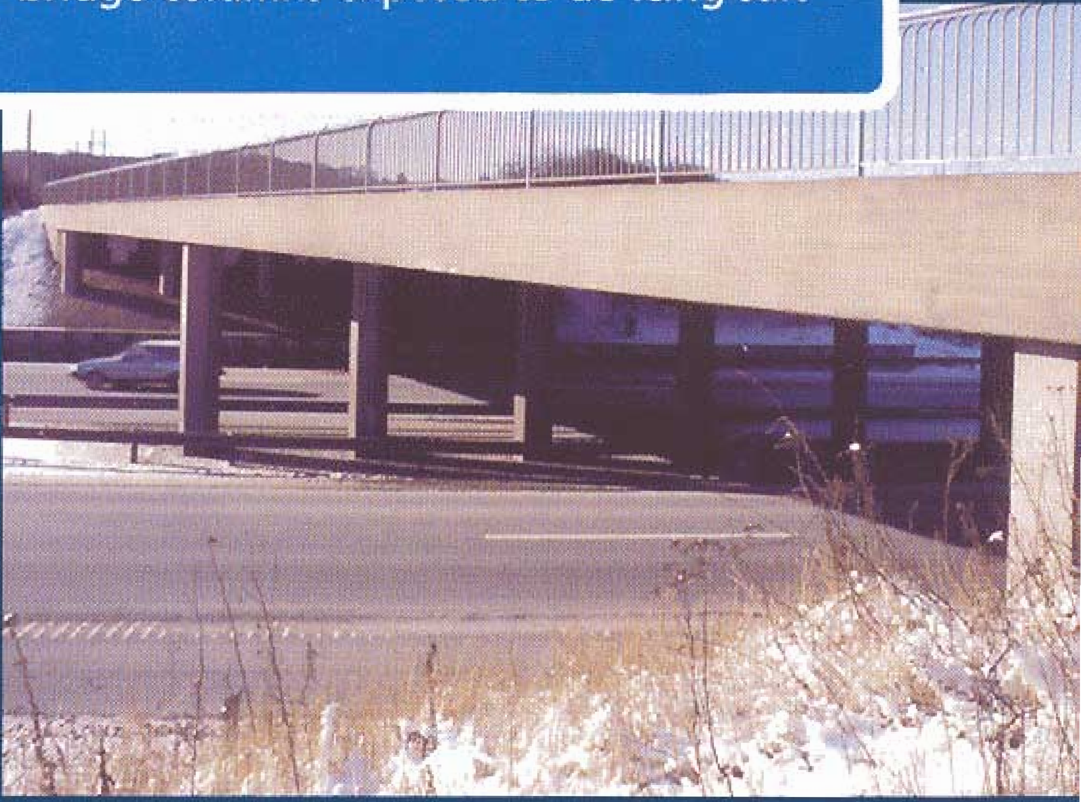
# HETEK

## Investigation of chloride penetration into bridge columns exposed to de-icing salt



Report No.82
1997

Road Directorate Denmark Ministry of Transport

# IRRD Information

| | |
|---|---|
| Title: | HETEK, Investigation of chloride penetration into bridge columns exposed to de-icing salt |
| Author: | A. Andersen |
| Subject classification: | Field 32: Concrete |

Key words:

| | |
|---|---|
| Concrete | 4755 |
| Chloride | 7314 |
| Bridge Pier | 3434 |
| Salt (De-icing) | 2598 |
| Moisture content | 5920 |
| Suction | 5771 |
| Drying | 5184 |
| Diffusion | 6769 |
| In situ | 6226 |
| Denmark | 8028 |


Abstract:

This report is part of a series of reports generated in the research project HETEK headed by the Danish Road Directorate. The present subtask is concerning chloride transport into concrete and this report presents data for chloride profiles from bridge columns.

The chloride profiles were measured for the second time in positions that were measured 4-5 years earlier. Only on very few bridges(five were found in Denmark) good quality chloride profiles were measured earlier.

The chloride profiles were measured by use of a profile grinding technique and on unaffected parts of the concrete the chloride diffusivity were measured according to the CTH-method. Also the moisture gradients in the columns were recorded.

The results of the investigation revealed that the chloride contents had not changed remarkably during the past 4-5 years. This together with the measurements of moisture gradients indicate that chloride penetration do not progress due to lack of moisture in the concrete pore system. This is in spite of the wet road environment. A possible explanation for the dry concrete is a slightly increased temperature of the concrete due to the restricted radiation (that would cool the surface) because of the bridge deck above.



UDK: 691.32
ISSN: 09 09 4288
ISBN: 87 7491 781 1

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# 1 Preface

### 1.1 Background

The Road Directorate in Denmark has launched a number of research projects in 1995 to be performed and completed during 1996. The package of projects has been given the name "HETEK", which is short, in Danish, for "High quality concrete, the Contractors TEChnology". The projects cover eight topics:

1. Test methods for chloride resistance of high quality concrete
2. Test methods for freeze/thaw durability of high quality concrete
3. Self-desiccation
4. Curing Technology
5. Casting and compaction
6. Curing treatment
7. Guidance in trial castings
8. Remedial measures during the execution phase

The projects are to give a state-of-the-art report, identify the need for further research, perform some of that research and finally give guidelines for the contractor.

This report is the third report from HETEK-1 and deals with field and laboratory investigations of reinforced concrete road bridges exposed to de-icing salts.

#### 1.1.1 About HETEK-1

The research consortium ACCE was given the first project HETEK-1 on chloride resistance of high quality concrete. The task for this project is to re-evaluate existing methods, and develop new ones, for determining chloride penetration in high quality concrete. The methods must consider the differences in environmental actions on the concrete structure. Quantitative criteria for approval shall be laid down to ensure compliance with the durability requirements and the economy of the methods shall be estimated.

The research consortium ACCE consists of the three partners: AEC, Chalmers University of Technology and Cementa AB.

#### 1.1.2 About the research consortium

AEC Consulting Engineers (Ltd.) A/S is a private consultant company in Den-mark. AEC works mainly in the field of concrete structures and topics related to the repair, durability and maintenance of those. The typical clients of AEC are other consultants, contractors, building owners, insurance companies, cement producers and suppliers and also producers of materials for concrete repair and maintenance. The company has two departments: a *structural* department, which offers constancy regarding specialised construction problems and conventional consultancy in civil engineering and a *materials* department. The materials department, the AEClaboratory, assesses deterioration of concrete structures, prescribes and develops repair methods and evaluates repair materials. Research and development regarding concrete durability tasks are solved for clients and/or financed by fundings.

Chalmers University of Technology educate civil engineers and researchers and do research in a number of basic and applied sciences and technologies. The department of Building Materials at the School of Civil Engineering, is participating in HETEK-1. The main research area is transport processes in porous building materials, mainly cement-based and wooden-based materials and surface materials on such materials. Examples of concrete research are: *Moisture* binding and flow properties of concrete, *self-desiccation and drying* of hardening high performance concrete, *plastic shrinkage* and early age cracking, *chloride penetration* into structures exposed to sea water and deicing salts. The relationships between mix design, micro and pore structure and properties are experimentally studied and the behaviour in different environments are modelled and verified on concrete structures.

Cementa AB is a cement producer in Sweden. The activities of Cementa regarding concrete research are as follows: *High Performance Concrete*, i.e. high strength, low water content and low permeability. *Concrete and environment*, i.e. low emission cement production and concrete building systems. *Durable Concrete*, i.e. long time experiments regarding chloride ingress, permeability, strength evolution, carbonation and frost resistance. *No Slump Concrete*, i.e. rheological aspects of making precast concrete products.

## 1.2 Scope

The scope of these investigations was to study chloride ingress in existing bridges, in order to evaluate the kinetics of chloride penetration. This was done by examining bridge columns where it was possible to study the effect on chloride penetration of

- prolonged exposure time,
- the position of the sampling point,
- the time of the sampling compared to the exposure cycle (a year).

Unfortunately only five Danish motorway bridges satisfy the above requirements because only here the chloride profiles were analysed with precision in a laboratory. The two earlier investigations by Henriksen et. al [1991] and by AEC 1991/1992 (unpublished) made it possible to compare new measurements of chloride profiles with measurements taken four to five years earlier. This report supply more material and references, for further studies.

## 1.3 Structure

A brief background to chloride exposure in the road environment is given in chapter 2. Chapter 3 describes the bridges, their environment and where previous measurements were made. The laboratory procedures are described in chapter 4. Results are presented in chapter 5 and comments to the measurements are given in chapter 6. Finally in chapter 7 conclusions are drawn.

## 1.4 Limitations

This investigation was made in a relative short period of time. Cores were taken in spring time, and the chloride profiles are "frozen" pictures in time. There is reason to believe that the profile vary between seasons, and profiles taken in the autumn would have a different form at least in the surface area. Another important aspect is that a chloride profile cannot be measured in exactly the same place, since the methods used are destructive. Avoiding cutting reinforcement bars and the safety of staff also limits the sampling procedure.

# 2 Introduction

In situ measurements in existing bridges and structures are an important part of developing valid models. The complexity of the mechanisms and the environment makes it important to isolate the decisive parameters and to simplify them with a minimum of distortion. This can be done by studying real structures and try to imitate the observations with mathematical models and laboratory measurements of the decisive parameters.

## 2.1 The Road Environment

The conditions in the road environment are summarised in Nilsson et al. [1996]. The distribution of chloride (concentrations at different depths) is a time dependent function of the environmental conditions, the design of the structure and the material properties. The mechanisms of chloride transport and binding involved are complicated and usually combined in a complicated way. The processes are not always understood and still not easy to quantify.

The transport and distribution of chlorides in a concrete structure is very much a function of the environmental conditions, mainly the concentration and duration of the solutions in contact with the concrete surface. The conditions are quite different in different exposure situations.

Salt water can be sucked into the concrete surface. Rain water washes the surface free from chlorides and may remove some of them. Evaporation increases the concentration. Chlorides move inwards and outwards due to moisture flow and ion diffusion.

The conditions are different at different heights from the road level. A maximum chloride content may be found at a height where salt water is frequently supplied to the surface but where the surface intermittently dries out.

Bridges and road structures that are exposed to de-icing salts have boundary conditions that vary with time. In wintertime parts of the structure are exposed to saturated salt solutions that are rapidly diluted as the ice and snow melts. This exposure can be repeated frequently, sometimes once a day. Rain water washes the surfaces and move salt water to drains and/or other parts of the structure.

Salt water penetrates cracks and joints very easily. Consequently, the occurrence and the effect of defects must be considered in the evaluation of the behaviour of a structure.

# 3 Investigated Bridges

The five bridges in this investigation were all examined earlier and they were not repaired or in any other way altered in the time from the previous and until this examination. The data regarding four of the bridges are published in Henriksen et. al [1991]. The data regarding the fifth bridge were unpublished until this report.

Big efforts were invested in taking the new cores as close to the previous cores as possible. This was not always the best point in view of the purpose of this investigation. The distance to earlier sampling points had to consider structural safety by not cutting reinforcement and available space for the drilling equipment.

## 3.1 Bridge 14-0036

The bridge is placed in Frederiksborgs County at the crossing of Hørsholm Kongevej (a 2 lane main road) over the Helsingør Motorvej (a 4 lane motorway), heading north-south.

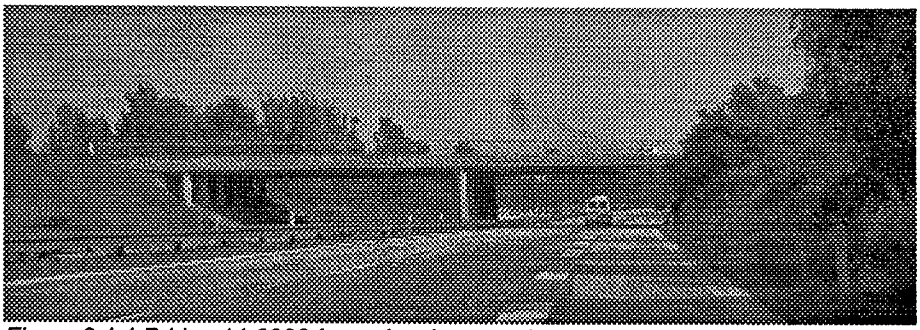


*Figure 3.1.1 Bridge 14-0036 from view from north.*

The bridge is supported in the middle by five pillars having multi edged cross sections. The previous measurements were made on two columns on faces that are directly exposed to the traffic splash, i.e. facing east and west respectively. The columns chosen were the second columns when counted in the direction of the traffic. The previous cores were taken from surfaces that mainly are exposed to traffic splash and where rain only seldom will hit the surfaces directly. Earlier two cores were taken from each column 1 m above road level. The distance from the columns to the traffic lanes is about 1.5 m.

For this investigation cores were taken 0.25 m above the previous cores. In addition two cores were taken from the north column in the road level and 1.93 m above.

