Observed Chloride Penetration in Eastern Scheldt Storm Surge Barrier, The Netherlands, after 20 years in North Sea Environment

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Abstract

On site and laboratory testing was performed with regard to durability of the **Eastern Scheldt Storm Surge Barrier**. The structure was built in the 1980s on the South West coast of The Netherlands. The Barrier stretches about 2800 m across the Eastern Scheldt estuary including two islands and consists of 65 openings, each with cast in-situ piers connected by precast beams and precast bridge elements and steel sliding doors. All concrete was made of blast furnace slag cement with a low w/c, using river sand and either dense river gravel or lightweight coarse aggregate. Cover depth to the reinforcement was measured. In the laboratory, chloride profiles, thin section microscopy and compressive strength and splitting tensile tests were performed. Chloride penetration is discussed with regard to concrete type and exposure. Service life calculations are presented using the DuraCrete model for chloride ingress induced corrosion initiation.

key words: concrete, chloride, corrosion, field study, marine environment, blast furnace slag, DuraCrete

Introduction

The Eastern Scheldt Storm Surge Barrier is located on the south-western coast of the Netherlands. The Eastern Scheldt Barrier was designed in the 1970s to protect the low-lying land against flooding from sea water. The main structure was designed for a service life of 200 years using then existing service life prediction models; the bridge superstructure was designed for 50 years. The dominant deterioration mechanism was considered to be chloride ingress induced reinforcement corrosion. The barrier was built in the period 1980-1986 and a few chloride profiles were taken in 1989 and 1994. Presently, the owner is considering the need for maintenance of the bridge superstructure in 2005-2010.

Intensive inspection and sampling of four test areas on the barrier was carried out as part of a larger project for CUR research committee B82 ‘Durability of Marine Concrete Structures’ (DuMaCon). The DuMaCon program aims to collect data and to validate the service life model developed in DuraCrete [1]. Additionally, large scale chloride profiling on the bridge superstructure was done for evaluating the need for maintenance. This paper concentrates on analysis of chloride ingress in the bridge superstructure.

DuraCrete model for chloride penetration induced reinforcement corrosion

The DuraCrete model for chloride penetration induced reinforcement corrosion assumes chloride transport by diffusion, based on a constant chloride surface content, a time-dependent diffusion coefficient and a constant critical chloride content at the reinforcement. All three variables depend on the exposure, which for marine structures is divided in submerged, tidal, splash and atmospheric zones. Corrosion is schematised in two phases: an initiation phase in which chloride penetrates to the reinforcement until the critical content is reached; and a propagation phase in which actual corrosion takes place until an unacceptable level of damage is reached. Chloride penetration is the dominant process during the initiation phase. Figure 1 shows an example of chloride profiles at two ages and the relationship to the two phases.

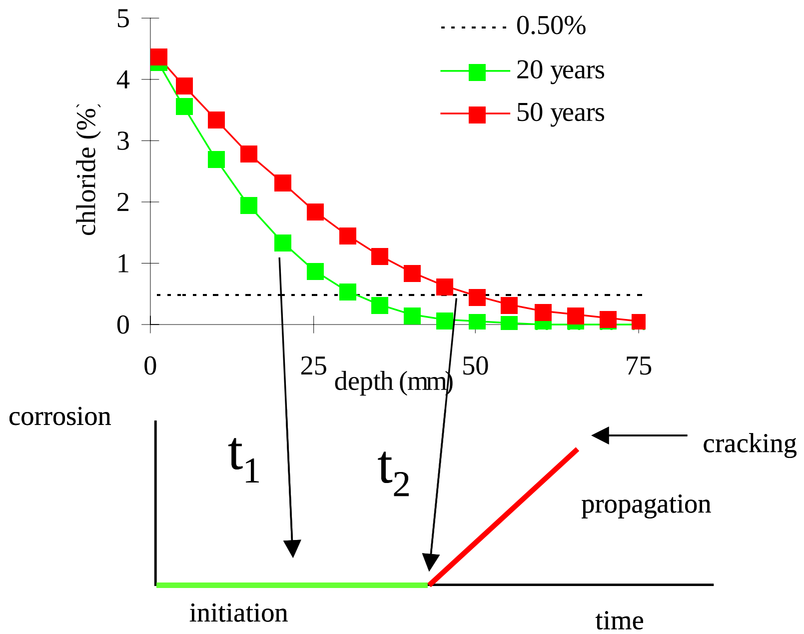


Figure 1 Chloride profiles in a concrete structure in marine environment at two ages and their relationship to the two phases in the corrosion process; critical chloride content 0.5%

