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Test Smart – Build Right

Testing examples

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1.Profile Grinding on-site on a concrete sea-wall

Profile grinding was performed on a concrete sea-wall, one year old, in the splashing zone. The cover was 50 mm.

Testing for chlorides was made in parallel to the grinding. Four powder samples were first taken with depth increments of 0.50 mm followed by additional six with 0.5 mm in between.

The results were plotted in relation to the depth, see figure 1. A rather high chloride content was found with a maximum peak at about 4 mm depth. This peak value corresponds to the depth of carbonation, tested by the Rainbow Indicator. The influence of the carbonation on the chloride profile is explained in detail by e.g. Tuuti, (ref. 5), Cady et al, (ref. 4) and Fangel et al, (ref. 6).

It was decided to keep on sampling at 0.50 mm depth increment intervals with 0.50 mm in between the samples until the chloride profile would level off. Another six samples was taken and measured with the RCT. To obtain the initial chloride content it was decided to drill out with an 18 mm drill bit at depths between 36-49 mm, respectively 61-81 mm.

The total profile was plotted as shown in figure 1.

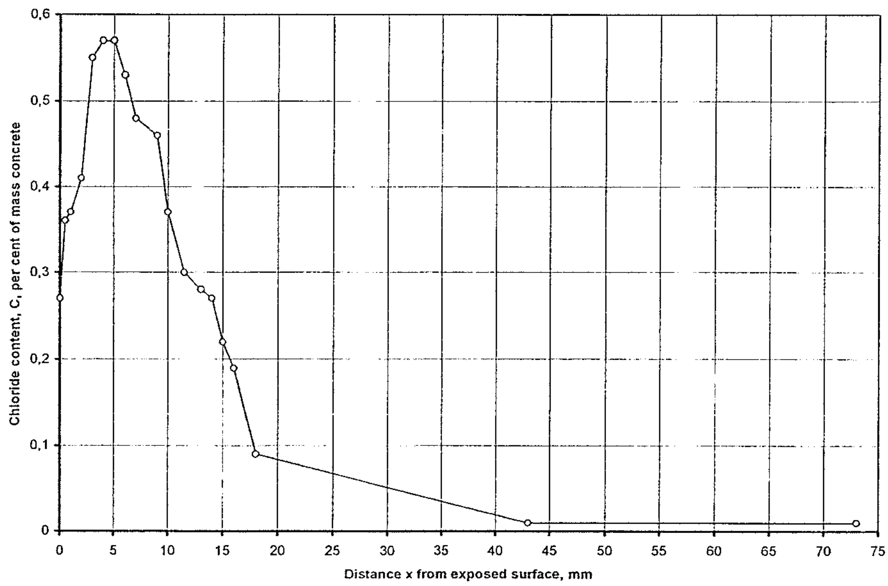

Fig. 1. Chloride profile data obtained on the sea-wall by profile grinding and RCT.

The purpose of the testing was to estimate the remaining service life of the sea-wall before chloride induced corrosion would occur according to Fick's Second Law of Diffusion:

$$C(x,t) = C_i + (C_s - C_i) \cdot erfc \frac{x}{2 \cdot \sqrt{t \cdot D_0}}$$

Where:

- C(x, t) is the chloride concentration at a depth "x" in mm from the exposed surface at an age "t" in years since the chloride exposure first took place.
- C_i is the initial chloride concentration in % Cl^- by concrete mass.
- C_s is the maximum chloride concentration at the surface in % Cl^- by concrete mass.
- *erfc* is the error function complement (the error function is tabulated in the mathematical handbooks), and
- D_0 is the chloride diffusion coefficient in mm^2/year

The calculations shown in the following comply with the approximate procedure outlined by Poulsen, (ref. 7 and 8).

In figure 2 the test data is given along with calculated parameters for the regression analysis to be performed.

