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Hvad er chloridtærskelværdien?
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OUTLINE

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- Chloride threshold value
- RILEM TC 235-CTC findings
- Femern field exposure site in Rødbyhavn
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- Preliminary chloride threshold values after 5 years exposure
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INTRODUCTION

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- Chloride induced reinforcement corrosion is typically the main concern for durability of marine structures
- Service life modeling of marine structures are based on estimates of the chloride penetration and the chloride threshold concentration (CTC) for corrosion initiation
- A standard test method for determination of CTC-values are not established (RILEM TC 235-CTC were not successful on that)
- Anode ladders for corrosion monitoring have been installed in many structures, but in many cases the evaluation of data from HCP-values has been difficult

CORROSION PROCESS

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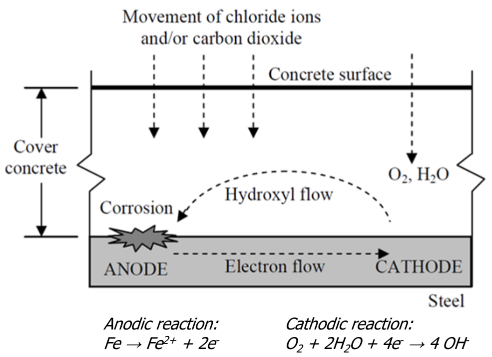

From:
J.R. Mackechnie and M.G. Alexander. *Repair principles for corrosion-damaged reinforced concrete structures.* Research Monograph No. 5, Department of Civil Engineering, University of Cape Town, 2001, p1-36.

CHLORIDE THRESHOLD VALUE

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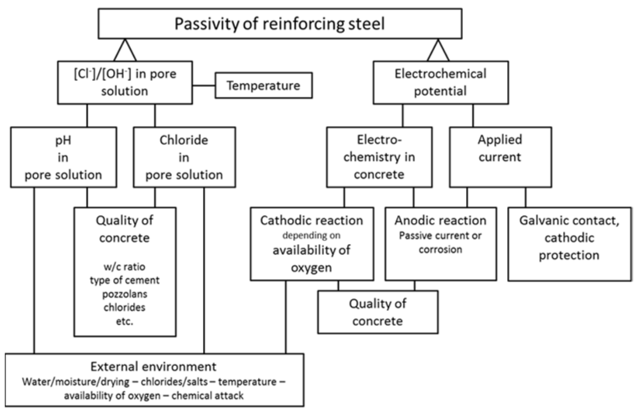
Parameters influencing the chloride threshold value



From:
H. Arup. *Bestemmelse af chloridtærskelværdi (Determination of chloride threshold level).* In: *Marina betongkonstruktioners livslängd.* Cementa AB, Sweden, 1993, p124-131.

CHLORIDE THRESHOLD VALUE

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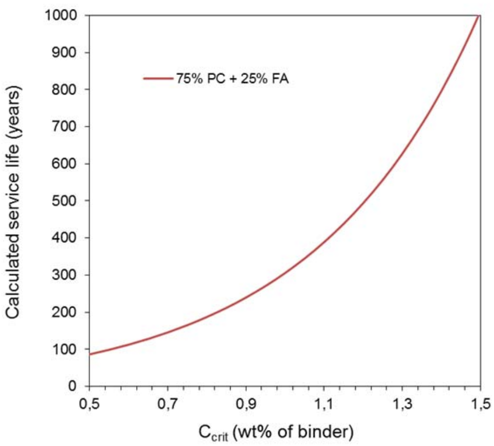
Estimation of service life by fib Model Code [fib Bulletin No. 34, 2006] – data from Träslövsläge and Fehmarn exposure sites

Influence of chloride threshold value (C_{crit})

Input parameter	Concrete
Binder	(75% PC + 25% FA)
C_{crit} [wt%/binder]	0.6 (0.5-2.2)
C_0 [wt%/binder]	0.001
$C_{S,\Delta x}$ [wt%/binder]	5.2
a [mm] (cover)	75
Δx [mm]	0
k_e [-]	1.25
b_e [K]	4800
T_{ref} [K]	293.15
T_{real} [K]	293.15
$D_{RCM,0}$ [mm²/år]	867
k_t [-]	1
n [-] (ageing factor)	0.6
t_0 [yr]	0.0877



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CHLORIDE THRESHOLD VALUE

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Estimation of service life by fib Model Code – TBM tunnel elements