Since the 1970s, chloride transport in concrete has been modelled as a diffusion process using Fick's second law. For the case of penetration from the outside into chloride-free concrete and C_s and D_{app} are constants, the chloride content C(x,t) at depth x (for instance at the front of the rebars) and at time t is then given by:

$C(x,t) = C_s\ [1 - \text{erf}\ (x/2\sqrt{}\ (D_{app}\ t)]$ (1)

with C_s *the chloride surface content* and D_{app} *the (apparent) chloride diffusion coefficient* and erf *the error function*.

From repeatedly investigated exposure sites and other work, it was discovered that the diffusion coefficient was not constant but appeared to decrease with time [2, Helland], and more strongly so for blended cements (blast furnace slag and fly ash cements) than for Portland cement. This led to the introduction of the time-dependency of the diffusion coefficient [3, Helland], which can be modelled as an exponential decrease:

$D_t = D_0\ (t_0/t)^n$ (2)

with D_t and D_0 the *diffusion coefficients at the time of inspection* t and *at a reference time* t_0 (for instance from a test at early age in the laboratory), respectively; the *aging exponent* n takes values between 0 and 1, depending on the environment and the cement type. The DuraCrete model further includes a set of *conditional coefficients* expressing the influence of the environment, the cement type and the curing, here together denoted K. The chloride content C(x,t) at depth x (for instance at the front of the rebars) and at time t is then given by:

$C(x,t) = C_s\,[1 - \mathrm{erf}\,(x/2\sqrt{\{K\,D_0\,(t_0/t)^n\}})]$ (3).

A slightly different solution has been proposed [Visser et al.]. DuraCrete provides a simple model for calculating C_s from the exposure zone and the concrete composition:

$C_s = A_{c,Cl}\,(w/b)$ (4)

with $A_{c,Cl}$ a *regression coefficient* depending on the cement type and the exposure zone; and (w/b) the *water-binder ratio*.
The DuraCrete Final Technical Report [1] provides tabulated values for n and (individual coefficients together forming) K, based on exposure data and expert opinion.

In the design stage for a new structure, the DuraCrete approach can be applied as follows. The chloride surface content is calculated for the particular exposure zone. The intended cover depth is determined and a limit value for the diffusion coefficient at 28 days is calculated using equation (3) from the desired length of the initiation period. Concrete compositions with potentially suitable diffusion coefficients are selected from a database. Then trial mixes are made and their diffusion coefficients are tested at 28 days age using a compliance test, for which DuraCrete has chosen the Rapid Chloride Migration (RCM) test [4]. RCM is a short term test based on acceleration of chloride penetration by an electric field. If necessary, the composition is modified until satisfactory D_0 values are obtained. Several major structures have been designed for service life using this method. It should be noted that for new structures, D_0 is known (measured) and C_s is predicted.

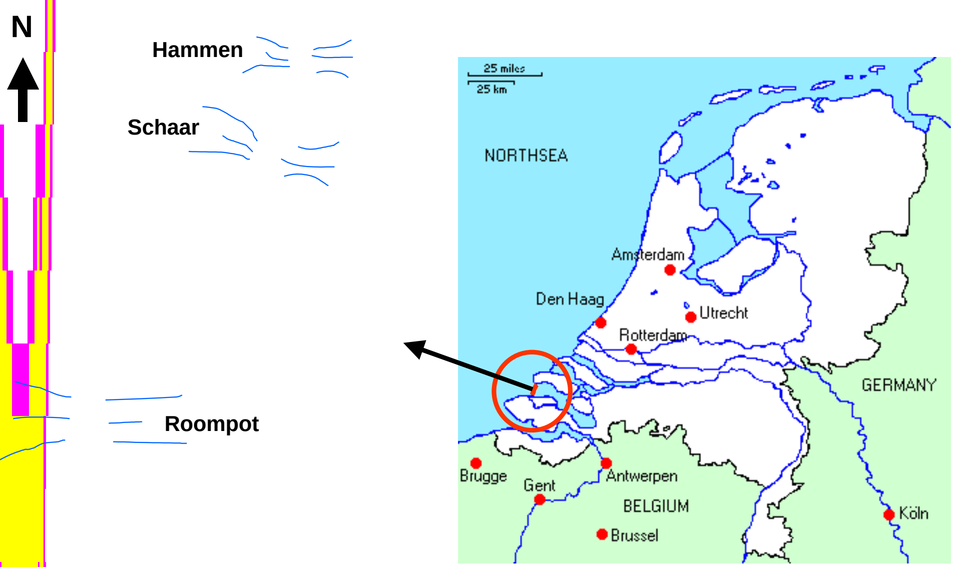
All considerations given here pertain to *mean* times-to-corrosion. DuraCrete provides both a full-probabilistic approach as well as partial factors for a LRFD based approach for calculating probabilities of failure. This is outside the present scope, however.

