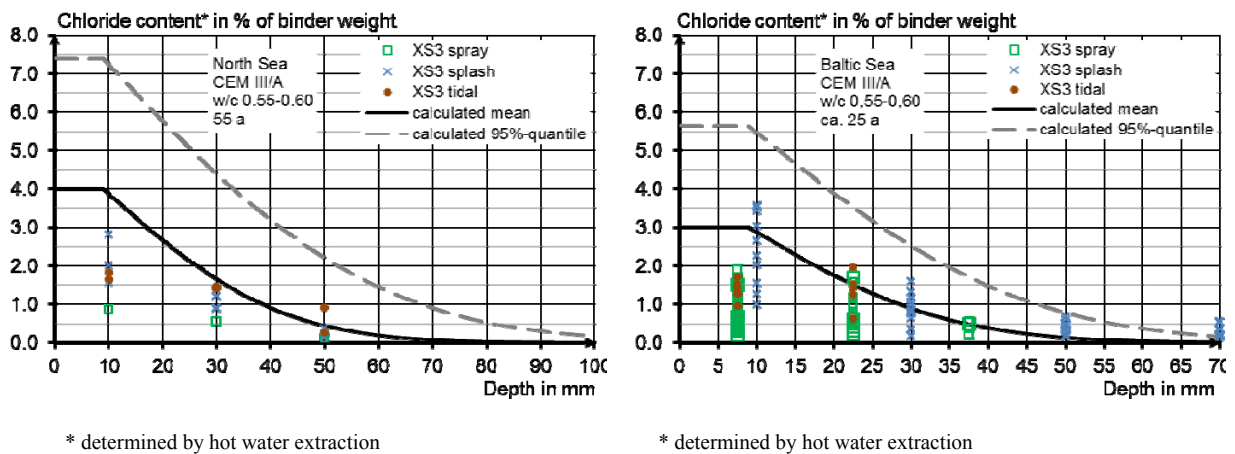


Figure 3: Measured and calculated chloride values; left: several elements of a 55-year-old marine lock on the North Sea; right: several elements of four different marine structures on the Baltic Sea with an age of around 25 years

Apart from real structures, valuable data for the validation and calibration of models can also be obtained by conducting exposure tests. The advantage of the latter is that they are able to provide sound information on the materials used and the conditions under which the test specimens were produced. The results of a long-term exposure test are presented in figure 5. In 1991, concrete slabs with the dimensions 2.45 x 1.40 x 0.15 m³ were produced and installed on the North Sea and Baltic Sea coasts [13]. Two types of concrete made with different types of cement, CEM I (concrete A) and CEM III/B (concrete B), were used. The w/c ratio was 0.50. Figure 6 shows the exposed slabs on the Baltic Sea coast. The slabs are divided into three zones according to the type of exposure: submerged (XS2), tidal and splash (XS3) zones.

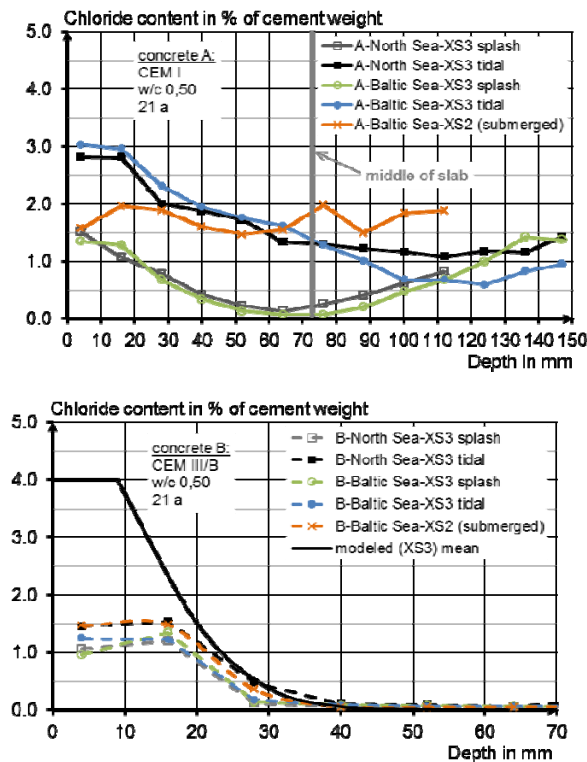


Figure 5: Chloride profiles in slabs after 21 years' exposure on the North and Baltic Sea coasts; left: without calculated profile for CEM I (Portland) concrete because of interpenetration; right: incl. calculated profile for CEM III (GGBS) concrete