Influence of chloride threshold value (C_{crit})

Symbol	Value	Unit	Explanation
C_{crit}	1.3	[wt%/binder]	Critical chloride content for corrosion initiation
C_0	0.019	[wt%/binder]	Initial chloride content in concrete
C_S	5.0	[wt%/binder]	Chloride content at the concrete surface
A	50	[mm]	Concrete cover
Δx	0	[mm]	Depth of the convection zone
b_e	4800	[K]	Regression variable
T_{ref}	293.15	[K]	Standard test temperature
T_{real}	291.15	[K]	Temperature of the structural element
$D_{RCM,0}$	131	[mm²/year]	Chloride migration coefficient
k_t	1	-	Transfer parameter
N	0.386	-	Ageing exponent, 0.0 ≤ n ≤ 1.0
t_0	0.0932	[years]	Maturity age when $D_{RCM,0}$ is measured

Input parameters			Predicted service life [years]
C_{crit} [wt% of binder]	n	C_s [wt% of binder]	
1.30	**0.386**	**5.0**	**141**
1.06	0.386	5.0	102
1.54	0.386	5.0	195

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RILEM TC 235-CTC (2009-2015)

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Round Robin Test

- New proposed standard test
- 10 laboratories participated
- No corrosion initiation in 5 labs

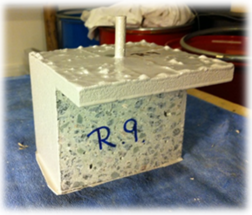
As-received

Cleaned

Pre-rusted

Exposure tank

Reference zinc elektrode



Epoxy coated concrete specimen

RILEM TC 235-CTC (2009-2015)

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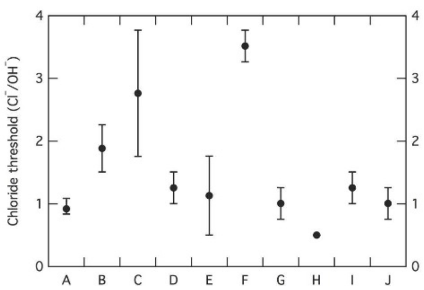
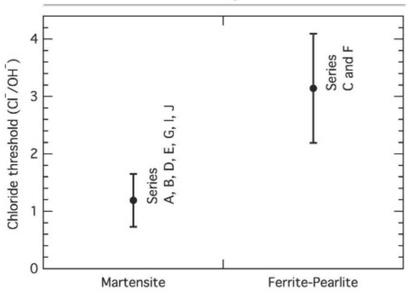
Test on as-received reinforcing steel

- Cyclic voltammetry with varying Cl/OH-ratios
- ETHZ in Zürich performed the testing on rebars from 10 different countries
- Very large variations in chloride threshold levels

Designation	Country
A	Switzerland
B	Denmark
C	Germany
D	France
E	Spain
F	The Netherlands
G	Sweden
H	China
I	Sweden
J	Norway





From:
U.M. Angst and B. Elsener. *Forecasting chloride-induced reinforcement corrosion in concrete – effect of realistic reinforcement steel surface conditions),* Proceedings of the ICCRRR conference, Leipzig, October 2015

FIELD EXPOSURE SITE - RØDBYHAVN

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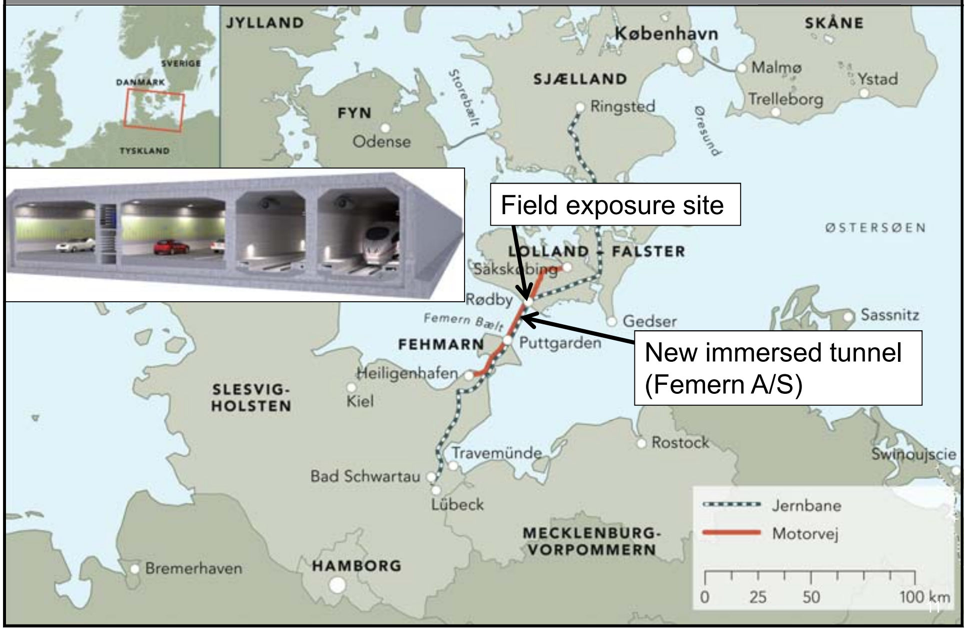