Verification of the DuraCrete model from existing structures

In principle the model is also applicable to existing structures. In most cases, however, the 28-day diffusion coefficient is not available because it has not been measured at the time of construction. Generally, only a set of chloride penetration profiles taken during an inspection at time t_{insp} will be available. The profiles are analysed using equation (1), which produces a set of pairs of C_s and D_{app} values. So for an existing structure having been inspected once, C_s is known and D_0 is not. One way of further analysis is to apply the tabulated aging exponent and environmental coefficient (calculating backwards in time), to arrive at D_0. Predictions for future penetration can now be made similarly to the situation for new structures by applying equation (3). Using C_s from the profiles instead of calculating it from equation (4) can be used for updating the service life design. However, this implies that the aging exponent and the conditional coefficients are reliable. At present, their reliability is limited. In this study, C_s and D_{app} are taken from the inspection profiles together with D_0 values from a database for similar concrete compositions; D_t (from calculation) is supposed equal to D_{app} (from inspection). Then the age exponent n and the conditional coefficient K that shows the best fit to all sets of C_s, D_{app} and D_0 are compared to the tabulated values.

Layout of the structure

ıe Eastern Scheldt has a length of 2800 m and is located in the
lands at the estuary of the Eastern Scheldt bay into the North
parts – Hammen, Schaar and Roompot – named after the
s (see figure 2). It contains 65 openings, of which 59 can be
ıring normal weather conditions the sliding doors are fixed in
lal movements. Only during periods of strongly increased
closed by lowering the sliding doors.



ıeldt Storm Surge Barrier and its three parts: Hammen,

of 62 concrete piers at 45 m centres. The piers are linked by
nd upper beams about 1 m above mean sea level (NAP). The
r beams are manufactured from gravel concrete with
l. A motorway “bridge” is built over the storm surge barrier
of prestressed concrete box girder elements. A schematic is shown in figure 3.

The bridge-elements consist of dense gravel concrete (max grain size 32 mm, 325 kg blast furnace CEM III/B per m^3, w/c 0.44) except for one span at each abutment, made of lightweight concrete with expanded shale as coarse aggregate (max 8 mm, 400 kg CEM III/B per m^3, w/c 0.38). Each section was precast and steam cured for 2 hours (max. temperature 37 °C). The bridge-elements were cast and placed mainly in 1984. The bridge-elements are T-shaped, which means that the investigated sides of the box girders are protected against direct precipitation. They are elevated between NAP + 7.0 m and NAP + 11.75 m. In the raised position, the lowest part of the sliding doors is about 1 m above NAP and their height varies between 5.90 m and 11.90 m with the highest doors near the midpoint of the original tide-ways. This means that the sliding doors will be shielding (part of) the bridge-elements facing the North Sea. Turbulent airstreams have been observed around the structure.