From (mm)	To (mm)	Mean (mm)	Chloride, C(%)	C-C_i	$\sqrt{C - C_i}$	Design
0.00	0.50	0.25	0.2600	0.2506	0.5006	void
0.50	1.00	0.75	0.3600	0.3506	0.5921	void
1.00	1.50	1.25	0.3700	0.3606	0.6005	void
1.50	2.00	1.75	0.4100	0.4006	0.6329	void
2.50	3.00	2.75	0.5500	0.5406	0.7353	void
3.50	4.00	3.75	0.5700	0.5406	0.7487	void
4.50	5.00	4.75	0.5700	0.5406	0.7487	0.7487
5.50	6.00	5.75	0.5300	0.5206	0.7215	0.7215
6.50	7.00	6.75	0.4800	0.4706	0.6860	0.6560
8.50	9.00	8.75	0.4600	0.4506	0.6713	0.6713
10.00	10.50	10.25	0.3700	0.3606	0.6005	0.6005
11.50	12.00	11.75	0.3000	0.2906	0.5395	0.5391
13.00	13.50	13.25	0.2750	0.2656	0.5154	0.5154
14.00	14.50	14.25	0.2600	0.2506	0.5006	0.5006
15.00	15.50	15.25	0.2150	0.2056	0.4534	0.4534
16.50	17.00	16.75	0.1900	0.1806	0.4250	0.4250
18.00	19.00	18.50	0.0940	0.0846	0.2909	0.2909
36.00	49.00	42.50	0.0105	0.0011	0.0332	void
61.00	81.00	71.00	0.0094	0.0000	0.000	void

Fig. 2. The chloride profile data along with parameters for the regression analysis, according to Poulsen, (ref. 7 and 8)

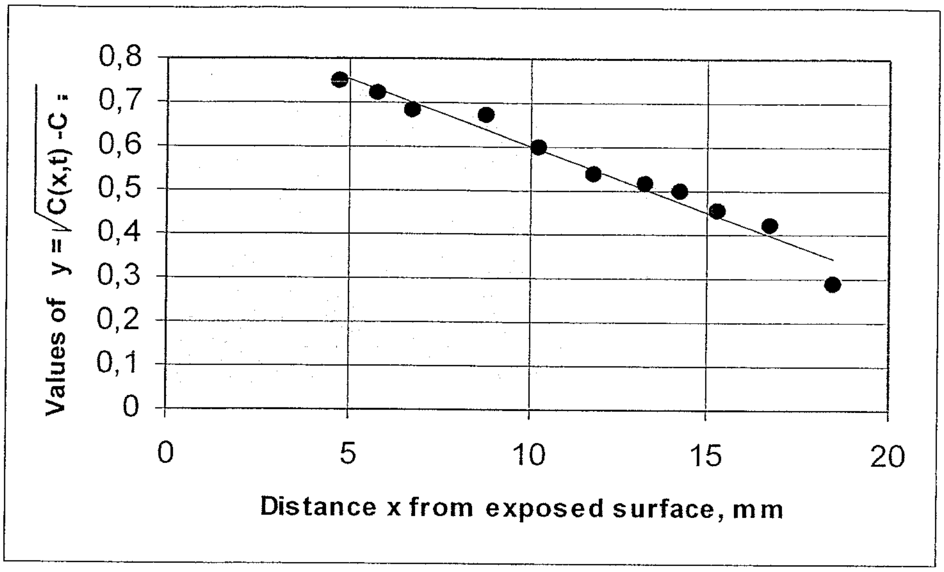

Fig. 3. Linear regression analysis for evaluation of the chloride concentration at the surface.

The Initial concentration (measured at a depth of 61.0 mm – 81.0 mm) is:

$C_i = 0{,}0094\%\ Cl^{\Gamma}$ by concrete mass

The regression analysis (fig.3) yields:

$y = 0{,}9060 - 0{,}0302\ Ax$

Which calculates the chloride concentration at the surface to be:

$C_s = 0{,}9060^2 + 0{,}0094 = 0{,}830\ \%\ Cl^{\Gamma}$ by concrete mass

and the chloride diffusion coefficient:

$$D_0 = \frac{\left(\frac{0{,}9060}{0{,}0302}\right)^2}{12 \cdot 1{,}0} = 75\, mm^2 / year$$

The first year ingress of the critical chloride concentration (0,050%) is:

$$K_1 = \left(1 - \sqrt{\frac{0{,}0500 - 0{,}0094}{0{,}8300 - 0{,}0094}}\right) \cdot \sqrt{12 \cdot 75} = 23{,}3\, mm\ per \sqrt{year}$$

According to Fick's Second Law of Diffusion, the critical chloride concentration (0,050%, acid soluble) will penetrate to the 50 mm reinforcement depth after another:

$$t = \left(\frac{50}{23{,}3}\right)^2 = 5\,years,$$

which may be regarded, based on diffusion theory, as the remaining service life of the structure before chloride induced corrosion will take place, unless remedial measures are taken.