FIELD EXPOSURE SITE - RØDBYHAVN

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CONCRETE BLOCKS - DESIGN

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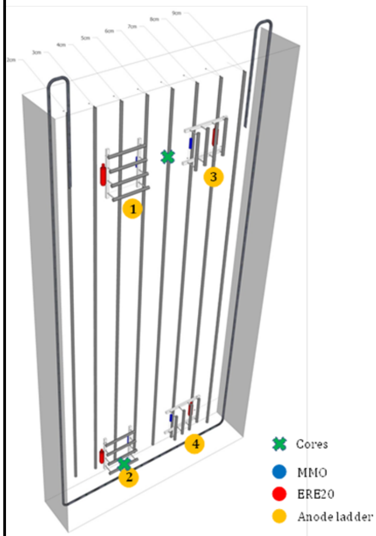

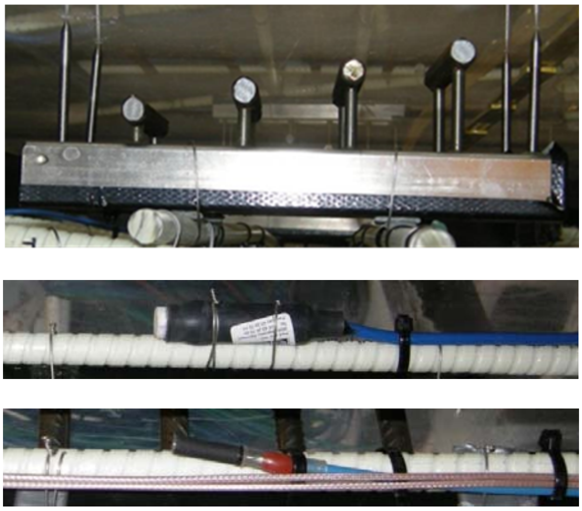

CONCRETE BLOCKS - CASTING

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CONCRETE MIX DESIGNS

ID	Three instrumented concrete blocks
Mix A (Portland cement)	Low-alkali SR Portland cement CEM I 42,5 N (HS/EA/≤ 2)
Mix F (3-powder mixed cement)	84% low-alkali SR Portland cement 12% fly ash 4% silica fume
Mix K (Slag cement)	Slag cement CEM III/B 42,5 N
w/b ratio	0.40
Anode cover depth	Approx. 10, 20, 30 and 40 mm

Details regarding cement composition and concrete mix designs are presented in the full paper on the conference CD-rom

FIELD EXPOSURE

SELECTED DATA FROM MIX A

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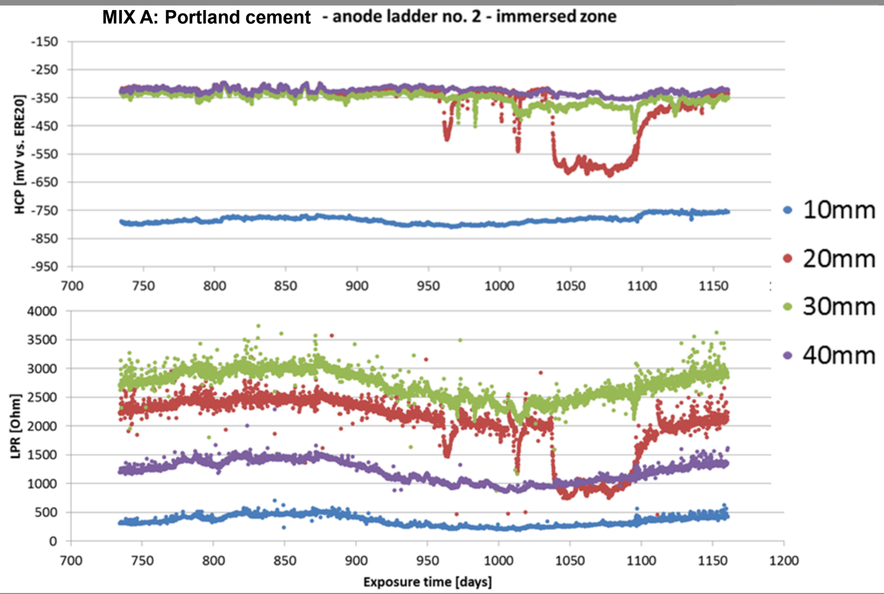