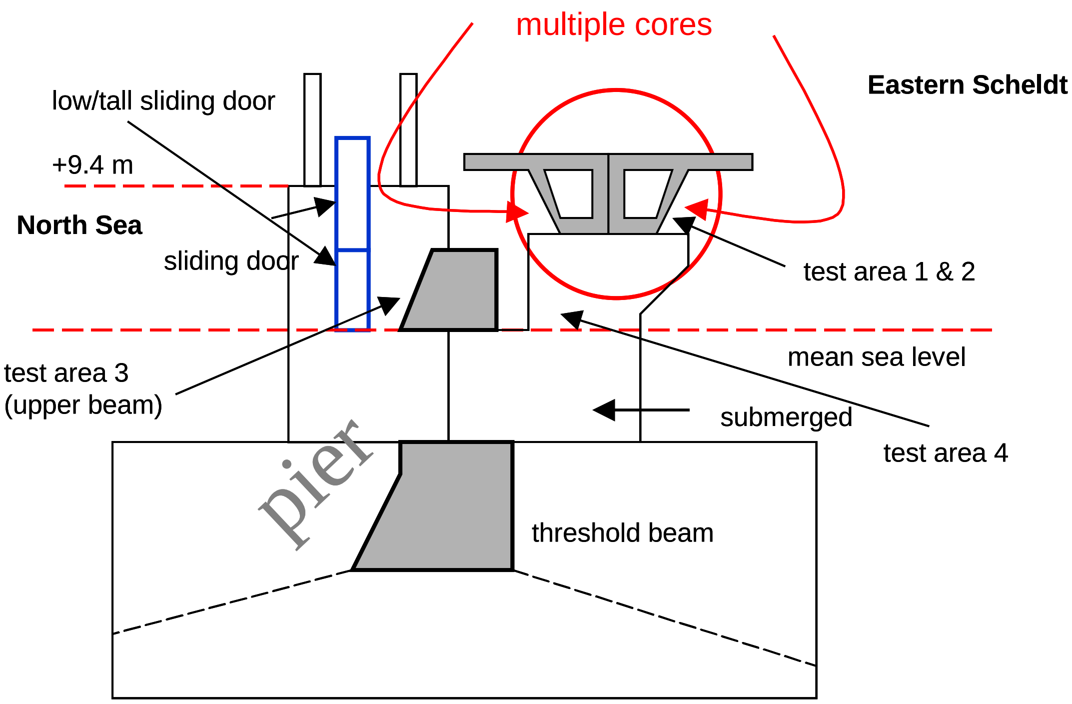


Figure 3 Cross section of pier, beams and bridge element, sliding door (in raised position), test areas and cores

Inspection and sampling

Intensive investigation for DuMaCon took place in 2002 on four test areas (1 - 4, each about 1 x 1 m^2, indicated in Figure 3). In test area 1, six cores were taken from the web of a gravel concrete bridge element on the Eastern Scheldt side; test area 2 was on lightweight concrete. Cores of 100 mm diameter were taken for compressive and tensile strength and RCM testing. For the additional profiling investigation (API), about 75 cores were taken from bridge elements, indicated "multiple cores", from both sides of the bridge and along the complete length of the barrier. Chloride profile cores had 50 mm diameter. They were diamond-sawn in 10 mm thick slices, which were powdered, dissolved in hot nitric acid and titrated according to Volhard. DuMaCon testing involved 6 slices (010, 10-20, .. 50-60 mm) and API testing involved 4 slices (10-20, 20-30, 30-40 and 40-50 mm).

Results

Mean chloride profiles are shown and discussed for various combinations of factors that could influence chloride penetration: concrete composition (lightweight/normal weight); North Sea/Eastern Scheldt side; height of sliding door. Some factors appear to interact. On the North sea side chloride ingress is much lower for lightweight concrete than for gravel concrete. This is also the case on the Eastern Scheldt side, but the difference is small compared to the scatter (see figure 4). For gravel concrete the chloride penetration is higher on the North sea than on the Eastern Scheldt side, while for lightweight concrete it is higher on the Eastern Scheldt side than on the North sea side.