A practical and quick approach for calculating the remaining service life approximately is the following, illustrated in five steps:

1. The present depth of the critical chloride level for corrosion occur, 0,05%, is at the moment approximately 25 mm(= d)
2. The structure has been exposed to chlorides for 1 year (= t)
3. A k-factor is calculated as $k = \frac{d}{\sqrt{t}} = \frac{25}{\sqrt{1\,year}} = 25\;mm/\sqrt{year}$
4. For a cover of D = 50 mm, the D/k relationship is $\frac{50\;mm}{25\;mm/\sqrt{year}} = 2\left(\sqrt{year}\right)$
5. The remaining service life is $\left(\frac{D}{k}\right)^2 = \left(2\sqrt{year}\right)^2 = 4\;years$

2. Profile Grinding on laboratory specimens after ponding

To evaluate the diffusion characteristics of a new mix design, specimens were cast and cured in the laboratory.

The specimens were applied a coating on the cylindrical faces and subjected to a chloride solution following NT BUILD 443 standard procedure, (ref.9)

After an exposure time of 35 days, profile grinding was done in eight steps, each 1 mm in depth increment.

Subsequently, it was decided to grind out additionally four powder samples in 2 x 1 mm steps and to use a drill bit to obtain powder from 16 mm to 30 mm depth.

One chloride profile in total is shown below in fig. 4.

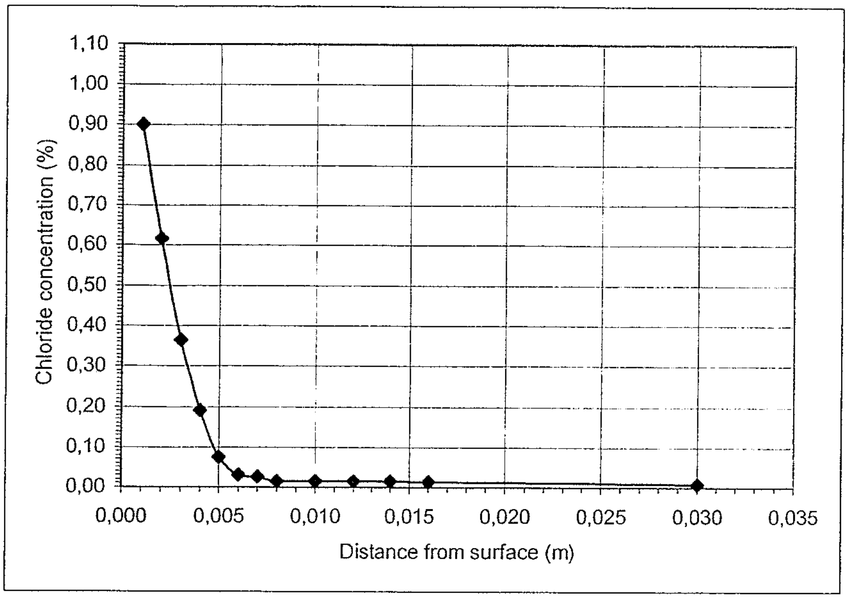

Fig. 4. Chloride profile of a specimen determined by profile grinding and testing for chlorides by the RCT.

A diffusion coefficient of $D = 0{,}91 \cong 10^{-12}$ (m^2/s) or 29 mm^2/year was calculated for service life estimation based on Fick's Second Law of Diffusion.

3. Other examples of chloride profiles, on-site

The following three figures illustrate other chloride profiles obtained after profile grinding and measurement with the RCT (for acid soluble chlorides) and the RCTW (for water soluble chlorides).