CORROSION INITIATION

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Observations of anodes with of possible corrosion initiation:

Mix/Ladder/Anode depth	Date/exposure time	mV drop	Remarks
Mix A/No. 1/10 mm	17-07-2014/1357 days	181 mV	46 days until repassivation
Mix A/No. 1/10 mm	23-09-2015/1790 days	172 mV	Corrosion until sampling after 1832 exp. day
Mix A/No. 2/10 mm	05-10-2011/342 days	447 mV	Corrosion continues
Mix A/No. 2/22 mm	30-08-2013/1037 days	287 mV	78 days until repassivation
Mix A/No. 2/22 mm	03-09-2015/1770 days	320 mV	Corrosion continues
Mix A/No. 3/8 mm	23-10-2015/1821 days	192 mV	Manual measurement
Mix A/No. 4/6 mm	18-02-2014/1208 days	286 mV	106 days until repassivation
Mix A/No. 4/6 mm	07-05-2015/1652 days	280 mV	38 days until repassivation
Mix A/No. 4/16 mm	22-05-2015/1667 days	343 mV	Corrosion until sampling after 1832 exp. day
Mix F/No. 2/7 mm	13-12-2010/46 days	286 mV	Corrosion continues
Mix F/No. 3/8 mm	At first exposure	271 mV	Initial corrosion continues
Mix F/No. 4/7 mm	25-03-2011/148 days	263 mV	Corrosion continues
Mix F/No. 4/17 mm	14-07-2015/1720 days	273 mV	Corrosion until sampling after 1832 exp. day

Corrosion initiation is defined by a potential drop of min. 150mV for at least 30 days

CORROSION INITIATION

Typical values for half-cell potential and linear polarisation resistance on passive anodes:

Exposure conditions	Immersed zone			Splash zone		
Concrete composition	Mix A	Mix F	Mix K	Mix A	Mix F	Mix K
HCP (mV vs. ERE20)	-300	-400	-600	-200	-300	-300
LPR (kOhm)	1-3	1-5	1-5	1-3	1-3	1-5

HCP-values are measured against the ERE20 reference electrode (Mn/MnO_2). Correction to CSE reference electrode ($Cu/CuSO_4$) is done by adding 100 mV.

Observations on corroding anodes show that the half-cell potential (HCP) with time drops to values below -800 mV vs. ERE20 and the linear polarisation resistance (LPR) drops to values in the range 100-400 Ohm.

CORE DRILLING

POSITION OF CORES – 532 DAYS

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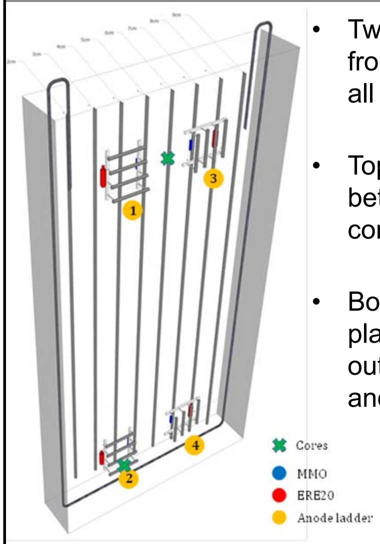

- Two cores were drilled from similar positions in all three blocks
- Top cores were placed between the two corrosion ladders
- Bottom cores were placed directly over the outmost horisontal anode