On this part of the motorway the traffic is heavy. The speed of the cars are relatively high in the mid lane, frequently well above 100 km/h. Most of the traffic is headed towards the city of Copenhagen in the mornings, i. e. heading south.

## 3.2 Bridge 40-0004

The bridge is placed in Fyns County at the crossing of Nordmarksvej (municipal road no. 126) over the Motorway (a 4 lane motorway) at the 132.181 km position mark. The motorway is heading north-south under this bridge.

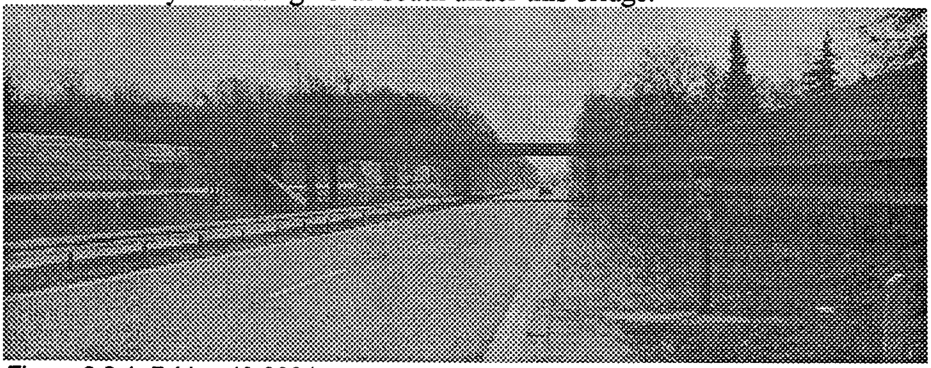


*Figure 3.2.1. Bridge 40-0004.*

The bridge is supported by two columns on each side of the motorway and between the lanes by two circular columns surrounded by sand. The previous measurements were made on the north column in the middle of the motorway on the north face that are directly exposed to the traffic splash. The distance between the centre columns and the left lanes are 1.5 m. This surface can be exposed to driving rain if the wind blows form the north. The previous measurements in 1991 were made on one core taken 0.1 m above road level. For this investigation two new cores were taken 0.2 m and 0.3 m above road level on the same column.

The motorway has not a very heavy traffic and the speed is often low, about 50 -70 km/h. Most of the traffic is related to the ferries, which gives a peak in traffic density each half hour.

## 3.3 Bridge 30-0016

The bridge is placed in Storstrøms County at the crossing of Tollerødvej (municipal road no. 26) over the motorway (a 4 lane motorway with safety lanes on each side) at the 54.025 km position mark. The motor way is heading north-south at this position.

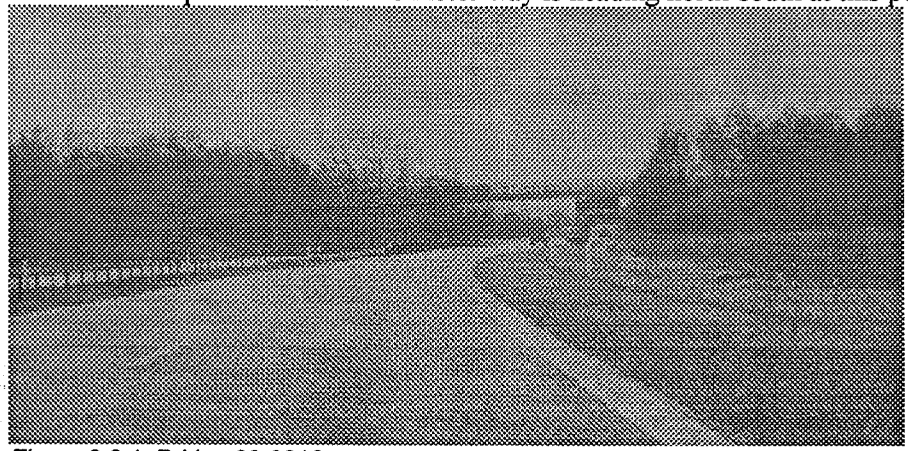


*Figure 3.3.1. Bridge 30-0016.*

The bridge is supported by six columns with rectangular cross section, two in the middle of the road and two columns on each side of the motorway. The distance from the traffic is about 4 meters to the side columns. The previous measurements were made on a column face that are directly exposed to the traffic splash, i.e. facing the road. The column were chosen as the second column when counted in the direction of the traffic on the west side of the bridge. The previous core were taken from a surface that is mainly exposed to traffic splash and where rain only seldom will hit the surfaces directly. That core was taken from the column 0.3 m above road level.

For this investigation cores were taken 0.3 m above the previous core. One core for chloride profile and one for moisture profile.

## 3.4 Bridge 10-0031

The bridge is placed in Roskilde County the crossing of Hundigevej (municipal road no. 1) over the motorway (an 8 lane motorway) at the 19.190 position mark.

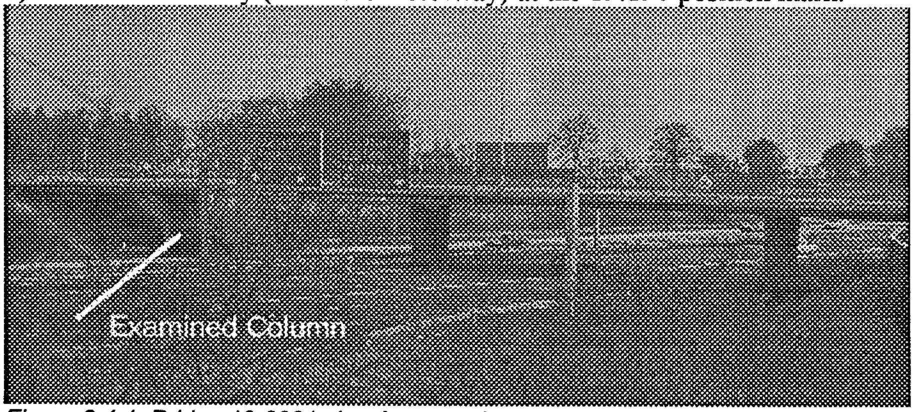



*Figure 3.4.1. Bridge 10-0031 view from south.*

The bridge is supported by three rigid rectangular columns, one in the middle and one on each side of the motorway. There are four lanes in each direction on the motorway. There is only 1.7 meter from the north column to the nearest lane. The surface on the ground surrounding the column is covered with concrete bricks but there were a couple of centimetres of dirt on the ground around the column spring and summer 1991. The surfaces are covered with dirt and look wet most of the time. The bridge was cleaner and the surface looked dryer in the autumn 1996.

The previous measurements were made on the north column on faces that are directly exposed to the traffic splash, i.e. facing south. The core was then taken from the middle of the column, mainly exposed to traffic splash and where rain only seldom will hit the surfaces directly. The core was taken 0.2 m above road level.

For this investigation three cores were taken 0.2 m above the previous cores. In addition one core was taken at the road level.

The motorway carries heavy traffic around the clock seven days a week.

### 3.5 Bridge 20-0085

The bridge is placed in Vestsjællands County at the crossing of Hemmeshøjvej (municipal road no. 8) over the motorway (a 4 lane motorway) at the 96.930 km position mark.

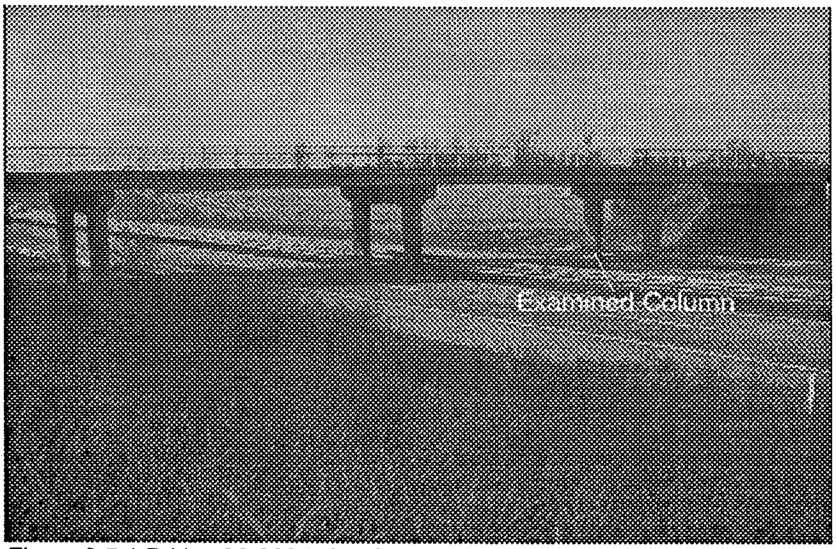



*Figure 3.5.1 Bridge 20-0085 view form south west.*

The bridge is supported by six columns with rectangular cross sections, two columns in the middle of the road and two on each side. The motorway has two lanes and one safety lane in each direction.

The columns on the north-west side were examined. The distance from the columns to traffic is about 5 meter. The surface surrounding the columns is covered with concrete bricks and relatively clean. The columns are not exposed to rain and the splash from the traffic is limited. The previous measurements were made on the north-west column on faces that are directly exposed to the traffic splash, i.e. facing south and west respectively. The columns chosen were no. 2 column when counted in the direction of the traffic. The earlier core was taken 0.3 m above road level on the south side.

For this investigation cores were taken 0.3 m above the road level and 0.1 m respectively 0.3m from the old core on the south side. In addition two cores were taken from the column on the west side 0.1 m and 0.7 m above road level.

The concrete in this bridge was remarkably easier to drill cores from compared to the other bridges.

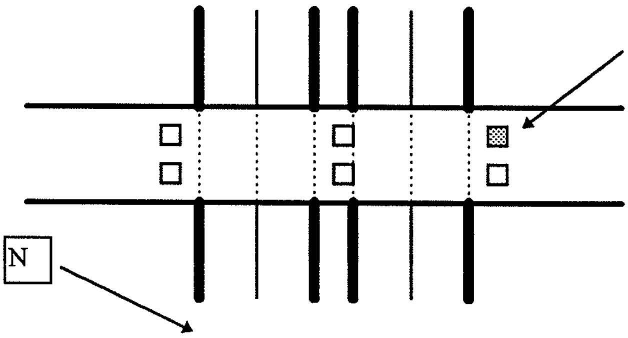



*Figure 3.5.2 Sketch of bridge 20-0085 from above. The investigated column is marked.*

## 3.6 Summary of bridges

Data on the age and conditions (quantitatively) for the bridges are given in table 3.6.1.

*Table 3.6.1 Salt and traffic data from 1990 (except bridge 14-0036), Henriksen et. al. (1991]*

| Bridge No. | Built year | salt/year $kg/m^2$ | Traffic units/ day | Lanes | Safety lane |
|---|---|---|---|---|---|
| 14-0036 | 1956 | 1.0 | 36400 | 4 | no |
| 40-0004 | 1956 | 0.9 | 9000 | 4 | no |
| 30-0016 | 1972 | 0.6 | 17000 | 4 | yes |
| 10-0031 | 1968 | 1.1 | 46000 | 8 | no |
| 20-0085 | 1963 | 0.8 | 10000 | 4 | yes |

# 4 Laboratory methods

The cores were used to determine chloride profiles, chloride diffusion coefficients and moisture profiles.

## 4.1 Chloride profiles

Chloride profiles were determined by profile grinding. The powder was analysed for chloride and calcium.

### 4.1.1 Grinding

Before grinding the surface skin of the core was removed using sand paper. The powder was ground off the cores in a modified turning-lathe. This enabled precision in the determination of the depth. The powder samples were collected on a filter paper and crushed until the sample passed through a 0.125 mm sieve. The powder was then put into paper envelopes and directly dried at 105 °C for 24 hours. After drying, the envelopes were stored in sealed plastic bags in a dry air tight box, until the chemical analysis.

### 4.1.2 Chemical analysis.

The powder was analysed for acid soluble chloride and calcium content. Approximately 1 gram of sample was taken and weighed to an accuracy of 0.001 g. Then 5 ml concentrated nitric acid and 50 ml boiling de-ionised water was added. The solution was agitated frequently under a 20 minutes period. The solution was filtered on a pre-wetted filter and the filter was flushed with 50 ml hot de-ionised water in small portions. The total volume of the filtrate was 100 - 110 ml.

The chloride content was determined by potentiometric titration with 0.0100 Molar $AgNO_3$ with a reference electrode and a chloride sensitive electrode. The procedure is similar to AASHTO T 260-84. The calcium content was determined with potentiometric titration with 0.100 molar EDTA with a reference electrode and a calcium sensitive electrode. Before titration with EDTA the pH value was corrected to pH>12 with NaOH(aq), and 5 ml (1:1 diluted) triethanolamine was added in order to neutralise interactions from other ions. The apparatus for the titration was a Metrohm 702 SET/MET Titrino. This procedure gives a very little error between the samples in the same series.