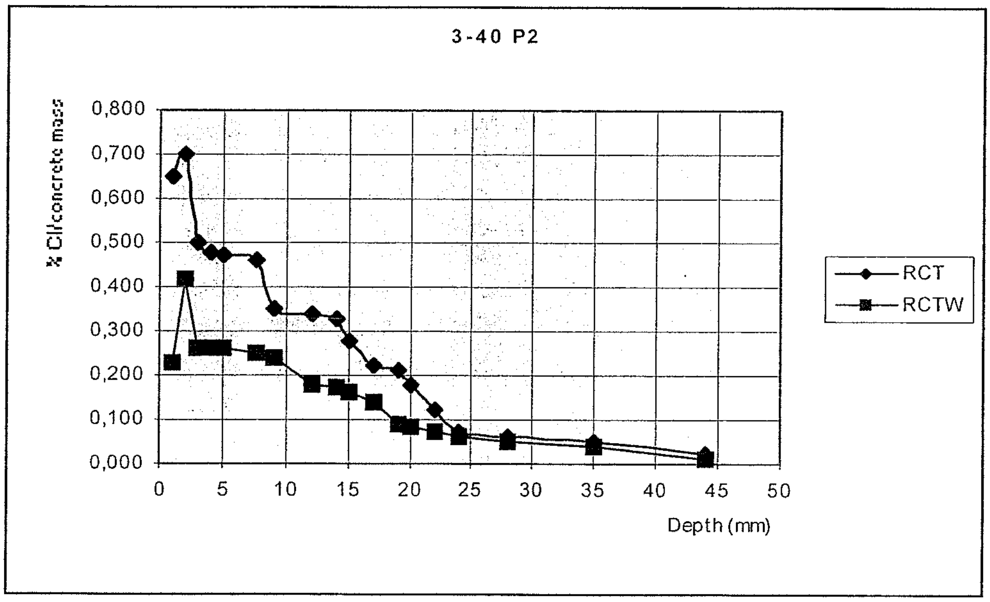

Fig. 5. RCT (acid-soluble) and RCTW (water-soluble) chloride measurements on powder after grinding out of a marine structure in the splashing zone, 2½ years old, 5% microsilica and w/(c+SF) = 0,40.

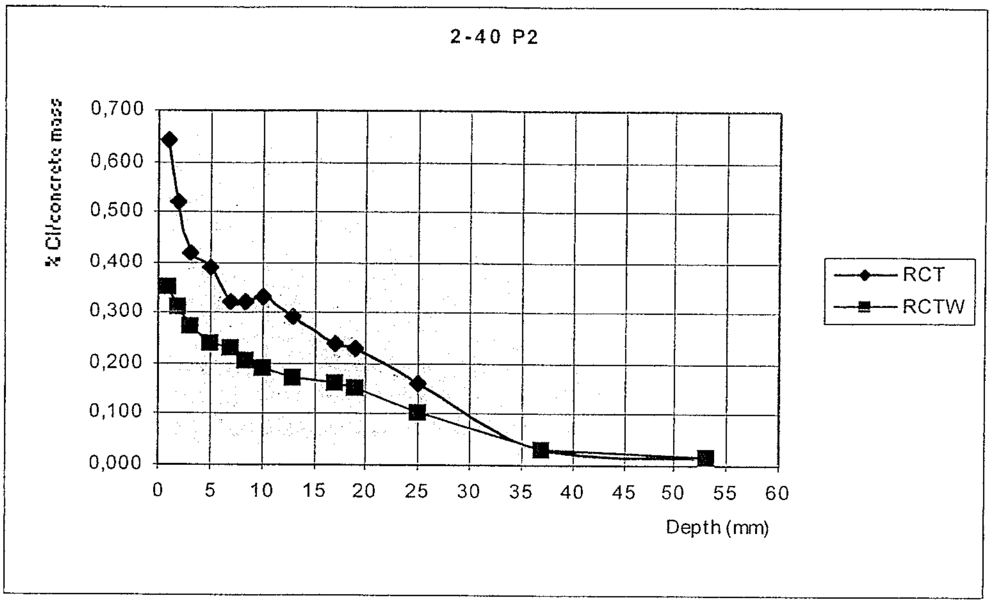

Fig. 6. RCT (acid-soluble) and RCTW (water-soluble) chloride measurements on powder after grinding out of a marine structure in the splashing zone, 2½ years old, no puzzolanes and w/c ratio of 0,40.