INSPECTION OF ANODES

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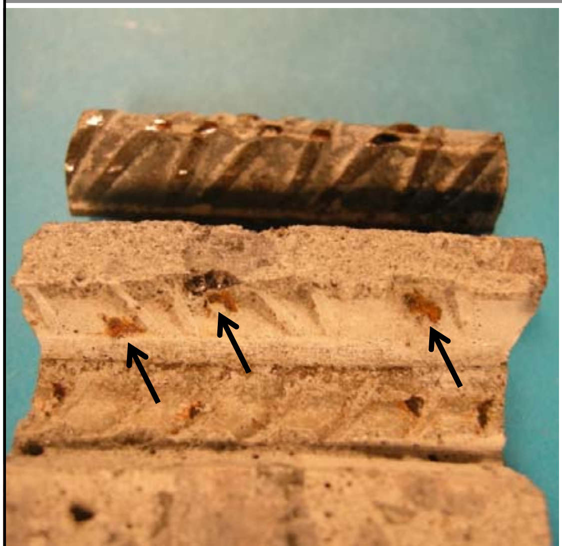

Example:

3-powder mixed cement: Three rusting spots is seen on the electrode and also in the concrete interface (arrows).

These three spots were dark just after breaking the sample, but became brown before the photo was taken.

CHLORIDE PROFILES

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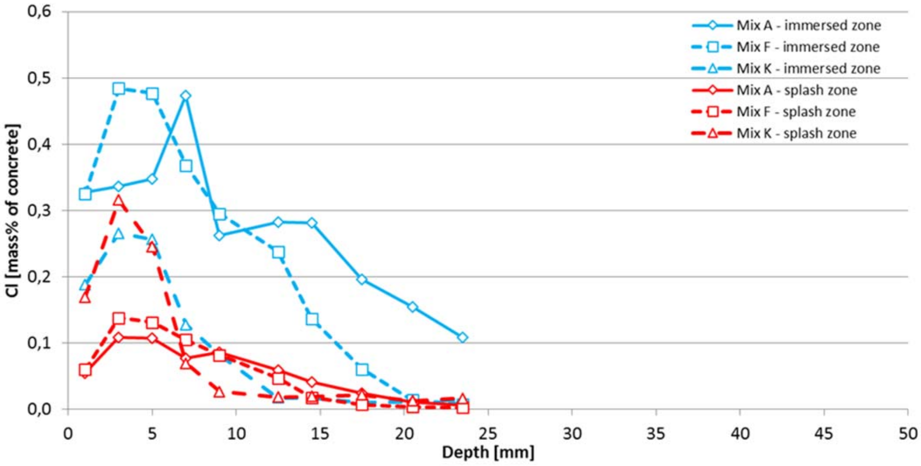

Mix A: Portland cement - Mix F: 3-powder mixed cement - Mix K: Slag cement

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CHLORIDE PROFILES

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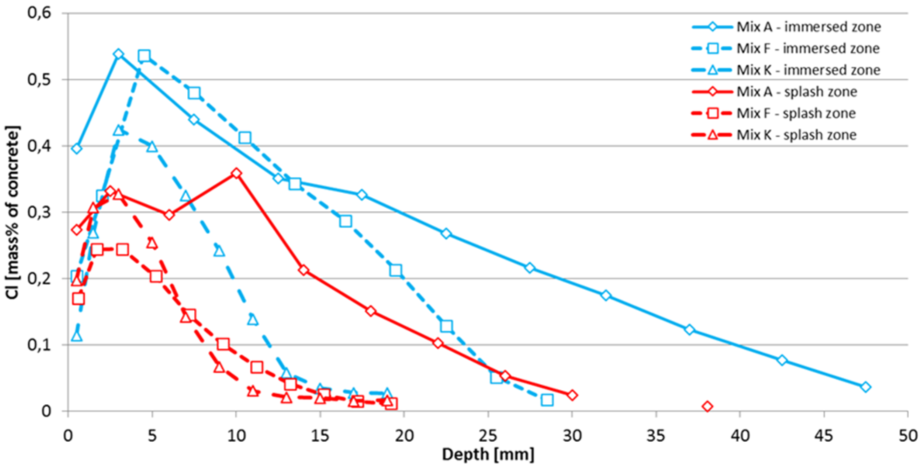