## 4.2 Diffusion coefficients

Specimens were cut from the cores, and the specimens were vacuum treated in lime water for 6 hours followed by 18 hours in lime water at atmospheric pressure. The prepared samples were placed in the CTH-test set-up, Tang [1996].

In Figure 2.2.1 the test set-up is shown. The procedure involved an exposure to a NaCl solution (Catholyte) with a 2 Molar chloride content at 20°C while simultaneously applying an electrical field of 30 V over the specimen. From the measurements of the initial current the recommended test duration was decided. The exposure lasted from 4 up to 48 hours.

Immediately after the exposure the specimens were split into two halves and sprayed with a 0.1 M $AgNO_3$ solution. The chloride contaminated area immediately becomes light grey (from the AgCl precipitate) and after exposure to light the unaffected areas becomes brownish. The penetration depth was measured as the distance from the chloride exposed surface down to the end of the light grey area. In all specimens a homogenous penetration depth was found.

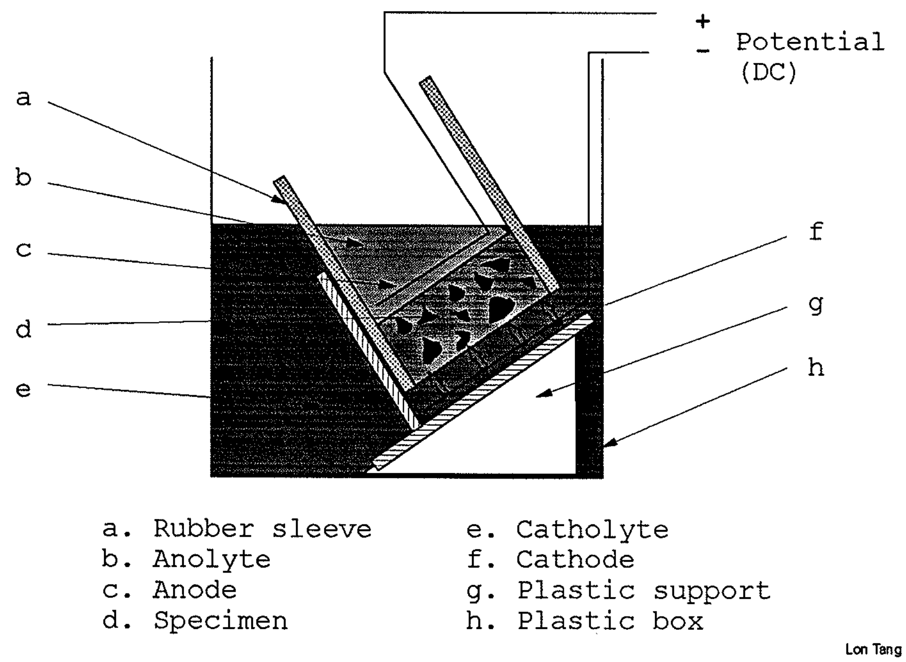



*Figure 4.2.1. Set up for determination of $D_{CTH}$.*

## 4.3 Moisture analysis

The centre part of the core was used for moisture analysis. The outer part of the core was contaminated by the cooling water used when drilling the cores. From experience the moisture analysis is not affected when the outer layer of approximately 10 to 15 mm is removed shortly after drilling. This procedure should be performed as soon as possible after the drilling, otherwise this is not a recommendable procedure. Because of redistribution of water inside the drilled core.

In this investigation the cores were split up within 30-100 minutes after the drilling. The samples were taken with hammer and chisel against a steel plate. Small pieces were used for RH determination (chapter 4.3.1) and put into test tubes directly after splitting. The test tubes were sealed with a rubber cork. The bigger pieces for determination of capillary saturation (chapter 4.3.2) were directly wrapped in double plastic bags. The depth from the surface was measured in mm for each piece.

The end parts of the core could be contaminated with cooling water from the drilling. Thus no definite conclusions should be drawn from the deepest part of the core.

### 4.3.1 Degree of capillary saturation

The degree of capillary saturation was determined using a gravimetric method. The principal set-up is shown in figure 2.3.1. The initial mass of each sample was determined with an accuracy of 0.01 g and each of the samples was then put in contact with a free water surface until capillary saturation (equilibrium <0.1% difference in more than 24 h) is reached. The last procedure was to dry the sample at 105 °C until an other equilibrium was obtained.

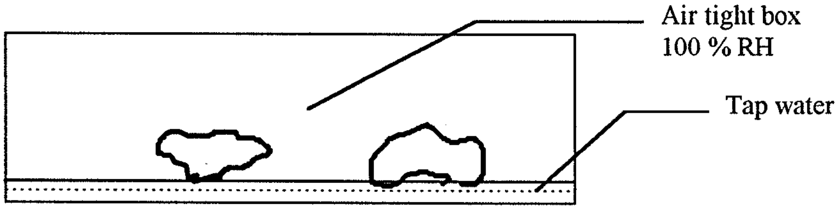



*Figure 4.3.1. Set-up for capillary saturation.*

The degree of capillary saturation is calculated from the following formula.

$$S_{cap} = \frac{m_0 - m_{105}}{m_{sat} - m_{105}}$$

where

| | | |
|---|---|---|
| $S_{cap}$ | = | degree of capillary saturation. |
| $m_0$ | = | initial mass of specimen. |
| $m_{105}$ | = | mass of dry specimen (105°C). |
| $m_{sat}$ | = | mass of capillary saturated specimen. |

By using capillary saturation in stead of only water content, errors due to differences in aggregate contents of the samples were minimised.

### 4.3.2 Relative Humidity

Relative humidity (RH) was measured with Vaisalaa RH-gauges in a temperature controlled room. The RH-gauges were calibrated and the measurements were corrected accordingly. The accuracy for the calibrated probes was ± 1% RH after calibration.

The measuring procedure was first to condition the RH-gauges in 50% RH for 24 hours. Then the probes were inserted into the test tubes as shown in figure 4.3.2. After 24 hours the RH value was read and corrected with the calibration curve.

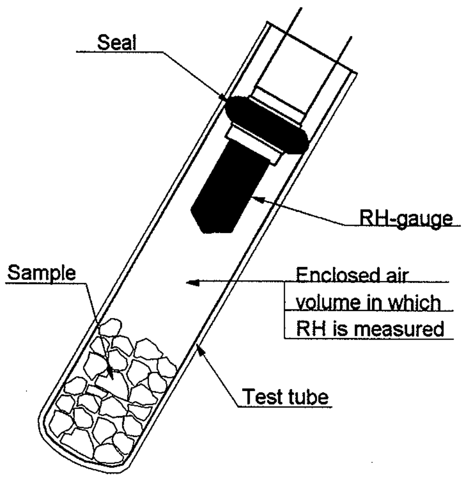



*Figure 4.3.2. Set-up for relative humidity measurement.*

# 5 Results

All results are given in appendix 1. In this chapter the results from the natural exposure are shown in separate sections for each of the five bridges. Diffusion coefficients and carbonation depths are given at the end of this chapter.

## 5.1 Bridge 14-0036

All chloride profiles are summarised in Figure 5.1.1. In Figure 5.1.2 and 5.1.3 the effect of age is shown for the north respectively the south column. Effect of height on the column is shown in Figure 5.1.4. The moisture profiles are shown in Figure 5.1.5. and 5.1.6.

The sample marked S are taken from the 2nd column from the south on the east side. Samples marked N are from the 2nd column from the north on the west side.