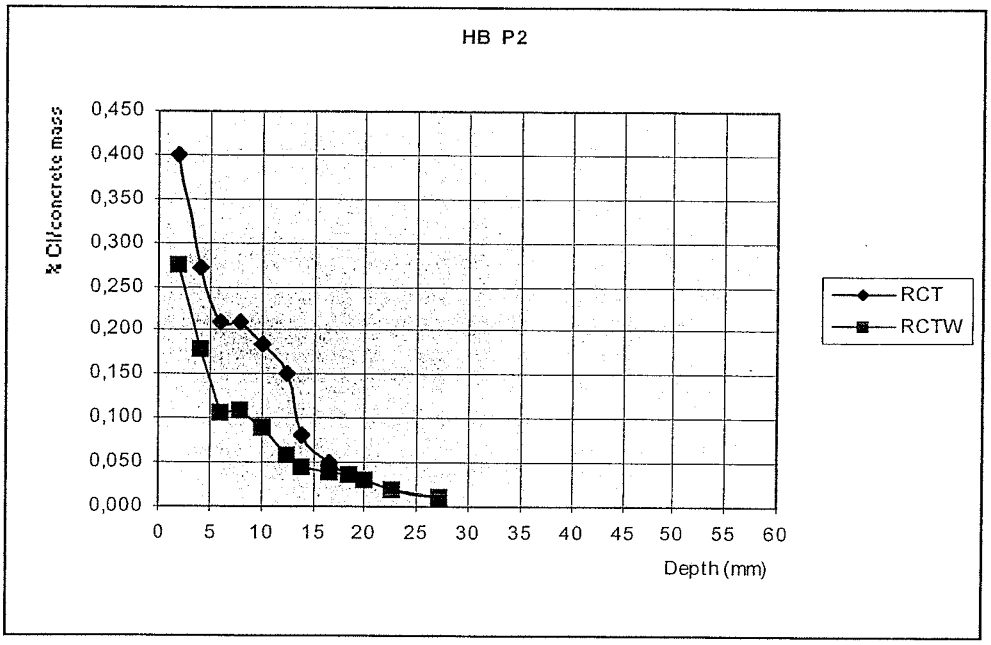

Fig. 7. RCT (acid-soluble) and RCTW (water-soluble) chloride measurements on powder after grinding out of a marine structure in the splashing zone, 2½ years old, 20% flyash and w/(c+0,3FA) = 0,30.

4.Testing and calculation example from a Mediteranian bridge structure

Testing was made on a sea structure in the Mediterranean for service life estimation.

The profile grinding is illustrated in fig. 8. Increments of the grinding were 1 mm.
After each step of grinding the chlorides were measured with the RCT, fig. 9.