Mix A: Portland cement - Mix F: 3-powder mixed cement - Mix K: Slag cement

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CHLORIDE THRESHOLD VALUES

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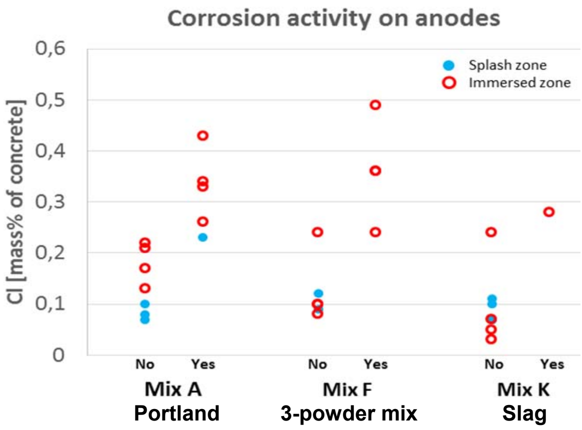

Correlation between measured chloride content and corrosion state for the outmost anodes in the three instrumented concrete blocks.
No: Passive anode, Yes: Corroding anode.
Blue dot: Anode in splash zone, Red ring: Anode in immersed zone.

CHLORIDE THRESHOLD VALUES

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Preliminary chloride threshold values from marine exposure for 5 years

Mix/Exposure zone	Corrosion activity	Chloride threshold value	
		[%Cl by mass of concrete]	[%Cl by mass of binder]
Mix A / Splash zone Mix A / Immersed zone	Corrosion on 1st anodes Corrosion on 1st and 2nd anodes	>0.14 and <0.23 >0.22 and <0.26	>0.9 and <1.5 >1.4 and <1.7
Mix F / Splash zone Mix F / Immersed zone	No corrosion on anodes Corrosion on 1st and 2nd anodes	>0.12 Approx. 0.24	>0.8 Approx. 1.6
Mix K / Splash zone Mix K / Immersed zone	No corrosion on anodes Corrosion on 1st anode	>0.11 >0.24 and <0.28	>0.7 >1.6 and <1.8

Mix A: Portland cement - **Mix F**: 3-powder mixed cement - **Mix K**: Slag cement

The chloride content at the depth of the anodes has been calculated from the curve fitted parameters at 532 days and 1832 days of marine exposure

CONCLUSIONS

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- Chloride threshold values can be estimated from in-situ HCP measurements on anode ladders combined with chloride analyses. A monitoring system with frequent measurements is required to produce reliable data on the corrosion initiation.
- LPR measurements can be used as an alternative or supplementary method to HCP measurements. So far, however, it seems as the more complex LPR measurements does not give any additional information on corrosion initiation compared to HCP measurements.
- In the present investigation with 5 years marine exposure of anode ladders in different concrete types with eqv. w/b ratio of 0.40 corrosion initation has been detected on anodes with concrete cover up to approx. 20 mm.
- The corresponding values of chloride content indicate that the chloride threshold values are at least 0.10 %Cl by mass of concrete (0.7 %Cl by mass of binder) in the splash zone and at least 0.20 %Cl by mass of concrete (1.4 %Cl by mass of binder) in the immersed zone for all three concrete mix designs.
- Furthermore, the observations indicate that the chloride threshold values for the two concrete types with Portland cement (Mix A) and 3-powder blended cement (Mix F) are not more than 0.24 %Cl by mass of concrete (1.6 %Cl by mass of binder) in the immersed zone. More observations are needed to extent the estimations of chloride threshold values.

ACKNOWLEDGEMENT

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Femern Sund≈Bælt

CONCRETE EXPERTCENTRE

The Concrete Expert Centre is a cooperation between the Danish Technological Institute and the Danish Technological University

PAPER KAN HENTES PÅ TI-STANDEN

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CHLORIDE THRESHOLD VALUES FROM CONCRETE BLOCKS EXPOSED AT RØDBYHAVN MARINE FIELD EXPOSURE SITE

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ABSTRACT

The threshold value for chloride initiated reinforcement corrosion is of major importance for the outcome of estimates from service life models. Unfortunately, a generally accepted standard test method for determination of this parameter does not exist. The durability of the coming Fehmarnbelt link between Denmark and Germany is highly depending on the choice of a correct design values for chloride penetration parameters and chloride threshold values. This resulted in start-up of a Danish marine field exposure site in Rødbyhavn harbour in 2010.

This paper presents details on the concrete composition, the layout of concrete blocks, the test setup, and the marine exposure for the ongoing reinforcement corrosion tests in Rødbyhavn marine field exposure site. Chloride profiles and data from corrosion measurements during the first 5 years exposure are presented, and chloride threshold values are estimated.