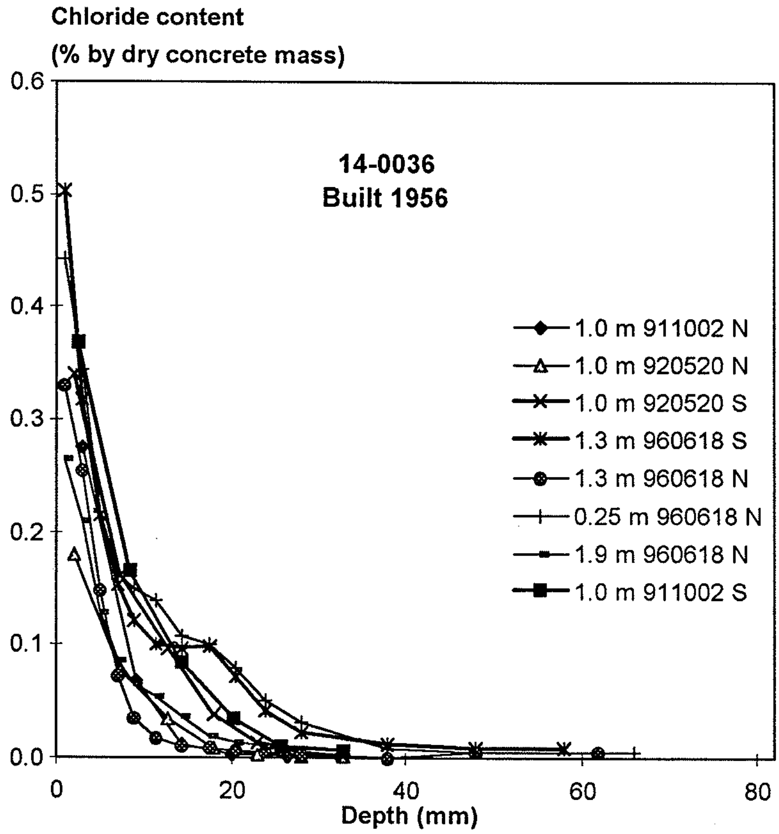



*Figure 5.1.1. All chloride profiles from bridge 14-0036.*

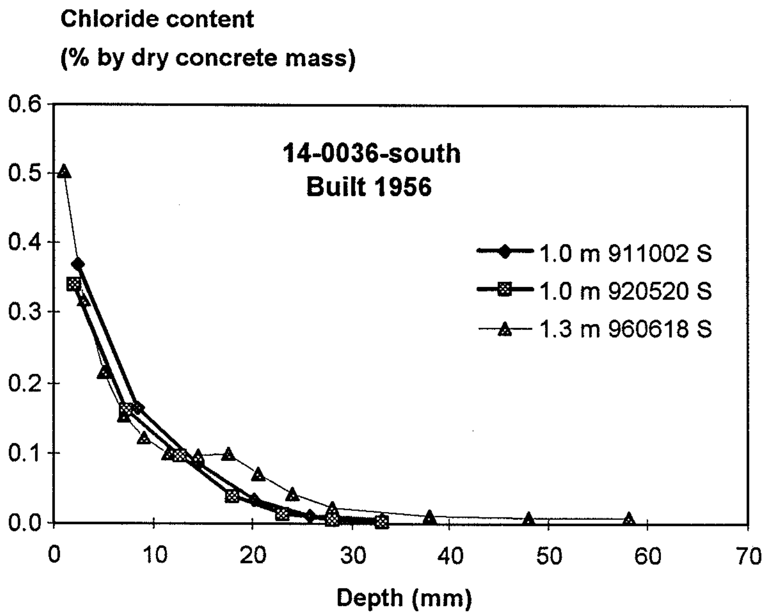



*Figure 5.1.2. Chloride profiles on the south column at different ages.*

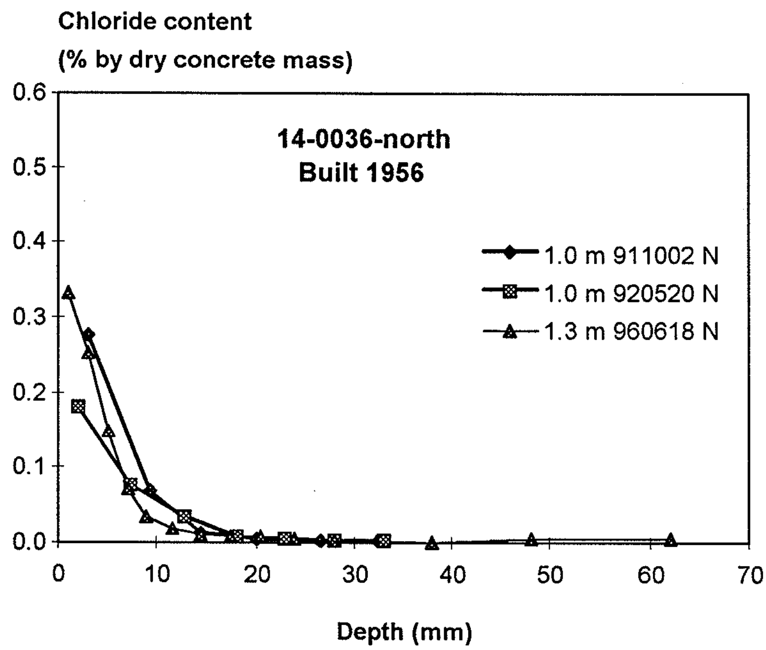



*Figure 5.1.3. Chloride profiles on the north column at different ages.*

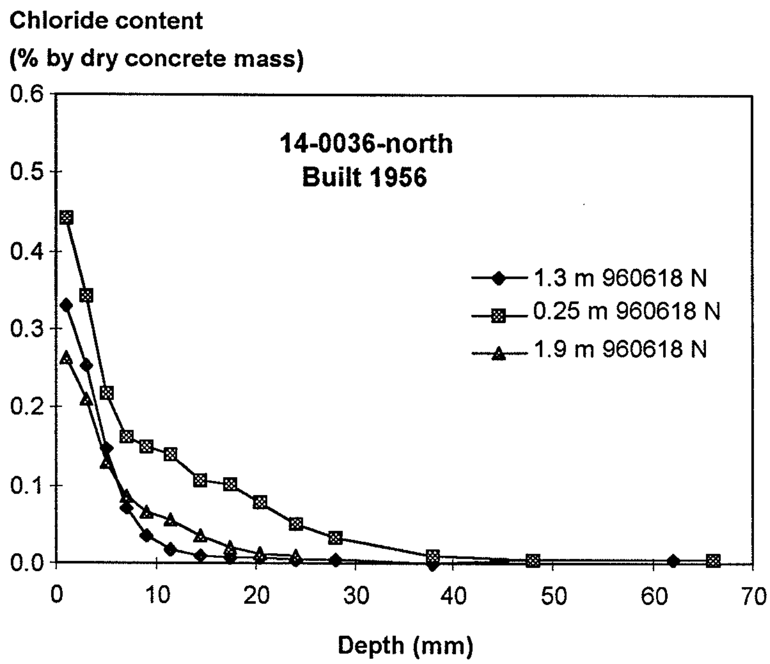



*Figure 5.1.4. Chloride profiles on the north column at different heights.*

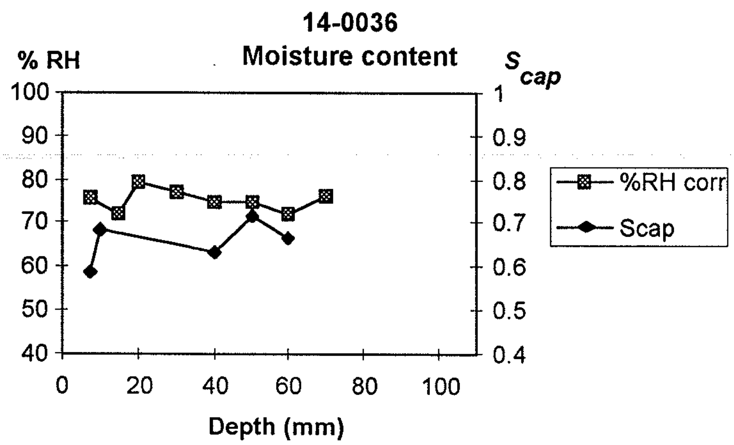



*Figure 5.1.5. Moisture profiles of bridge 14-0036, June 1996. The core was taken 1.30 m above road level on the north column.*

## 5.2 Bridge 40-0004

Samples are taken just above the 1991 core at 20 cm and 33 cm above road level. No carbonation was observed in these cores. No moisture measurement was made on this bridge.

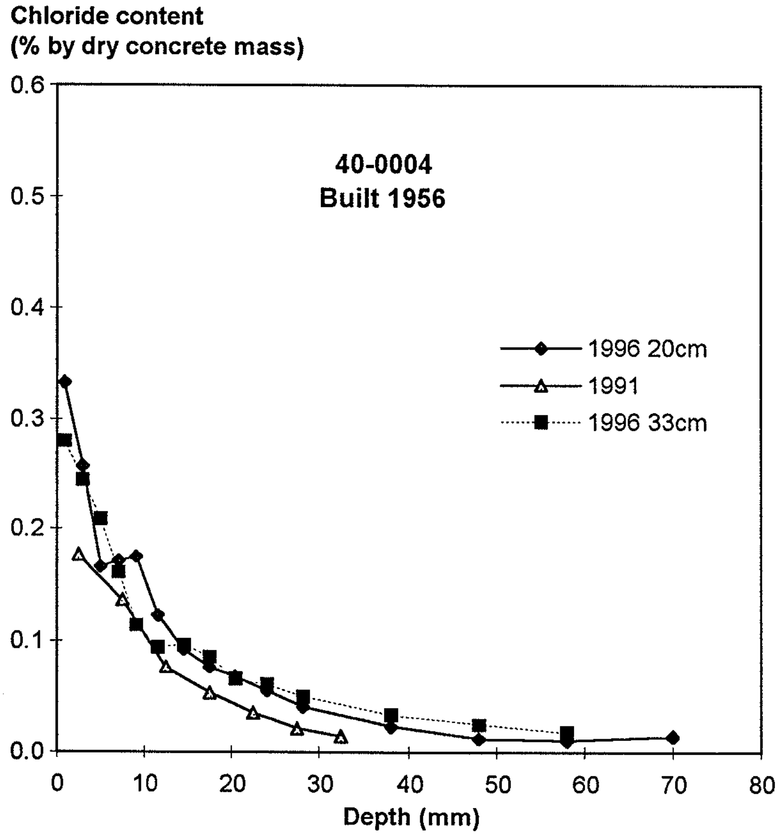



*Figure 5.2.1 Chloride profiles from bridge 40-0004 The sample 1991 was taken just below the other two samples.*

## 5.3 Bridge 30-0016

Two cores from 1996 were taken just above the 1991 core. One for moisture analysis and one for profile grinding and measurement of chloride diffusion coefficient.

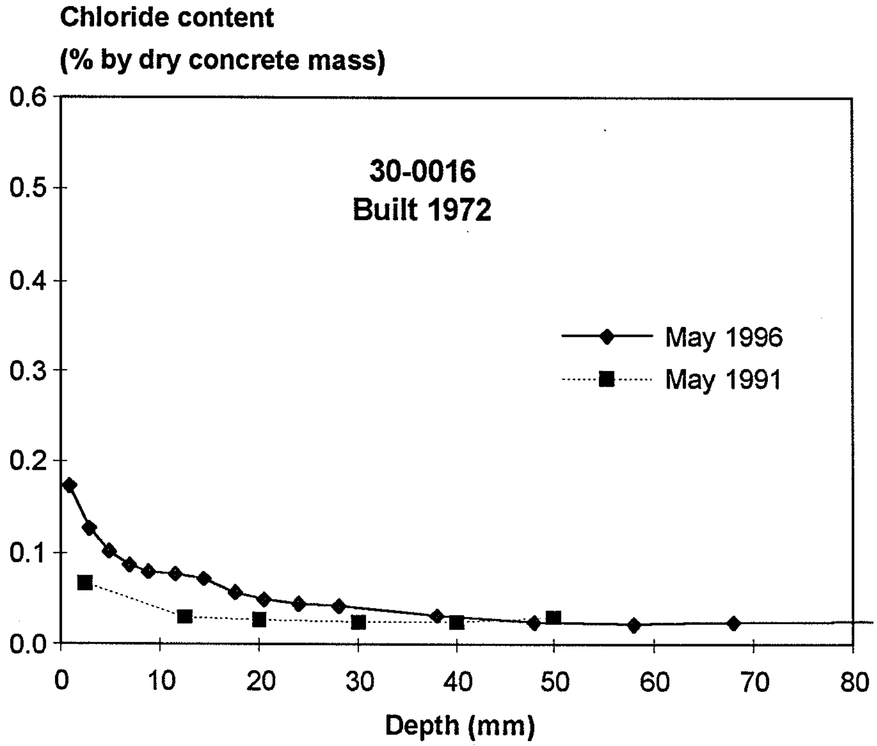



*Figure 5.3.1. Chloride profiles from bridge 30-0016, from a column 4 m from the lane.*

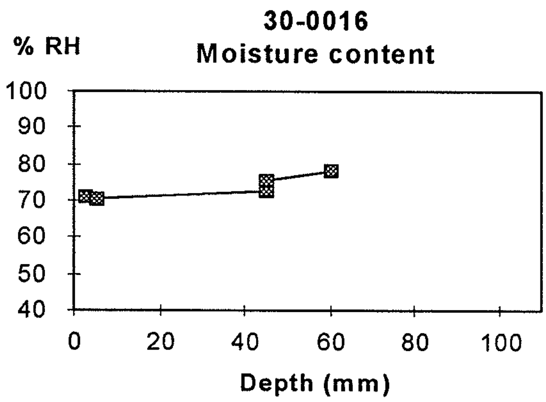



*Figure 5.3.2. Profile of relative humidity vs. depth. Bridge 30-0016, April 1996. The inner point could be contaminated by cooling water from the drilling of the core.*

## 5.4 Bridge 10-0031

Cores marked 1 and 2 were taken at the same height as the 1991 profiles and one core were taken at ground level.

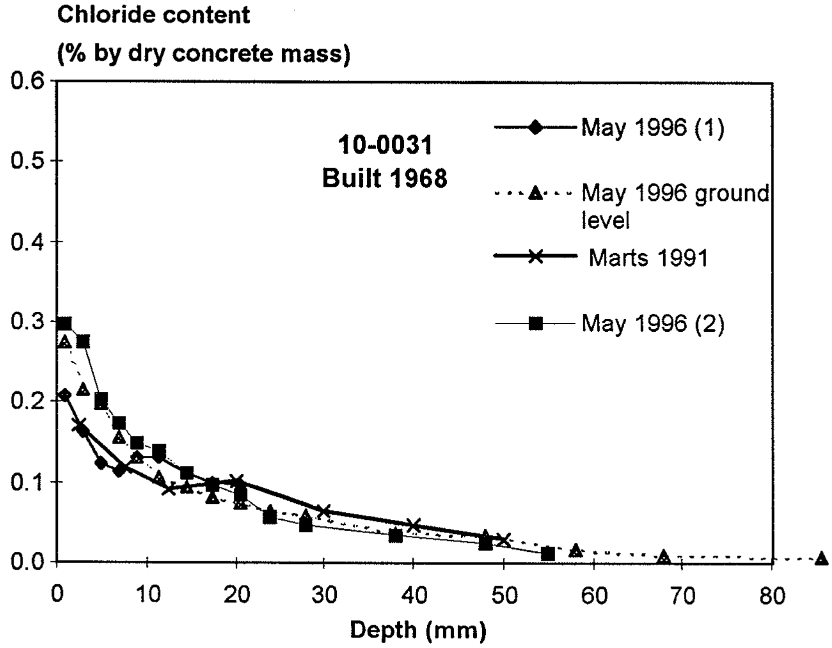



*Figure 5.4.1. All chloride profiles from bridge 10-0031.*

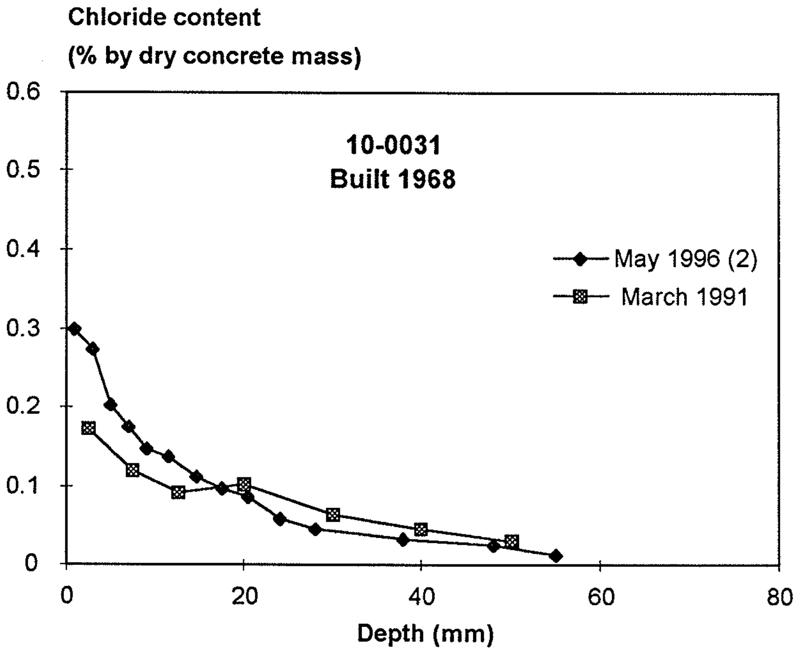



*Figure 5.4.2. Comparable chloride profiles from 1991 and 1996, bridge 10-0031.*

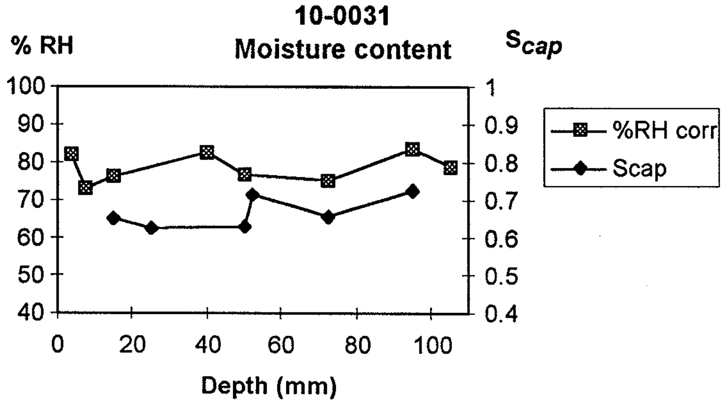



*Figure 5.4.3 Moisture profiles on bridge 10-0031, May 1996.*

## 5.5 Bridge 20-0085

The chloride profile marked 1 was taken close to the 1991 profile 30 cm above ground level. $D_{cth}$ specimens were prepared from sample 3 and 4. Sample 3 was taken 7 cm above ground level on the west side of the column and sample 4 was taken 67 cm above ground level on the same side.