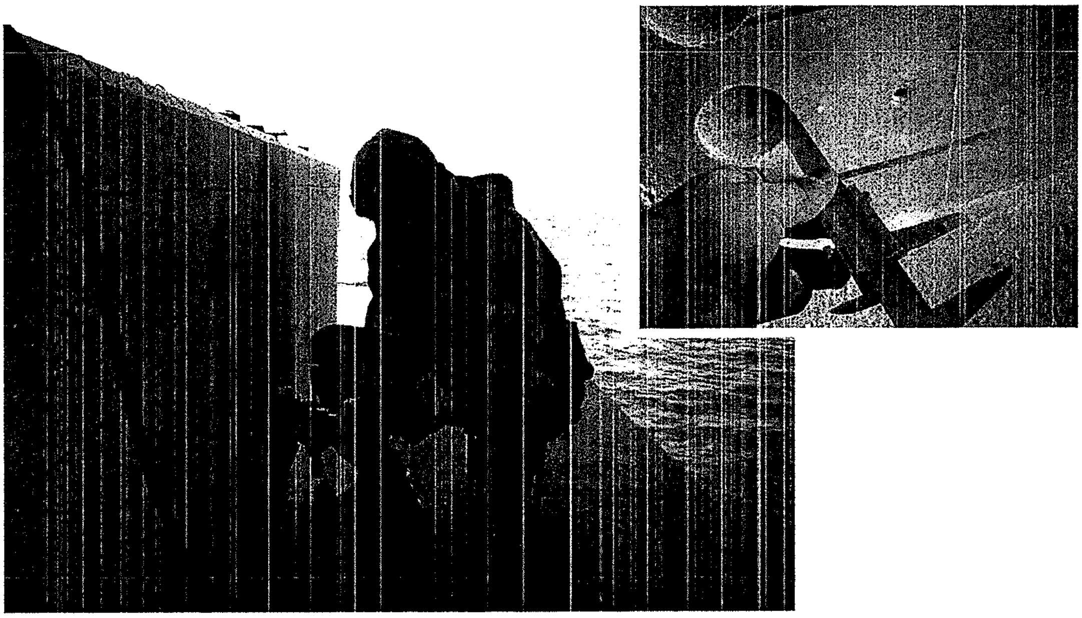

Fig. 8. Profile grinding in progress

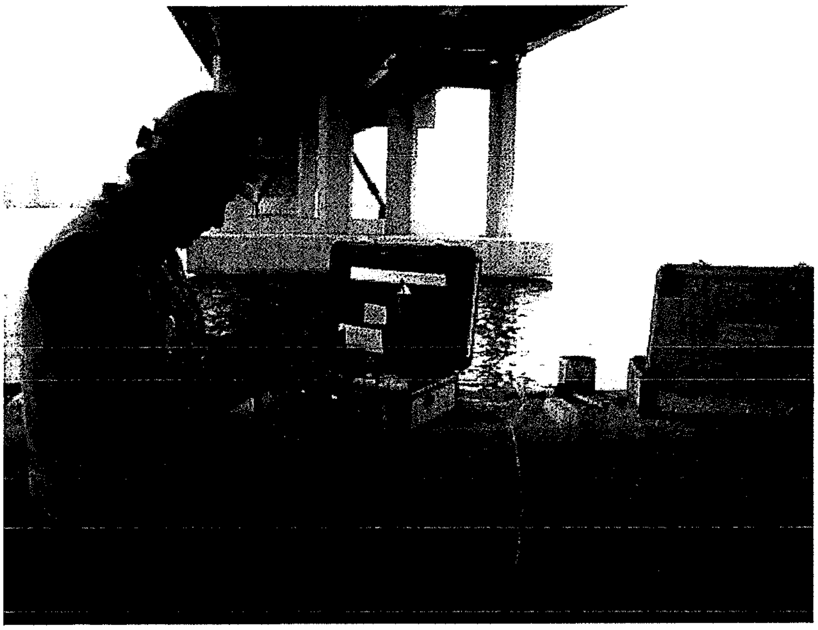

Fig. 9. Chlorides being measured with the RCT after each step of grinding

The calibration curve used for the RCT electrode in question is shown in fig. 10, relating the measured mV-readings to acid soluble chlorides in percentage of concrete weight, calibrated on the four RCT-1030 calibration liquids containing 0.005%, 0.020%, 0.050% and 0.500% chlorides by concrete weight.

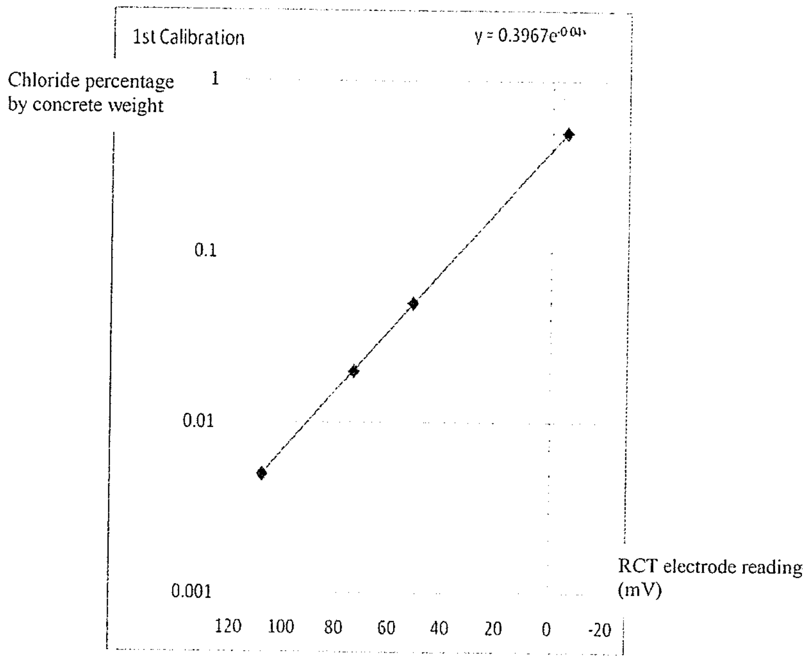

Fig. 10. Calibration curve used for relating the mV-readings of the RCT electrode to the amount of chlorides by concrete weight

The stability of the calibration curve was checked before and after the test series.

Testing of the concrete power samples produced by the profile grinding was subsequently done after each increment of powder grinded out. In this manner the grinding was optimized, producing the necessary and sufficient amount of data.

The results after 5 minutes of shaking the RCT vial were corrected to 24 hour results as illustrated in the RCT manual, and later re-checked by measuring the actual 24 hour results.