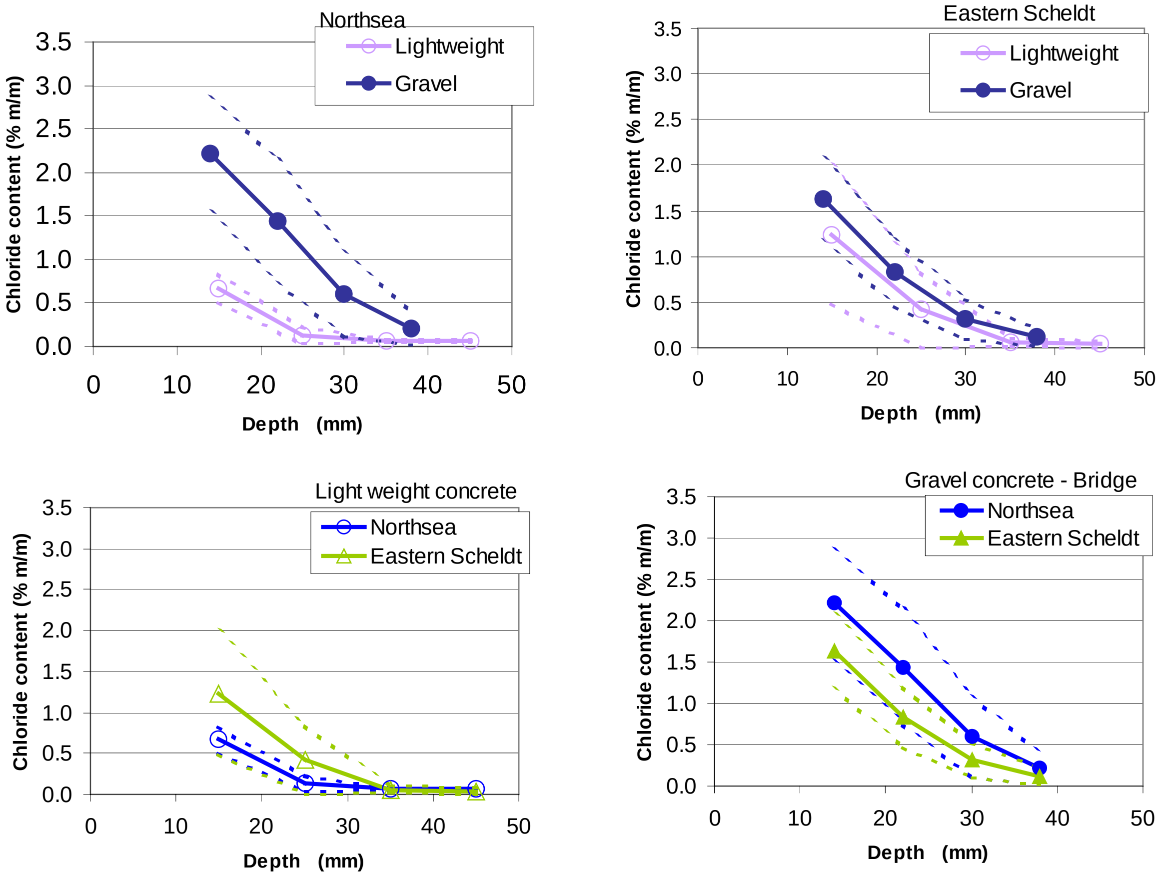


Figure 4 Various groups of chloride profiles; solid lines: mean; hatched lines: mean plus or minus one standard deviation

Another source of variation is related to the position along each of the three parts of the barrier (Hammen, Schaar, Roompot), associated with the depth of the flow channel and the height of the sliding doors. Mean chloride profiles have been plotted per bridge element and compared to the relative door height in Figure 5. It shows that the lowest chloride ingress has occurred behind the highest doors and that the effect is most pronounced in the Schaar part of the barrier. It appears that the sliding doors shield and partly protect the bridge-element at the North sea side. On the Eastern Scheldt side no noticeable effect of the size of the doors was found. This issue concerns only gravel concrete, as there are no sliding doors in front of the lightweight spans.

Chloride penetration profiles are characterised by C_s and D_{app} obtained by fitting the diffusion equation (1). Table 1 summarizes the data. The chloride surface content C_s for gravel concrete appears to be rather constant at 4.5 to 5%, except for the influence of slide door height (extremes 6.8 and 2.6%). C_s for lightweight concrete is lower on the North Sea side, but apparently it varies between locations on the Eastern Scheldt side. The mean value of 9 cores taken along the complete barrier was 5.5%, with extremes 3.1% and 10.8%. In test area 2 (Hammen 16), the mean of 6 cores taken within 1 m^2 of concrete surface was 3.1%. D_{app} is remarkably constant for gravel concrete, about 0.30 * 10^{-12} m^2/s; and slightly more variable for lightweight concrete between 0.13 and 0.21 * 10^{-12} m^2/s.