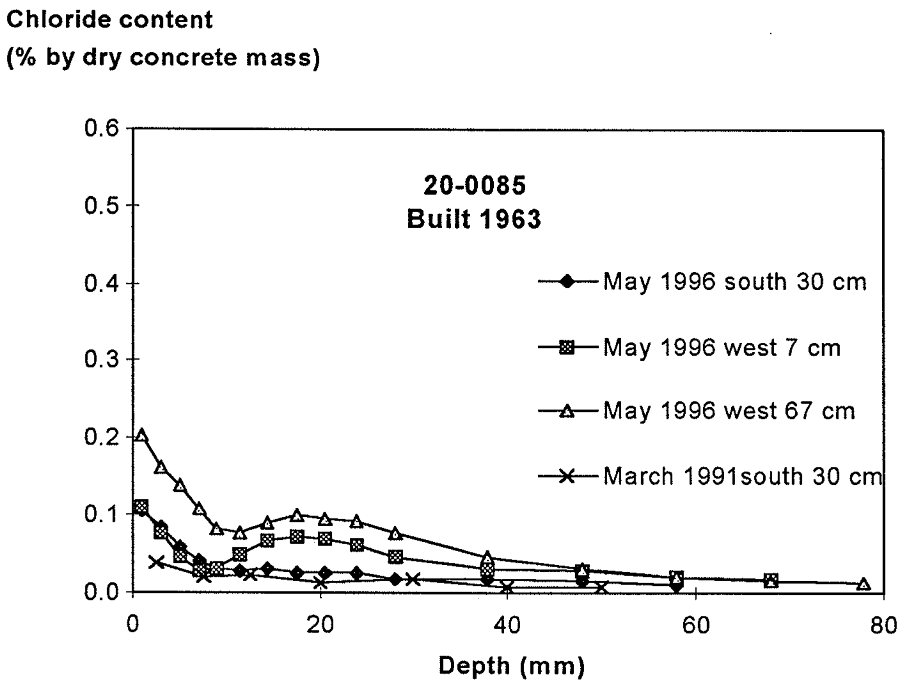



*Figure 5.5.1 All chloride profiles from bridge 20-0085.*

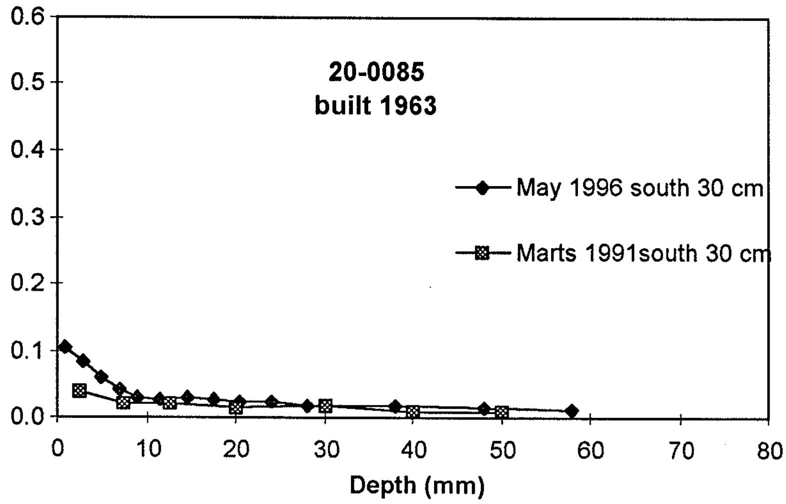



*Figure 5.5.2 Chloride profiles from the same place at different ages. 5 m from the nearest lane and facing the road.*

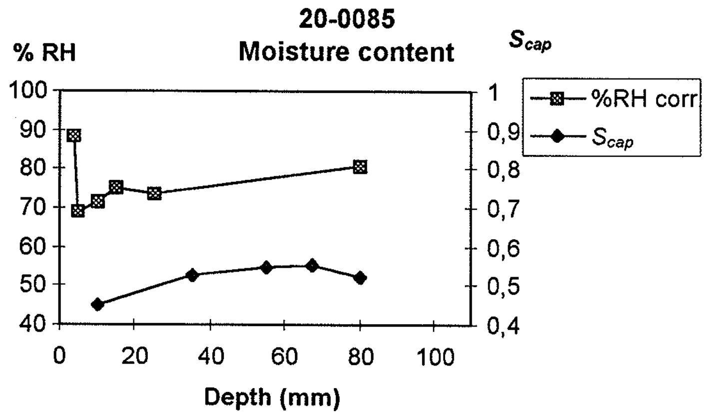



*Figure 5.5.3 Moisture profile on bridge 20-0085, May 1996.*

## 5.6 Chloride penetration depth, diffusion coefficients and carbonation depth.

The chloride penetration depths, diffusion coefficients and carbonation depths from all the bridges are shown in Table 5.6.1. The penetration depth of the concentration 0.05% vs. age is plotted in Figure 5.6.2.

*Table 5.6.1. Chloride penetration depths, carbonation depths and chloride diffusion coefficients for the cores taken from the bridges. $x_{0.05}$ is the depth where the chloride content is 0.05 % by weight of sample.*

| Bridge built | Sampling date | Core Mark | Height above road level [m] | $x_{0.05}$ [mm] | $x_{CO3}$ [mm] | $D_{CTH}$ [x $10^{-12}$m$^2$/s] |
|---|---|---|---|---|---|---|
| 10-0031 | 960512 | 1 | 0.2 | >20 | 2 | |
| 1968 | 960512 | 2 | 0.2 | 26 | 0 | 8.2 |
| | 960512 | 3 | 0.0 | 32 | 0 | |
| | 9103 | | 0.2 | 37 | | |
| 30-0016 | 960425 | 1 | 0.5 | 20 | - | 10 |
| 1972 | 9103 | | 0.2 | 7 | | |
| 20-0085 | 960511 | 1 | 0.3 | 6 | 7-14 | |
| 1963 | 960511 | 3 | 0.1 | 26 | 5-15 | 35 and 32 |
| | 960511 | 4 | 0.7 | 35 | 7-10 | 79 and 37 |
| | 9103 | | 0.3 | 0 | | |
| 40-0004 | 960526 | "20" | 0.2 | 25 | 0 | |
| 1956 | 960526 | "33" | 0.3 | 28 | 0 | |
| | 9103 | | 0.15 | 18 | | |
| 14-0036 | 960619 | S | 1.3 | 23 | 4 | 7.5 |
| 1956 | 960619 | N1 | 1.3 | 8 | 2 | 9.0 |
| | 960619 | N3 | 0.2 | 24 | 2 | 4.6 |
| | 960619 | N4 | 1.9 | 12 | 3 | |
| | 911002 | S | 1.0 | 16 | | |
| | 911002 | N | 1.0 | 10 | | |
| | 920520 | S | 1.0 | 17 | | |
| | 920520 | N | 1.0 | 11 | | |

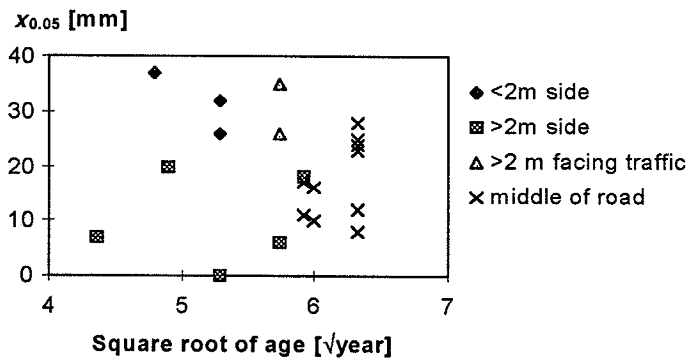



*Figure 5.6.2 Chloride penetration ($x_{0.05}$) vs. age in all bridges.*

# 6 Discussion

## 6.1 Reproducibility

The analysis techniques are destructive, so exactly the same spot can not be examined more than one time. In this study effort has been put into taking cores as close as possible to the previous cores. In no case the distance exceeded more than 0.3 m vertically and 0.5 m horizontally. Avoiding cutting reinforcement bars was the single most important factor in adding distance between the cores.

Moisture analysis in field conditions are difficult and the results are depending on weather conditions on the sampling site. The profiles could be used as an indication on the accuracy of the technique used. Conclusions should always be drawn from several measurements (points in a profile).

Even concrete made in laboratory conditions and exposed to chloride (NT build 443) shows different chloride surface contents. The difference in double samples in Frederiksen [1996] was around 5 to 20 percent in most cases. Better results from field studies can not be expected, due to inhomogeneity both in concrete and exposure conditions.

Comparing chloride profiles could lead to strange conclusions in some cases. Due to an accident when drilling the cores from bridge 10-0031 a 20 mm long core (core 2) was obtained from the surface close to core 1 on the same bridge. Comparing the chloride content per sample indicate a significant difference in chloride content in the surface, figure 6.1.1. But if the chloride content is plotted vs. calcium content the difference in chloride profiles is smaller, see figure 6.1.2. This indicates that difference in binder content should be treated as an important factor close to the surface. The binder content varies in the cores especially in the surface area.

At depths larger than 10 mm the reproducibility is good.

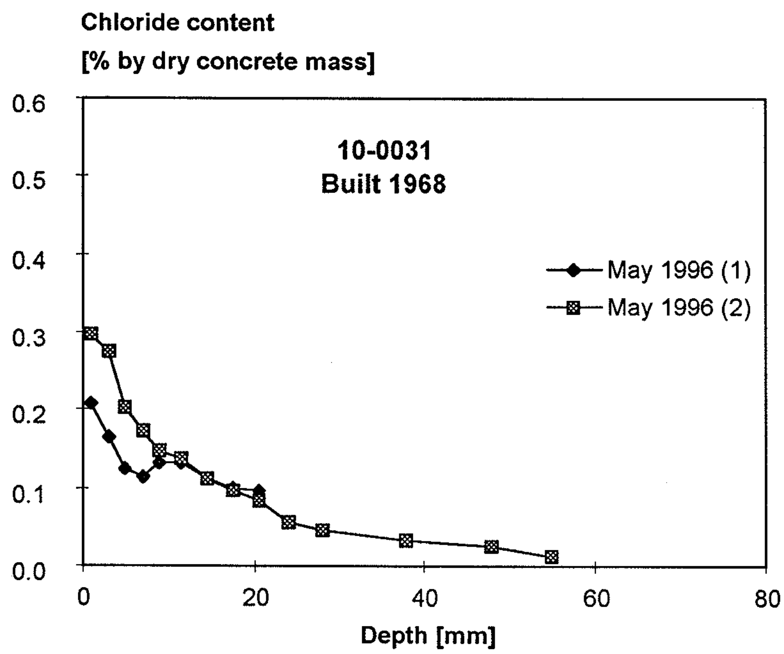



*Figure 6.1.1 Chloride profiles from bridge 10-0031 in cores taken close to each other.*

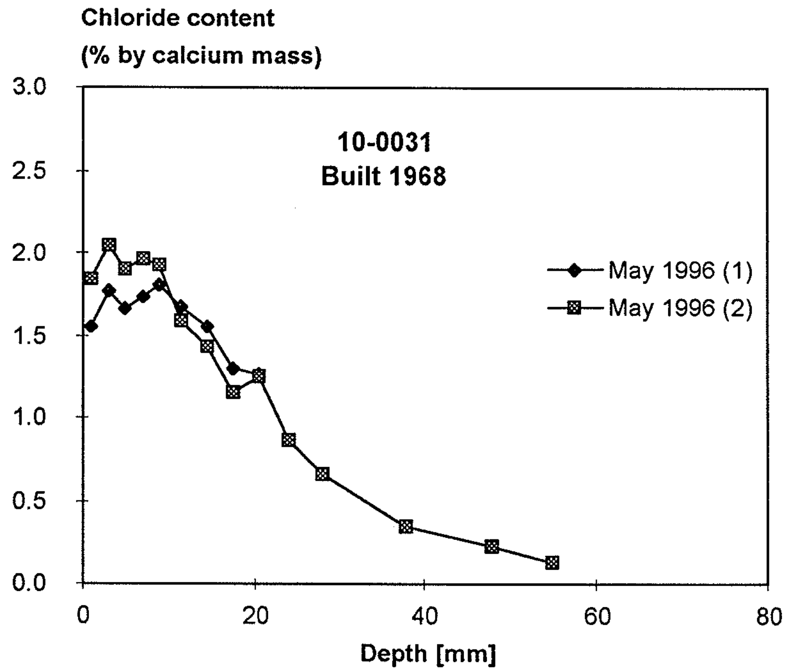



*Figure 6.1.2. Chloride vs. calcium profiles from bridge 10-0031.*

## 6.2 Effect of concrete quality

Even though the exposure may well have been quite different the concrete composition is expected to be quite similar (e.g. mix of plain Portland cement with no mineral additions) in all the bridges. It is however, obvious that the concrete in bridge 20-0085 is very different from the others. (In fact it was very much easier to drill out the cores). The diffusion coefficients were five times higher in this bridge. The depth of carbonation was extremely large in spite of the humidity being almost equal to the other bridges. Additionally, the relationship between RH and $S_{cap}$ was different in this bridge. That is an indication of a deviating concrete quality (quite another *w/c*, see figure 6.2).