The chloride profiles of the slabs made of concrete A after around 21 years' exposure are shown in figure 5, left. The slabs are exposed on both sides and the chloride profiles show that the chlorides have already interpenetrated them, particularly in the tidal and submerged zones. Such profiles cannot be calculated by using equation (1). This was the reason why no calculation was performed for chloride profiles measured on CEM I samples, figure 5, left. However, it may be assumed that the edges of the slab sections in the tidal and splash zones have not yet been permeated by chlorides.

The profiles on the North and Baltic Sea coasts are strikingly similar although the chloride content of the North Sea is more than twice that of the Baltic. The chloride values in the splash zone are considerably lower than in the other zones.

The penetration patterns of the chlorides differ on the front (facing the sea, left half of the diagram) and the back (facing the wall, right half of the diagram) of the slabs. In the tidal zone, higher chloride values are to be found on the front of the slabs which can be explained as follows. On the one hand, the back of the slabs is shaded from the sun and thus has a lower temperature than the front, which slows down the diffusion of chloride ions. On the other hand – and which is far more significant – the back of the slabs is covered with algae growths which makes it more difficult for chlorides to penetrate into the concrete. Furthermore, the

different pore structures of each surface (front: concrete surface cast against the formwork, back: as-poured concrete surface) are also significant.

This difference is less marked in the splash zone and in some cases is even reversed. The water rebounding from the wall onto the back of the slabs and thus the greater availability of chloride ions may counteract the effects referred to above, resulting in the slightly higher chloride values on the back of the slabs. Similar patterns can be seen in the results of the investigations after 3 and 6 years' exposure [13]. In this case, the effect of the microclimate on the penetration behavior of the chlorides in the slabs can be clearly seen.

The chloride values of the slabs made from concrete B are presented in figure 5, right. The CEM III concrete exhibits a much greater resistance to chloride ingress than the CEM I concrete. The very low surface chloride content (first depth) in all slabs and for all exposures is striking. This again confirms that using the sorption isotherms to calculate the surface chloride content (see above) leads to inaccurate results as, according to that method, the CEM III concrete ought to exhibit a higher surface chloride content than the CEM I concrete. The chloride profiles for the edge zones are far below the calculated profile.



Figure 6: Exposed slabs on the Baltic Sea coast

The results after 21 years' exposure were obtained by studying a single drilled core taken from each slab and for each type of exposure. For the studies conducted after 3 and 6 years' exposure, several drilled cores were taken and analyzed [13]. The results have shown that a certain degree of scatter can be expected, even in relatively small areas within individual exposure zones, e.g. in the lower, middle and upper sections of the tidal zone.

The statistical calculations for the model and the reliability analyses were performed numerically using the STRUREL program [14].

4. VALIDITY OF MEASURED CHOLIDE CONTENTS OF STRUCTURES

While laboratory tests form the basis for developing durability models, it is essential to use the values of structures obtained from measurements to calibrate and validate them. The model parameters for chloride transport in concrete such as the ageing exponent, surface

chloride content, convection zone, etc. can be modified with the aid of chloride profiles determined by studying structures and the model thus adapted to the conditions in practice. This raises the question as to whether the measured chloride values are representative and accurate. Several aspects of the reliability and validity of the measured chloride values for structures are discussed below.