Site 41				24 hrs	
Sample	From(mm)	To (mm)	Mean (mm)	(mV)	Cl^- (%) by wt of Concrete
41(0)	0	1.2	0.6	21.5	0.173
41(1)	1.2	2.2	1.7	20.8	0.178
41(2)	2.2	3.2	2.7	3.3	0.364
41(3)	3.2	4.2	3.7	-2.7	0.465
41(4)	4.2	5.2	4.7	-3.6	0.483
41(5)	5.2	6.2	5.7	-5.5	0.522
41(6)	6.2	7.2	6.7	-5	0.511
41(7)	7.2	8.2	7.7	-2.5	0.462
41(8)	8.2	9.2	8.7	3	0.368
41(9)	9.2	10.2	9.7	4.6	0.330
41(10)	10.2	11.2	10.7	7.1	0.311
41(11)	11.2	12.2	11.7	9.2	0.286
41(12)	12.2	13.2	12.7	11.3	0.262
41(13-14)	13.2	15.2	14.2	21.6	0.172
41(15-16)	15.2	17.2	16.2	37.9	0.088
41(17-18)	17.2	19.2	18.2	60.3	0.035
41(19-20)	19.2	21.2	20.2	85.5	0.013
41(21-22)	21.2	23.2	22.2	92.4	0.009
41(24-25)	24.2	26.2	25.2	94.1	0.009
41(26-27)	26.2	28.2	27.2	97.8	0.008
41(28-29)	28.2	30.2	29.2	102.5	0.006
41(3-4cm)	30.2	40	35.1	92.5	0.009
41(4-5cm)	40	50	45	97	0.008
41(5-6cm)	50	60	55	96.1	0.008

Fig. 11. The testing results

Notice: At a depth of approximately 23 mm the profile has leveled off and no further 1 mm step grinding is needed.

The concrete powder produced at depth 3-4 cm, 3-4 cm and 5-6 cm depth was made by using an 18 mm masonry drill bit.

The profile produced is shown in fig. 12, illustrating the RCT acid soluble chlorides in percentage of concrete weight in dependence of depth.

The depth of carbonation was 2 mm.

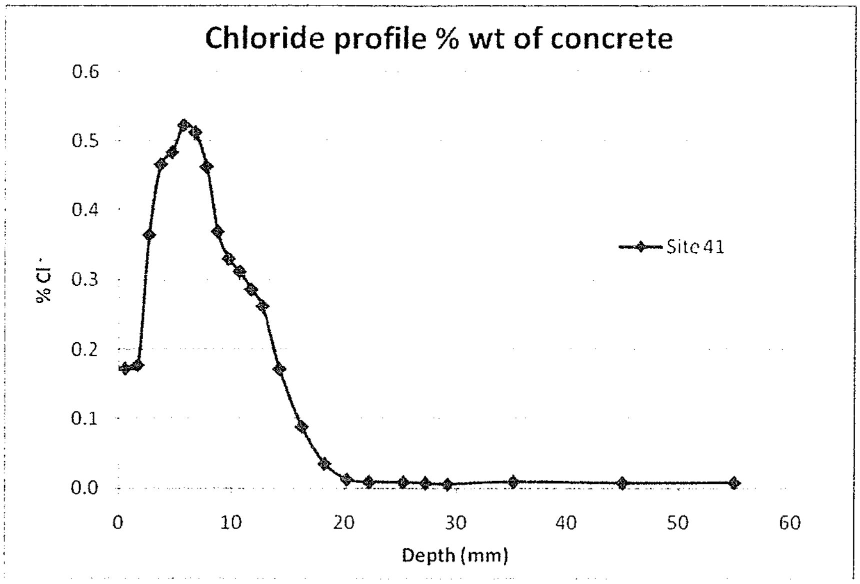

Fig. 12. The chloride profile obtained.