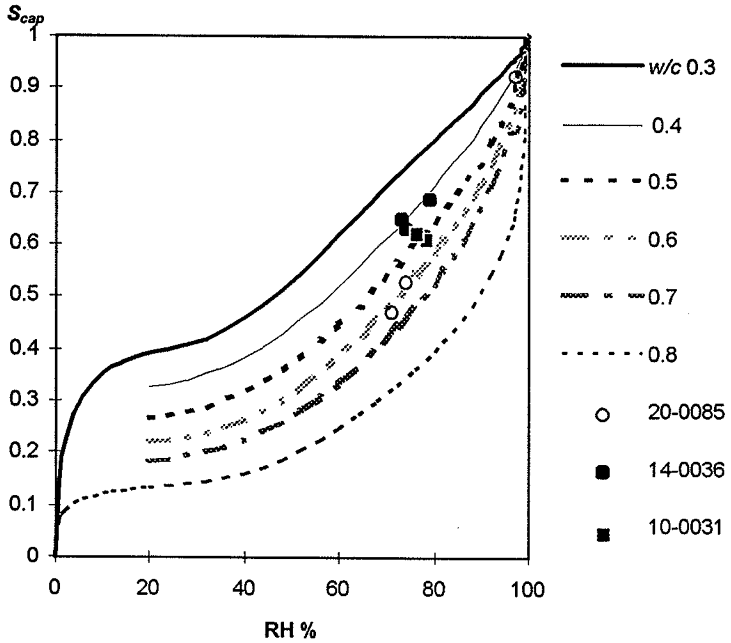



*Figure 6.2. Relation between RH and $S_{cap}$, data from Nilsson [1980].*

## 6.3 Effect of age

The bridges are 24 to 40 years old, and the five year period between the earlier and new chloride profiles is a relative short period in the life time of the bridges. The effect of age is shown in some of the figures in chapter 5, Figures 5.1.2, 5.2.2, 5.2.3, 5.2.3, 5.2.4 and 5.2.5. The difference in chloride profiles is rather small, as expected. Taking the remarks in Chapter 6.1 in respect, the difference in chloride ingress is smaller than the reproducibility of these measurements. The difference in the profiles, could be explained by the variability of the concrete and the micro environment. It is however important to note a slightly higher surface content in all cores from 1996. That is probably a combination of the weather just before the sampling and the fact that the surface analysis is from the outer 2 mm material, but slightly deeper in the 1991 and 1992 cores.

## 6.4 Effect of sampling point

The distance from the road and the height above the road seems to have a big influence on the chloride ingress. Even the orientation both geographically and relative to the traffic, is important, see Figures 5.1.1-5.1.4 and Figure 5.5.1.

## 6.5 Profile shape

The shape of the profiles varies from a plain profile of decreasing chloride content cf. Figure 5.1.3 and 5.2.1, to profiles with a bump (Figure 5.1.2) and in one case a peak (Figure 5.5.1). The start of these peaks coincides with the depth of carbonation, cf. Table 5.6.1. Since carbonation dramatically reduces chloride binding, the carbonated layer only contains free chloride in pores, and then the total chloride content is reduced.

## 6.6 Effect of time of year

From the measurements in this investigation no conclusions could be drawn on the effect of the seasons. The bridge 14-0036 was earlier examined both in autumn and in spring time. The results are presented in Chapter 5.1 and the Figure 5.1.2 and 5.1.3 indicate a slightly higher surface concentration in the spring measurements.

## 6.7 Moisture profiles

The relative humidity profiles varies very little from bridge to bridge. In all bridges the profiles are between 70 to 80 % RH. This would be expected as they are all exposed to the same climate. There are bigger variations in degree of capillary saturation cf. section 6.2. The relationship between RH and capillary saturation varies with material properties such as water cement ratio and cement type. The moisture content is probably an important input to a chloride ingress model.

The RH-profiles are very flat i.e. there is little sign of wetting or drying. It seems as if the sampling points are not exposed to rain but more or less in equilibrium with the surrounding air humidity.

# 7 Conclusions

Even though the new observations are accurate the available data are few and the findings should be treated as indications. In spite of this the following conclusions are drawn:

- The five years of further exposure of the bridges gave no significant increase in the chloride ingress.
- In this investigation the position of the sampling point is more important than the increase in exposure time of the bridge.
- The distance from the road seems to be an important factor, both horizontally and vertically.
- Orientation of surfaces towards traffic splash and driving rain is indicated to be an important factor.
- Chloride penetration clearly is a function of exposure conditions, both chloride (intensity) and climate (wetness).
- The parts of the bridges that were examined in this study, and the previous ones, are obviously fairly dry, properly because they are not significantly exposed to driving rain nor direct splash from the traffic.
- The chloride exposure for the columns beneath a bridge seems to be mainly airborne chloride following the air stream in the direction of the traffic. Other parts of bridges more exposed to direct splash of salt water could be very much wetter and provide more adverse conditions for deeper chloride penetration.

# 8 Proposals for further studies

More research is obviously needed to determine the boundary conditions for concrete structures in the road environment, in order to quantify the environmental load on road bridges. Climate conditions, such as

- air temperature,
- radiation,
- air humidity,
- rain and
- wind

some distances from a bridge, and close to the concrete surfaces, should be monitored to get data for describing the micro climate at surfaces from meteorological data.

Splash of rain water, salt water, and airborne chlorides, from the traffic should be measured at different heights and distances from the traffic and at surfaces with different orientations.

The response of the structures to the environmental load should be quantified both in depth and in width, i.e. both with detailed measurements on selected parts of a limited number of bridges and with a survey of a large number of bridges. Such a survey should always include a quantification of the environmental conditions.

The response should be quantified both in terms of chloride penetration and in moisture variations. Samples for determining potential chloride diffusion properties and moisture transport properties should be taken simultaneously.

The study should cover characteristic parts of structures in some typical environments on existing bridges. Additionally, new bridges or specimens on exposure sites, should be examined more thoroughly during the first year cycles with sampling after and before the first couple of winters to better understand the penetration process in a road environment.

In order to make such effort valuable for future application generally approved methods should be followed. A number of methods are needed. These are:

- Method for selecting structural components for analysis.
- Method for positioning the sampling points.
- Method for taking and handling samples for moisture analysis.
- Method for measuring moisture contents.

Already approved methods such as NT BUILD 208 for chloride analysis and NT BUILD 357 (principle) for measuring depth of carbonation must be included as parts of the methods.

# References


1991 Henriksen, C; Stoltzner, E; Lauridsen, J.: *Chloride-induced corrosion.* Vejdirektoratet Broområdet, Denmark.

1996 Tang L.: *Electrically accelerated methods for determining chlo ride diffusivity in concrete-current development.* Magazine of concrete research, **48,** No 176, Sept, 173 - 179.

1996 L.O. Nilsson, E. Poulsen, P. Sandberg, H.E. Sørensen: *HETEK Chloride penetration into concrete. State of the Art.* Report No. 53, The Danish Road Directorate.

1996 J.M. Frederiksen, H.E. Sørensen, A. Andersen, O. Klinghoffer: *HETEK The effect of the w/c ratio on chloride diffusivity.* Report No. 54, The Danish Road Directorate.

1980 Nilsson L.O. : *Hydroscopic moisture in concrete- drying, measurements & related material properties.* Rapport TVBM-1003, Lund, Sweden.

# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendices

Report No. 82
1996

# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendix 1

Report No. 82
1996

# Kloridbetinget korrosion

## Undersøgelse af kloridbelastning og korrosion på brosøjler

## Bilagsrapport

**Broområdet** **1991**

## BEREGNING af $C_S$ og D ved hjælp af "Profile grinding"

For yderligere at vurdere nøjagtigheden af de diffusionsberegninger er der på 4 broer foretaget en nærmere bestemmelse af kloridprofilet og en efterfølgende beregning af $C_s$ og D. Kloridprofilbestemmelsen er foretaget ved "profile grinding" på borekerner udtaget 50-130 mm over terræn. Beregningerne af $C_s$ og D er derefter foretaget ud fra FICK's 2. lov.

Målinger og beregninger er foretaget af Force-instituterne og fremgår af de følgende bilag.

20.0085

| Depth (mm) | C (%) | Cfit (%) |
|---|---|---|
| 2.500 | .038 | .030 |
| 7.500 | .020 | .027 |
| 12.500 | .022 | .023 |
| 20.000 | .014 | .019 |
| 30.000 | .017 | .013 |
| 40.000 | .008 | .009 |
| 50.000 | .008 | .005 |
| 100.000 | .000 | .000 |

Diffusion coef. D = 7.6454E-13 m^2/s
Time t = 9856 days
Surface conc. Cs = .0320 %
Base conc. Co = .0000 %
regr. coef.= .83592
==============================================

10.0031

| Depth (mm) | C (%) | Cfit (%) |
|---|---|---|
| 2.500 | .172 | .150 |
| 7.500 | .120 | .133 |
| 12.500 | .092 | .116 |
| 20.000 | .101 | .092 |
| 30.000 | .064 | .064 |
| 40.000 | .046 | .042 |
| 50.000 | .030 | .026 |
| 100.000 | .000 | .001 |

Diffusion coef. D = 9.2017E-13 m^2/s
Time t = 8096 days
Surface conc. Cs = .1589 %
Base conc. Co = .0000 %
regr. coef.= .93719
==============================================

30.0016

| Depth (mm) | C (%) | Cfit (%) |
|---|---|---|
| 2.500 | .068 | .058 |
| 12.500 | .040 | .047 |
| 20.000 | .030 | .039 |
| 30.000 | .027 | .030 |
| 40.000 | .026 | .022 |
| 50.000 | .024 | .016 |
| 100.000 | .000 | .001 |

Diffusion coef. D = 1.7092E-12 m^2/s
Time t = 6688 days
Surface conc. Cs = .0605 %
Base conc. Co = .0000 %
regr. coef.= .86443
==============================================

40.0004

| Depth (mm) | C (%) | Cfit (%) |
|---|---|---|
| 2.500 | .177 | .177 |
| 7.500 | .136 | .129 |
| 12.500 | .076 | .087 |
| 17.500 | .053 | .055 |
| 22.500 | .035 | .032 |
| 27.500 | .021 | .017 |
| 32.500 | .014 | .008 |
| 100.000 | .000 | .000 |

```
Diffusion coef. D =  1.1859E-13  m^2/s
Time            t =  12320 days
Surface conc.  Cs =  .2025  %
Base conc.     Co =  .0000  %
regr. coef.= .99119
=============================================
```

# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendix 2

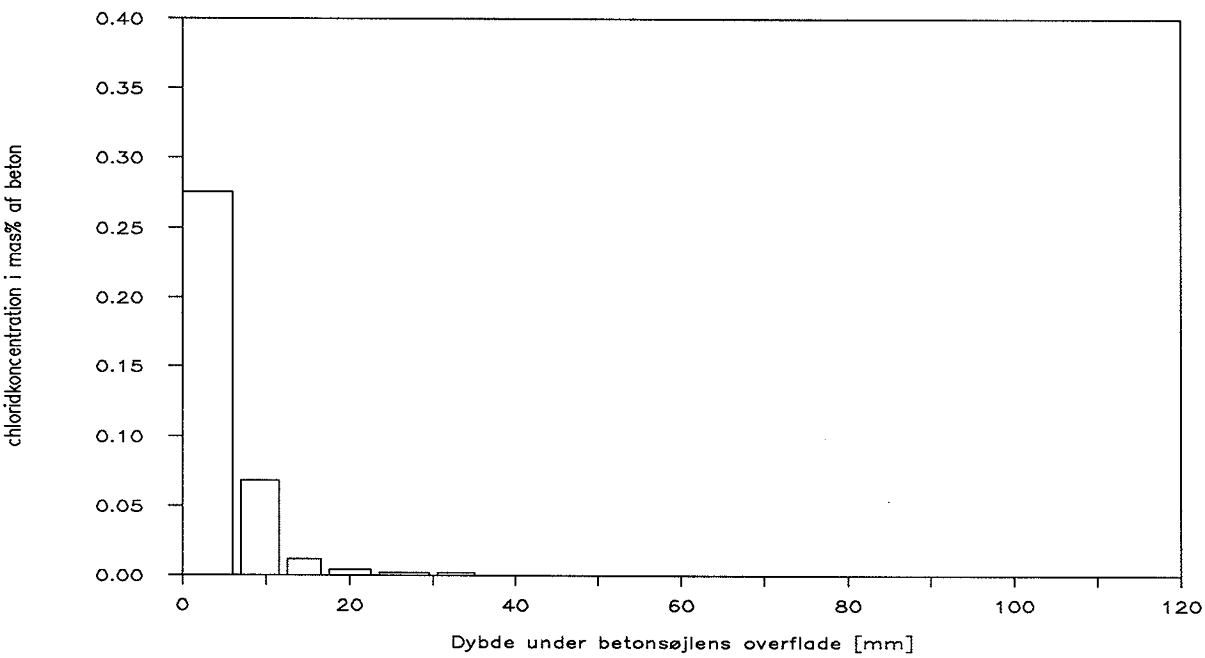
Report No. 82
1996

# MAKROCHLORIDPROFIL
## DS 423.28

AEClaboratoriet
Staktoften 20
2950 Vedbæk
45 66 12 66

Lab nr: 510
Prøve nr: 1
Init: jh/jmf
Udskrift: 03/12/96

## CHLORIDPROFIL




## ANALYSERESULTATER iht DS 423.28

| Delprøve nr | Måleinterval [mm] | Prøvestørrelse [g] | Cl i beton [mas%] |
|---|---|---|---|
| 1 | 0.0 - 6.0 | 29.21 | 0.276 |
| 2 | 7.0 - 11.5 | 24.03 | 0.068 |
| 3 | 12.5 - 16.5 | 21.25 | 0.012 |
| 4 | 17.5 - 22.5 | 23.58 | 0.004 |
| 5 | 23.5 - 29.5 | 27.44 | 0.002 |
| 6 | 30.5 - 35.0 | 19.96 | 0.002 |

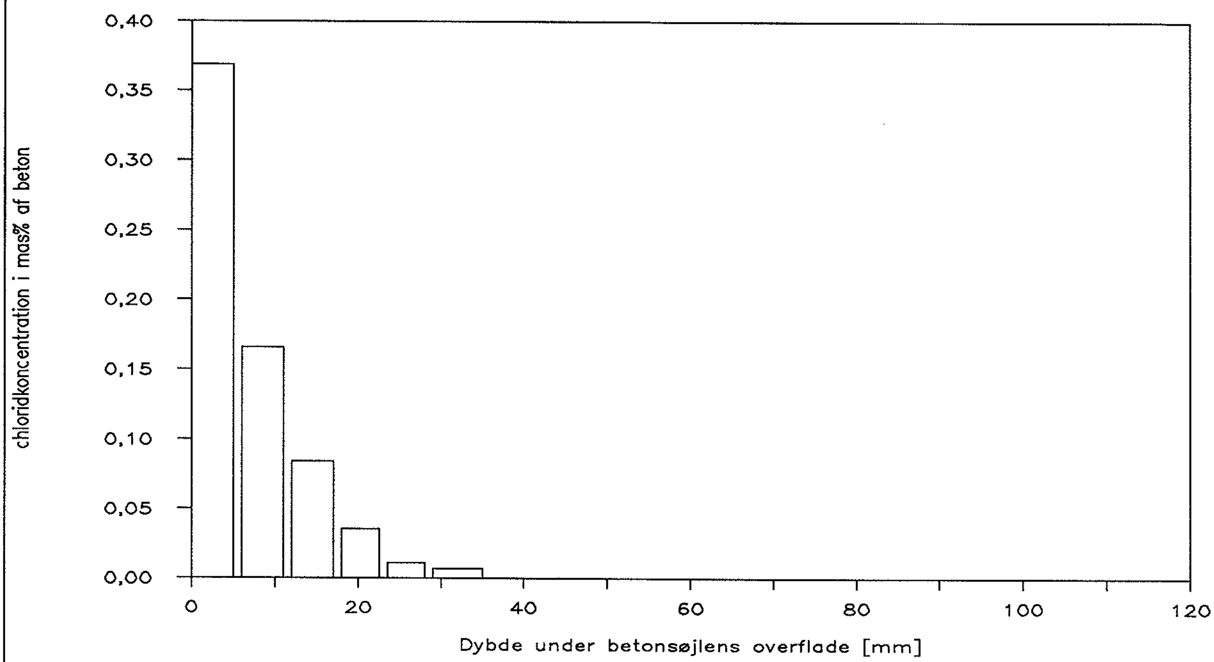
## KOMMENTARER

# MAKROCHLORIDPROFIL
## DS 423.28

AEClaboratoriet
Staktoften 20
2950 Vedbæk
45 66 12 66

Lab nr: 510
Prøve nr: 2
Init: JH/jmf
Udskrift: 03/12/96

### CHLORIDPROFIL




### ANALYSERESULTATER iht DS 423.28

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|---|---|---|---|
| 1 | 0.0 - 5.0 | 21.90 | 0.369 |
| 2 | 6.0 - 11.0 | 26.66 | 0.166 |
| 3 | 12.0 - 17.0 | 27.90 | 0.084 |
| 4 | 18.0 - 22.5 | 24.14 | 0.035 |
| 5 | 23.5 - 28.0 | 18.95 | 0.011 |
| 6 | 29.0 - 35.0 | 22.84 | 0.007 |

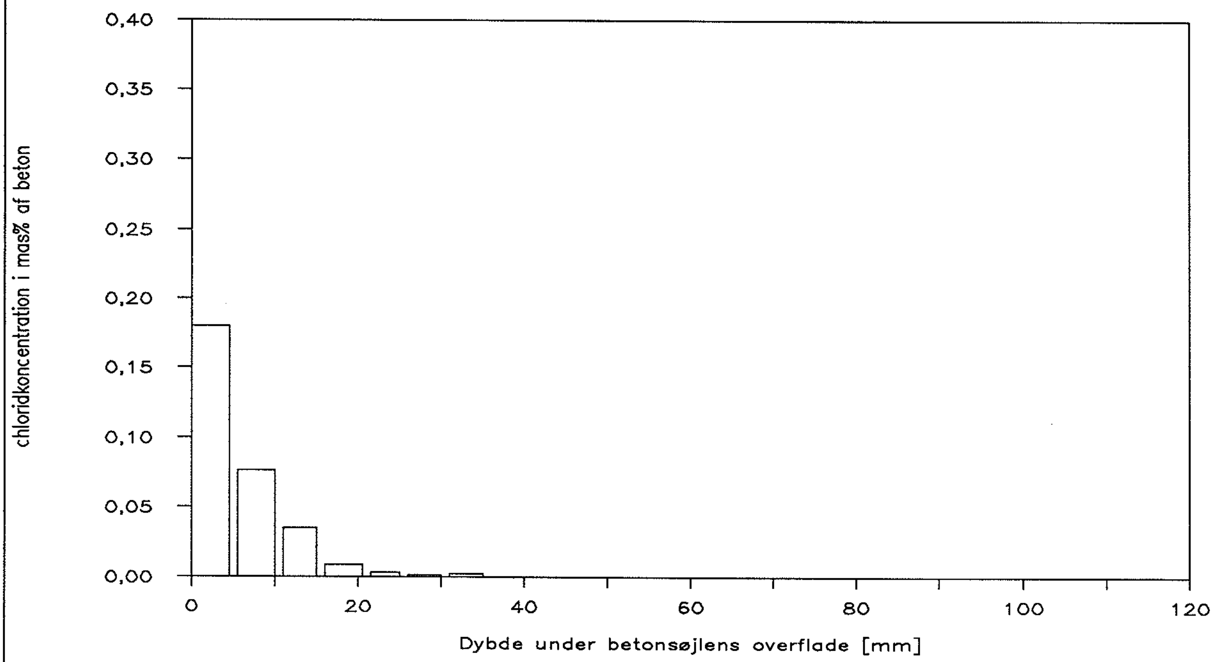
### KOMMENTARER

# MAKROCHLORIDPROFIL
## DS 423.28

AEClaboratoriet
Staktoften 20
2950 Vedbæk
45 66 12 66

Lab nr: 510
Prøve nr: 3
Init: jh/jmf
Udskrift: 03/12/96

## CHLORIDPROFIL




## ANALYSERESULTATER iht DS 423.28

| Delprøve nr | Måleinterval [mm] | Prøvestørrelse [g] | Cl i beton [mas%] |
|---|---|---|---|
| 1 | 0.0 - 4.5 | 21.47 | 0.180 |
| 2 | 5.5 - 10.0 | 20.04 | 0.077 |
| 3 | 11.0 - 15.0 | 26.37 | 0.035 |
| 4 | 16.0 - 20.5 | 22.14 | 0.009 |
| 5 | 21.5 - 25.0 | 18.64 | 0.004 |
| 6 | 26.0 - 30.0 | 17.04 | 0.002 |
| 7 | 31.0 - 35.0 | 15.78 | 0.002 |

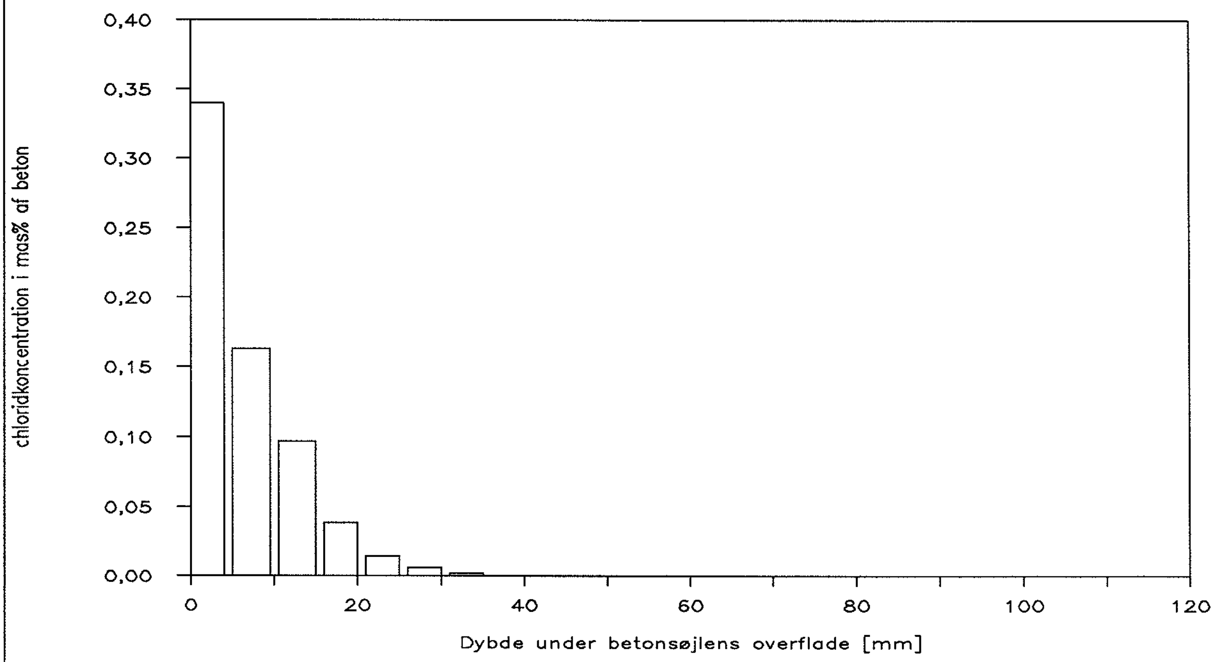
## KOMMENTARER

# MAKROCHLORIDPROFIL
## DS 423.28

AEClaboratoriet
Staktoften 20
2950 Vedbæk
45 66 12 66

Lab nr: *510*
Prøve nr: *4*
Init: *jh/jmf*
Udskrift: *03/12/96*

**CHLORIDPROFIL**




**ANALYSERESULTATER iht DS 423.28**

| Delprøve nr | Måleinterval [mm] | Prøvestørrelse [g] | Cl i beton [mas%] |
|---|---|---|---|
| 1 | 0.0 - 4.0 | 15.47 | 0.340 |
| 2 | 5.0 - 9.5 | 21.50 | 0.163 |
| 3 | 10.5 - 15.0 | 18.18 | 0.097 |
| 4 | 16.0 - 20.0 | 16.93 | 0.039 |
| 5 | 21.0 - 25.0 | 20.18 | 0.014 |
| 6 | 26.0 - 30.0 | 20.55 | 0.006 |
| 7 | 31.0 - 35.0 | 19.41 | 0.002 |