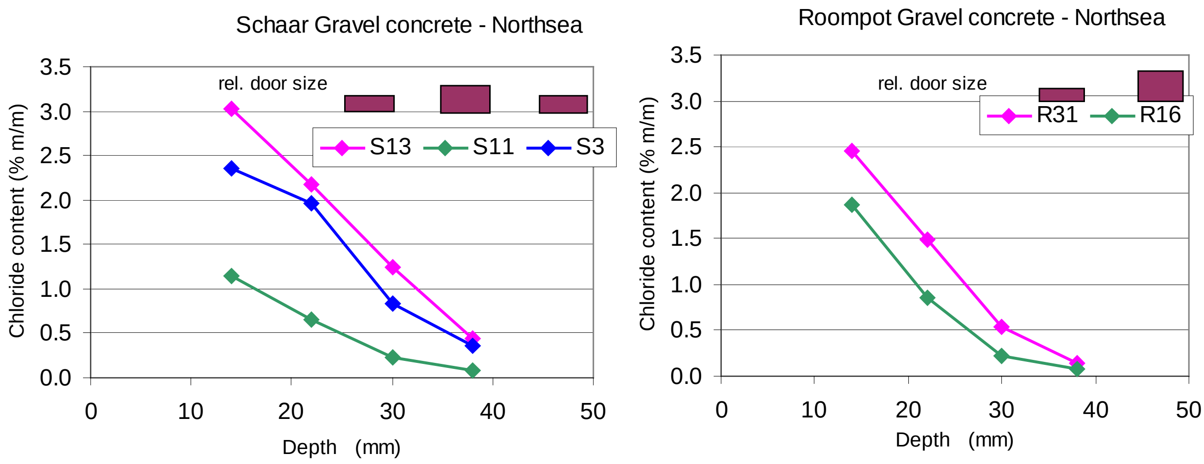


Figure 5 Chloride profiles in gravel concrete on North sea side, on different positions along the flow channels Schaar and Roompot with relative door height indicated

Table 1 Mean values (and standard deviation, SD) for C_s and D_{app} for various combinations of exposure, concrete composition and door height; API additional multiple core testing; TA1, 2 Test Areas 1 and 2; Schaar 13 and 11 are sub-sets of API; number of cores per data-set

concrete	gravel			lightweight			gravel	
dataset (door height)	API	API	TA 1	API	API	TA 2	Schaar 13 (5.9 m)	Schaar 11 (11.9 m)
exposure side	North Sea	Eastern Scheldt	Eastern Scheldt	North Sea	Eastern Scheldt	Eastern Scheldt	North Sea	North Sea
Surface content (% by mass of cement)	4.9 (1.3)	4.4 (1.3)	5.3 (1.5)	3.4 (1.2)	5.5 (2.4)	3.1 (0.1)	6.8	2.6
Diffusion coefficient ($\times 10^{-12}$ m^2/s)	0.33 (0.12)	0.26 (0.09)	0.28 (0.12)	0.13 (0.05)	0.21 (0.09)	0.13 (0.01)	0.27	0.30
no. of cores	14	12	6	16	9	6	1	2

Microscopy of 13 samples showed that the concrete was properly mixed and compacted. The cement type was blast furnace (>65% slag) and the degree of hydration was moderate to high, the original w/c about 0.45. Paste-aggregate bond was good (gravel) to excellent (lightweight). No deterioration was observed due to frost, sulphate, alkali-silica reaction or leaching. Carbonation depths were generally a few mm. Deposition of products of reaction between cement paste and sea water (such as calcite, brucite, ettringite) were restricted to a layer of 0.1 mm thickness on the surface and voids down to a few mm depth. The overall quality was good (gravel) to excellent (lightweight). Compressive (tensile) strength for both mixes was c. 60 MPa (4 MPa), wet density about 2420 (gravel) and 1830 (lightweight) kg/m^3. During the inspection, cover depths were measured using a scanning cover meter. Steel in gravel concrete in Test Area 1 had a mean cover depth of 41.1 mm (SD 1.4 mm). The outer bars in lightweight concrete in Test Area 2 had a mean cover depth of 47.7 mm (SD 3.2 mm).