Measurement #	Depth (mm)	Measured (% Cl / weight)	Fick II (% Cl / weight)
1	5.7	0.522	0.515
2	10.7	0.311	0.262
3	18.7	0.035	0.063
4	35.0	0.009	0.008
5	45.0	0.008	0.008

Fig. 13. The values obtained of the measured % of chlorides by concrete weight and the best fitted by Fick II

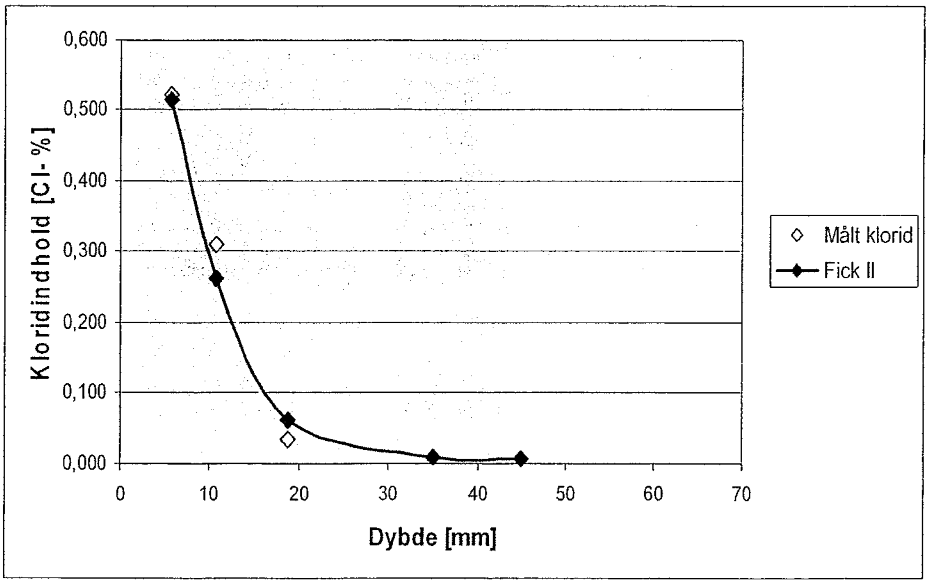

Fig. 14. Average values of the established profile (light blue) compared to Fick II (dark blue) The percentage of chlorides by concrete weight is shown in relation to depth in mm.

Calculations:

For:

Age of bridge t (year)	5
Initial chloride concentration C_i (% Cl / weight)	0.008
Surface concentration C_s (% Cl / weight)	0.900

a diffusion coefficient D_0 of 10.0 mm^2/year is calculated from Fick II:

$$C(x,t) = C_i + (C_s - C_i) \cdot erfc \frac{x}{2 \cdot \sqrt{t \cdot D_0}}$$

Service life:

With a cover layer of 80 mm (depth to the reinforcement) the service life (time to chloride initilization), provided the capilary pores are water saturated, is the following:

Critial chloride concentration at 80 mm depth (% Cl / weight)	Service life (years)
0.100	120
0.050	81

Should the capilary pores not be water saturated the service life is considerable longer.

5.Testing example from a bridge structure in the Great Belt, Denmark

Similar profiles were established on the Great Belt Link structure in Denmark, fig. 15.

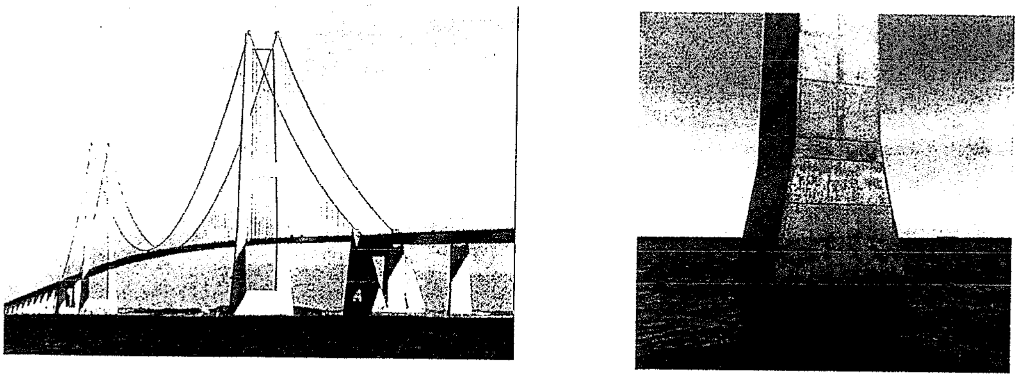

Fig. 15. The Great Belt Link with one of the pillars tested

The bridge finished in 1991 was tested at various locations in 1998 and in 2005.

Examples of the chloride profiles established are shown in fig. 16.

The five profiles obtained in 1998 on the pillar (black curves) are from different locations in variation of the height of the pillar.