Sampling: The position at which the samples are taken and the sampling procedure are both of great importance. The chloride samples used to validate the model must be appropriate for the exposure, be taken from representative sampling locations and must not exhibit any singularities (such as cracks). Sampling is either carried out by drilling cores which are subsequently sawn into segments or by taking samples of borehole cuttings. When sampling the latter, care must be taken to ensure that chlorides from the upper levels do not contaminate the lower levels. Lack of care during sampling or an inappropriate choice of sampling location will result in chloride values that lead to errors when assessing the structural elements and the model.

Sample preparation and analysis: The preparation and chemical analysis of the samples is specified in EN 14629 [15] although national provisions, such as [16] in Germany, are also applied. These may differ with regard to the extraction method (hot / cold), fineness, homogenization and the way in which the chemical characteristics are determined (potentiometric or photometric method). Furthermore, water extraction is often used for an approximate determination of the free chloride content, while the chloride transport model according to [1] deals with the total chloride content which is determined by acid-extraction of the chlorides in the samples [15].

Initial chloride content: As shown by equation (1), the initial chloride content of the concrete is one of the parameters in the model. The initial chloride content of the concrete comprises the chloride contents of the constituents, such as cement, aggregates and water, but is unknown for nearly all old structures and many recent ones.

Interaction of different actions and degradation mechanisms: Apart from chloride-induced corrosion, concrete structures in a marine environment are affected by other degradation phenomena such as carbonation, alkali-silica reaction, scaling, internal cracks, etc. caused by different actions such as ice abrasion and frost as well as mechanical loads. These damage mechanisms may interact and affect each other. This aspect must be considered when evaluating the chloride values obtained.

5. CONCLUSIONS

The following conclusions can be drawn from the studied measured chloride contents of various concrete elements and the test slabs installed on the German North Sea and Baltic Sea coasts:

- The type of binder is of great importance for the resistance of concrete to chloride ingress. As expected, CEM III (GGBS cement) concretes have a far greater resistance to chloride ingress than CEM I concretes. CEM I (Portland cement) concretes without additives are not suitable for applications in marine conditions.
- Exposure class XS2 (submerged) is similar to, and in some cases, even more severe than exposure class XS3 (spray, splash, tidal). The chloride content in zones close to the surface and within the elements is similar for both types of exposure.
- The intensity of XS3 exposure class is generally as follows: tidal > splash > spray. However, this depends to a great extent on the prevailing climatic and geometrical conditions.
- The differences in the microclimatic conditions in the structural elements result in different chloride ingress patterns, which also vary within an exposure class.
- Although the chloride concentration of the Baltic Sea is less than half that of the North Sea, the chloride profiles determined from structural elements on the coasts of both seas are similar. This applies to both the surface chloride concentration and the chloride content in the lower sections of the elements. Further studies are required in order to be able to assess the effect of the concentration of the chloride source on the chloride penetration in concrete elements.

The predictive model developed by fib [1] was able to deliver an approximate reproduction of the actual chloride contents. The correspondence between the measured and calculated chloride profiles was closer for XS3 exposure class than for XS2 exposure class and was also closer for the lower depths than for the surface of the structural elements. As the measured chloride values of the elements do not correspond to the total chloride content (extraction by hot water instead of acid) they can only be compared with the results of the model to a limited extent.

The need for predictive models for the performance-based design of concrete structures for durability is undisputed. In the case of chloride-induced corrosion of the reinforcement, the model developed by fib [1] can be used to obtain an approximate predict of the time- and depth-dependent chloride contents in concrete for the purpose of estimating and assessing the service life of structures.

The predictive models are initially derived from the results of laboratory tests and subsequently verified by data obtained for actual structures and by exposure tests. The next step is to calibrate and validate the models both generally and for specific cases, again using actual data for structures. When using the latter, it must be taken into account that such data may sometimes be subject to large degrees of scatter and uncertainty. Apart from the natural inhomogeneity of concrete and inconsistencies in execution, the scatter and uncertainties may also be due to other factors such as lack of care during sampling and unsuitable sampling locations as well as differences or errors in the preparation of the samples and when

performing the chemical analysis. In addition, influences due to the possible interaction of other damage mechanisms need to be taken into account when calibrating and validating the model.

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