DuraCrete calculation of time to corrosion initiation

Table 2 reports the input and output of DuraCrete model calculations for gravel concrete from Test Area 1 for 3 cases. A 4th case is added, based on the observed mean values for the chloride surface content and diffusion coefficient (assumed constant). Case 1 is based on equation (3) and the conditional coefficients for the atmospheric zone. Both the chloride surface content and diffusion coefficient are strongly underestimated. The time-to-initiation is about 90 million years. This value is obviously too optimistic; it is not realistic to design the bridge elements for atmospheric exposure. Case 2 is based on equation (3) and splash zone exposure coefficients. The time-to-initiation is about 230 years. Because the calculation underestimates C_s, this result must be regarded as optimistic; the diffusion coefficient is correctly predicted. Case 3 is based on splash zone exposure, however, the surface content is taken (updated) from the measurements (Table 1). The time-to-initiation is about 90 years; this seems to be a realistic mean time-to-initiation. For the worst case with the highest surface content due to limited shielding by a low sliding door (Schaar 13, Table 1), a time-to-initiation was found of 65 years. Case 4 is based on the observed surface content and diffusion coefficient and equation (1). It assumes the latter to be constant during the remaining service life, without considering its decrease over time and therefore it is outside the DuraCrete model. This approach does not take into account the beneficial effect of further hydration or the effect of drying out (n = 0). The time-to-initiation for Case 4 is about 34 years. Summarising, the DuraCrete prediction (using the splash zone model) for the gravel concrete bridge elements is too optimistic, because the chloride surface content is underestimated. Updating with the observed surface content after 18 years appears to produce a realistic *mean* time-to-initiation. Figure 6 presents the chloride profiles calculated using case 1, 2 and 3 and the mean profile as observed on Test Area 1.

It appears that whatever model is used, the *mean* time-to-initiation of the gravel concrete bridge element is well beyond the required design life of 50 years. The lowest time-to-initiation may be found for elements where the steel sliding doors are lowest.

Table 2 Input and output of DuraCrete model calculations for 3 cases and time-independent calculation from observed values for surface chloride content and chloride diffusion coefficient; gravel concrete bridge element Hammen 8; RCM at 28 days 4.5 * 10^{-12} m^2/s [5]; critical chloride content 0.5%, cover 41.1 mm

test area	1			
location	gravel concrete bridge element Hammen 8, Eastern Scheldt side			
case	1	2	3	4
DuraCrete zone	atmospheric	splash	splash + C_s (update)	observed
n (-)	0.85	0.60	0.60	D constant
C_s (% mass of cement)	1.4	3.0	5.3	5.3
D_t (10^{-12} m^2/s)	0.18	0.28	0.28	0.28
t_{ini} (year)	$9*10^7$	230	92	34

Table 3 reports the input and output for 3 cases of DuraCrete model calculations for lightweight concrete (test area 2). As above, a 4th case is added based on the observed values for surface chloride content and diffusion coefficient. Case 1 is based on DuraCrete calculations for the atmospheric zone. The time-to-initiation is 700 million years. This value is too optimistic, due to the strongly underestimated chloride surface content. Case 2 is based on splash zone exposure. The time-to-initiation is about 600 years. Because the calculation overestimates D_{Cl}, strictly spoken this result must be regarded as pessimistic. Case 3 is based on splash zone exposure, however, the age exponent is increased (updated) in order to arrive at the diffusion coefficient found after 18 years. The time-to-initiation is 80,000 years. Case 4 is based on the observed surface content and diffusion coefficient. As mentioned above, this is outside the DuraCrete model. The time-to-initiation for Case 4 is about 160 years.