Keywords: Chloride threshold value, Reinforcement corrosion, Field exposure, Marine environment, Monitoring.

1. Introduction

The threshold value for chloride initiated reinforcement corrosion is of major importance for the outcome of estimates from service life models and the corresponding design of concrete cover and concrete quality for concrete structures subjected to chloride exposure. In the period 2009-2016 the RILEM Technical Committee 235-CTC *(RILEM, 2016)* worked on the development of a commonly accepted test method for determination of chloride threshold values. A test method was defined and a Round Robin Test was performed. However, the results were not satisfactory, so the RILEM TC 235-CTC activities did not succeed in developing a standard laboratory test method for determination of chloride threshold values.

The durability of the coming Fehmarnbelt link between Denmark and Germany *(Femern, 2016)* is highly depending on the choice of correct design values for chloride penetration parameters and chloride threshold values. This resulted in start-up of a marine field exposure site in Rødbyhavn harbour in 2010 where the field tests is designed and operated by Danish Technological Institute and financed by Femern A/S. Due to the lack of reliable test methods for determination of chloride threshold values, it was decided not only to test chloride ingress into different concrete mix designs, but also to include reinforcement corrosion tests on instrumented concrete blocks. This was included in order to determine chloride threshold values on field exposed concrete with relevant reinforcement type, concrete composition, and exposure conditions.

2. Design and production of instrumented concrete blocks

The instrumented concrete blocks were designed in a co-operation between Femern A/S and Danish Technological Institute. Based on experience from former field exposure tests in Sweden *(Sandberg, 1998)* and Denmark *(Hager, 2008)* it was decided that instrumented concrete blocks with rebars and anode ladders should be produced with dimensions of 2x1x0.2 m (HxWxD). This size should allow long-term exposure before interaction from the opposite exposed face needs to be taken into consideration. Furthermore, the large exposed area allows many samples to be extracted from a concrete specimen, that is still having operational size and weight. Each concrete block has a ring reinforcement of stainless steel, which also

forms two eyebolts on top of the block (Fig. 1). The stainless steel ring reinforcement used in all blocks is made from Ø10 mm ribbed rebar grade 1.4362 (duplex). Detailed information regarding the design is given in the following subsections.

2.1 Reinforcing bar diameters and detailing

The concrete blocks have 8 nos. of vertical Ø12x1800 mm ribbed rebars facing the front with concrete covers from 2 cm to 9 cm (Fig. 1). Four anode ladders are placed on the backside. The two upper anode ladders are located in the splash zone and the two lower anode ladders are located in the submerged zone, when the concrete blocks are exposed to sea water. One of the two upper anode ladders has 4 nos. of vertical rebars and the other ladder has 4 nos. of horizontal rebars. The two lower anode ladders are positioned in the same way. Each anode ladder has a separate reference electrode and a separate working electrode. The reference electrode is an ERE20 electrode based on manganese dioxide. The working electrode is a mixed metal oxide (MMO) activated titanium electrode.

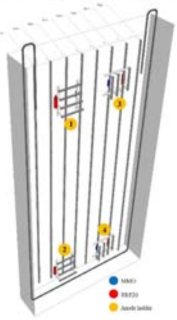

Fig. 1. Principle of the design of the concrete blocks. Only steel reinforcement, electrodes and sensors are shown. View from back side.

All the ordinary steel rebars and the anode ladders used in the instrumented blocks were made from Ø12 mm ribbed rebar type K550. All the steel bars were cut into the appropriate lengths and burrs were removed from the cut faces. The steel was pre-rusted by outside exposure before use in order to simulate a real situation.

The anode ladders were custom made for this project (Fig. 2). Four 15 cm long anodes were made from the same material as the steel rebars. The four anodes have a nominal cover of 10, 20, 30 and 40 mm for anode No. 1, 2, 3, and 4, respectively. All anodes were pre-rusted by natural exposure before installation. The anodes were kept in the right distances to the concrete surface by four titanium rods mounted on the base bars of the anode ladder. An insulated wire was connected to each anode through a cable eye mounted in the base bar on the bottom of one of the two titanium rods holding the anode. The base bar, which is made of stainless steel grade 1.4401, is electrically isolated from the anodes. The base bar is filled with epoxy.