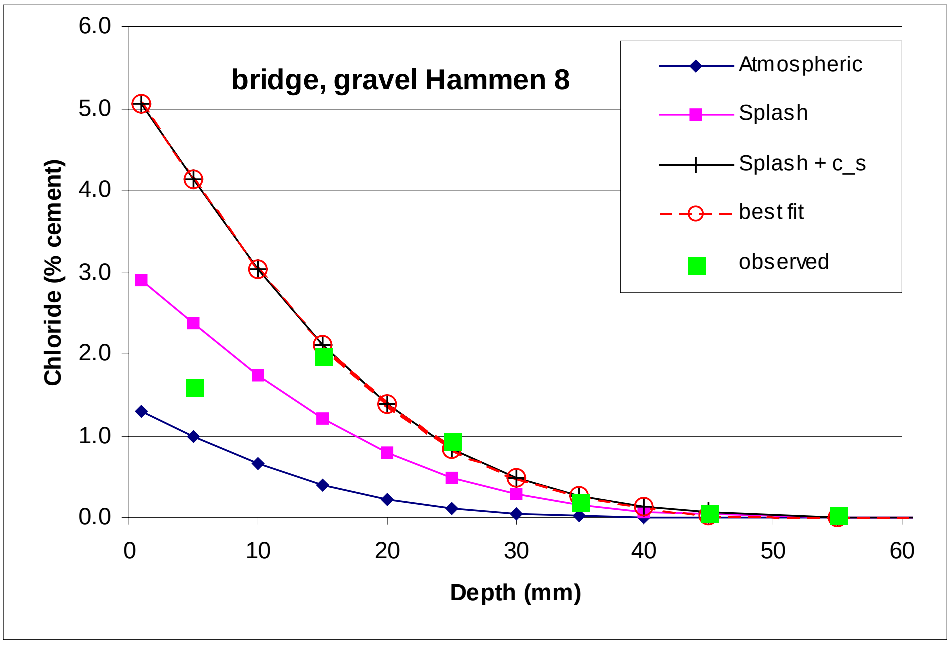


Figure 6 Chloride profiles calculated using case 1, 2 and 3 and the mean profile as observed on test area 1 (case 4)

Considering the data from all cores taken in lightweight concrete, the results change slightly. The cores taken for API from the Eastern Scheldt side (Table 1) show a much higher surface content and a much higher diffusion coefficient than test area 2. Consequently, the time-to-initiation is significantly shorter. By coincidence, test area 2 is the most favourable location of all lightweight elements sampled. Using the mean values for all lightweight concrete on the Eastern Scheldt side (see Table 1), a modified DuraCrete splash zone calculation produced a mean time-to-initiation of 750 years (instead of 80,000, case 3) and a constant diffusion coefficient produced 66 years (case 4). Taking the results from Schaar 17, where chloride penetration was most advanced of all lightweight elements, the case 3 result was 275 years.

Table 3 Input and output of DuraCrete model calculations for 3 cases and for observed values for surface chloride content and (constant) chloride diffusion coefficient; lightweight concrete bridge element Hammen 16; RCM at 28 days assumed 4.5 * 10^{-12} m^2/s [5]; critical chloride content 0.5%, cover 47.7 mm

test area	2			
location	lightweight concrete bridge element Hammen 16, Eastern Scheldt side			
case	1	2	3	4
DuraCrete zone	atmospheric	splash	splash + n (update)	observed
n (-)	0.85	0.60	0.74	D constant
C_s (% mass of cement)	1.4	3.0	3.0	3.0
D_t (10^{-12} m^2/s)	0.18	0.28	0.13	0.13
t_{ini} (year)	$7*10^8$	485	$8*10^4$ *750 mean for API*	160 *66 mean for API*

It appears that whatever model is used, the *mean* time-to-initiation of this element is well beyond the required design life of 50 years; it is probably beyond the required service life of the complete barrier (200 years). It should be noted, however, that the DuraCrete models may not apply for lightweight concrete, as the Final Technical report does not explicitly give parameter values for concrete made with lightweight aggregate.

Conclusions

A large scale investigation of chloride penetration was carried out on the Eastern Scheldt Storm Surge barrier, constructed on the North Sea coast in the 1980s. This paper concentrates on the bridge superstructure.

Data after c. 18 years marine exposure show advanced chloride penetration, which depends on concrete type (gravel or lightweight), orientation (North Sea or Eastern Scheldt side) and shielding by sliding doors.

Analysis using a time-independent diffusion equation shows relatively consistent values for chloride surface content and diffusion coefficient for gravel concrete; however, more scatter was present in these parameters for lightweight concrete.

Further analysis was made using the DuraCrete time-dependent diffusion model. Modelling as atmospheric exposure strongly underestimated chloride penetration. Reasonable fits to observed profiles were obtained using coefficients for splash zone exposure. Times-to-corrosion-initiation resulted of about 230 years (gravel concrete) and about 500 years (lightweight concrete). The prediction was updated from the inspection using the observed chloride surface content (gravel concrete) or the age exponent (lightweight concrete). Updated times-to-corrosion-initiation resulted between 65 and 90 years (worst case and mean for gravel concrete) and between 275 and 750 years (worst case and mean for lightweight concrete).

Regarding the DuraCrete model and its tabulated coefficients, chloride transport in the gravel concrete was modelled correctly, but the surface content was underestimated. For lightweight concrete, the surface content was modelled correctly but the rate of chloride transport was overestimated.

Future maintenance of the bridge superstructure, in principle scheduled for 2005-2010, will be based on the results of the inspection.

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