**KOMMENTARER**

# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendix 3

Report No. 82
1996

DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS
Chalmers University of Technology

Bridge 10-0031
core 1

Test conducted by: NY Date 25-06-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| I1 | 1 | 0,902 | 5,277 | 30,034 | 0,207 | 13,345 | 1,554 |
| | 3 | 0,913 | 4,233 | 21,162 | 0,164 | 9,290 | 1,769 |
| | 5 | 0,911 | 3,197 | 17,04 | 0,124 | 7,497 | 1,659 |
| | 7 | 0,91 | 2,949 | 15,056 | 0,115 | 6,631 | 1,732 |
| | 9 | 0,902 | 3,334 | 16,347 | 0,131 | 7,264 | 1,804 |
| | 11,5 | 0,933 | 3,482 | 18,395 | 0,132 | 7,902 | 1,674 |
| | 14,5 | 0,917 | 2,862 | 16,247 | 0,111 | 7,101 | 1,558 |
| | 17,5 | 0,898 | 2,529 | 17,242 | 0,100 | 7,696 | 1,297 |
| | 20,5 | 0,91 | 2,505 | 17,485 | 0,098 | 7,701 | 1,267 |

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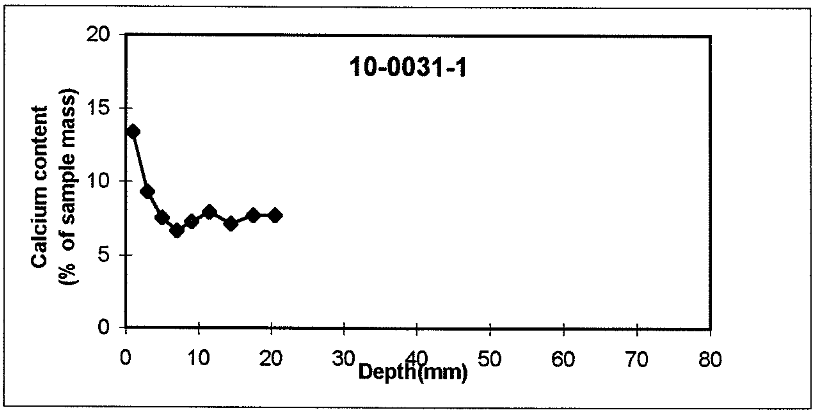


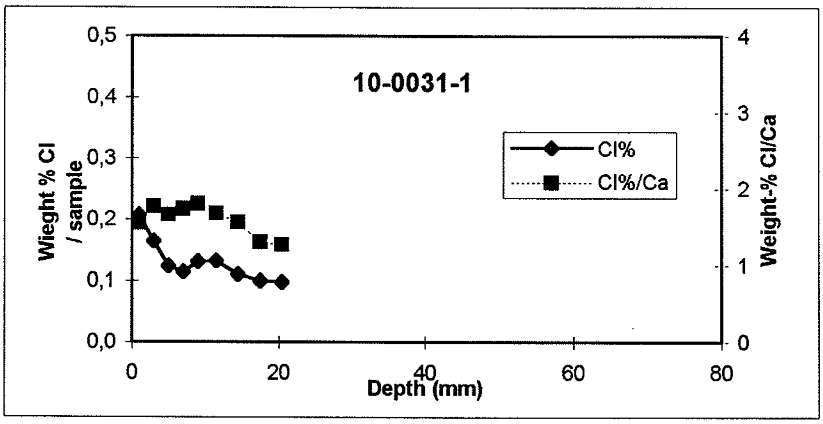

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 10-0031
Core 2

Test conducted by: NY Date 26-06-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,941 | 7,905 | 38 | 0,298 | 16,185 | 1,840 |
| | 3 | 0,945 | 7,322 | 31,65 | 0,275 | 13,424 | 2,046 |
| | 5 | 0,95 | 5,419 | 25,235 | 0,202 | 10,647 | 1,899 |
| | 7 | 0,905 | 4,443 | 19,95 | 0,174 | 8,835 | 1,970 |
| | 9 | 0,916 | 3,817 | 17,522 | 0,148 | 7,667 | 1,927 |
| | 11,5 | 0,917 | 3,562 | 19,875 | 0,138 | 8,687 | 1,585 |
| | 14,5 | 0,906 | 2,861 | 17,637 | 0,112 | 7,802 | 1,435 |
| | 17,5 | 0,918 | 2,482 | 18,956 | 0,096 | 8,276 | 1,158 |
| | 20,5 | 0,907 | 2,17 | 15,333 | 0,085 | 6,776 | 1,252 |
| | 24 | 0,926 | 1,494 | 15,218 | 0,057 | 6,587 | 0,868 |
| | 28 | 0,94 | 1,231 | 16,393 | 0,046 | 6,990 | 0,664 |
| | 38 | 0,94 | 0,894 | 23,011 | 0,034 | 9,811 | 0,344 |
| | 48 | 0,923 | 0,652 | 25,57 | 0,025 | 11,103 | 0,226 |
| | 55 | 0,939 | 0,335 | 21,709 | 0,013 | 9,266 | 0,136 |

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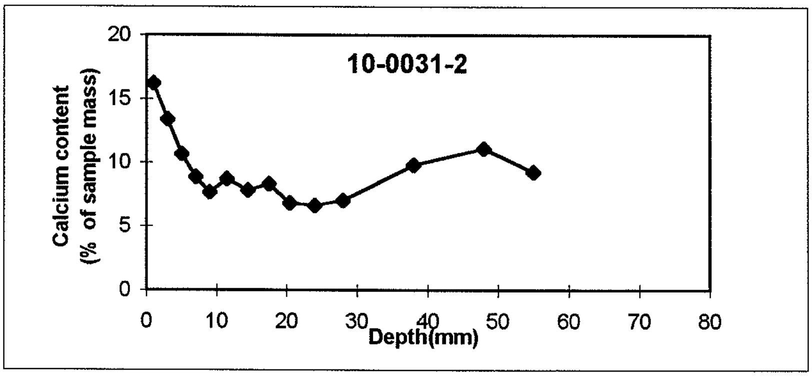


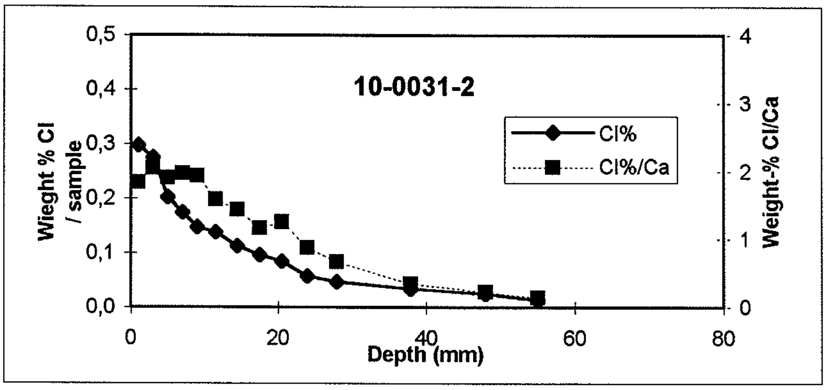

**DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS**
Chalmers University of Technology

Bridge 10-0031
Core 3

Test conducted by: NY Date 26-06-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| I3 | 1 | 0,541 | 4,211 | 20,497 | 0,276 | 15,185 | 1,817 |
| | 3 | 0,934 | 5,691 | 29,418 | 0,216 | 12,624 | 1,711 |
| | 5 | 0,96 | 5,352 | 28,344 | 0,198 | 11,834 | 1,670 |
| | 7 | 0,952 | 4,227 | 23,35 | 0,157 | 9,831 | 1,601 |
| | 9 | 0,943 | 3,484 | 18,092 | 0,131 | 7,690 | 1,703 |
| | 11,5 | 0,909 | 2,762 | 15,752 | 0,108 | 6,945 | 1,551 |
| | 14,5 | 0,912 | 2,408 | 16,188 | 0,094 | 7,114 | 1,316 |
| | 17,5 | 0,909 | 2,078 | 15,352 | 0,081 | 6,769 | 1,197 |
| | 20,5 | 0,901 | 1,879 | 15,209 | 0,074 | 6,766 | 1,093 |
| | 24 | 0,909 | 1,662 | 17,217 | 0,065 | 7,591 | 0,854 |
| | 28 | 0,918 | 1,519 | 20,406 | 0,059 | 8,909 | 0,658 |
| | 38 | 0,949 | 1,013 | 23,569 | 0,038 | 9,954 | 0,380 |
| | 48 | 0,954 | 0,928 | 24,081 | 0,034 | 10,117 | 0,341 |
| | 58 | 0,948 | 0,495 | 24,411 | 0,019 | 10,321 | 0,179 |
| | 68 | 0,916 | 0,261 | 18,2 | 0,010 | 7,963 | 0,127 |
| | 85,5 | 0,915 | 0,172 | 18,718 | 0,007 | 8,199 | 0,081 |

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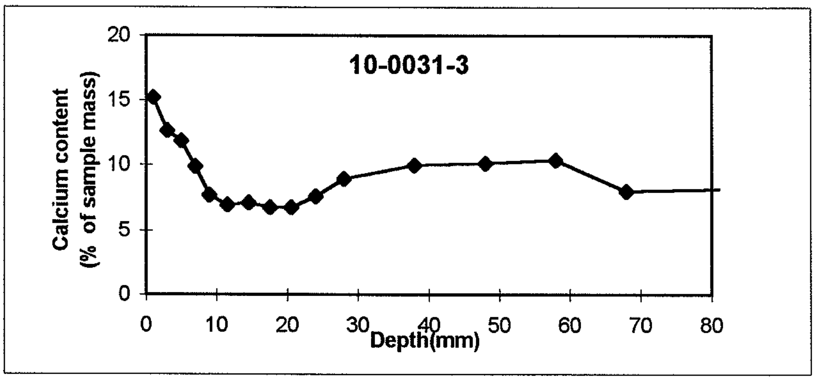


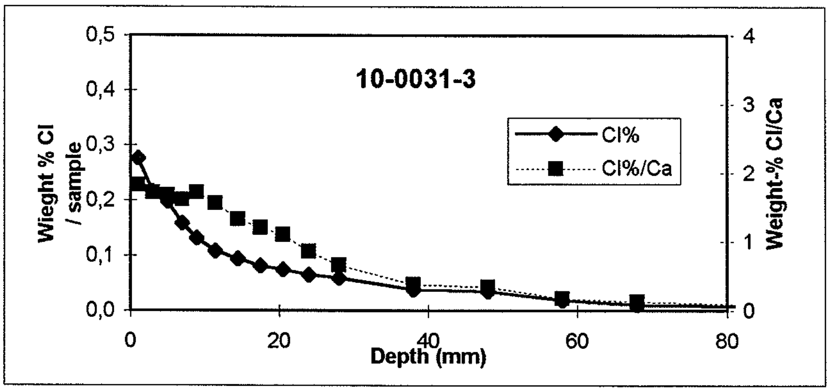

**DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS**
Chalmers University of Technology

Bridge 30-0016
Core 1

Test conducted by: NY Date 05-07-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,928 | 4,541 | 39,8 | 0,173 | 17,189 | 1,009 |
| | 3 | 0,939 | 3,335 | 35,323 | 0,126 | 15,077 | 0,835 |
| | 5 | 0,943 | 2,688 | 29,85 | 0,101 | 12,687 | 0,796477 |
| | 7 | 0,932 | 2,282 | 26,12 | 0,087 | 11,233 | 0,772736 |
| | 9 | 0,934 | 2,098 | 25,209 | 0,080 | 10,818 | 0,736103 |
| | 11,5 | 0,92 | 1,988 | 26,233 | 0,077 | 11,428 | 0,670281 |
| | 14,5 | 0,924 | 1,843 | 26,743 | 0,071 | 11,600 | 0,609542 |
| | 17,5 | 0,92 | 1,489 | 24,092 | 0,057 | 10,496 | 0,546651 |
| | 20,5 | 0,922 | 1,285 | 21,594 | 0,049 | 9,387 | 0,526331 |
| | 24 | 0,939 | 1,163 | 20,951 | 0,044 | 8,943 | 0,49098 |
| | 28 | 0,918 | 1,081 | 21,892 | 0,042 | 9,558 | 0,436746 |
| | 38 | 0,932 | 0,823 | 22,008 | 0,031 | 9,464 | 0,330756 |
| | 48 | 0,973 | 0,707 | 22,373 | 0,026 | 9,216 | 0,279501 |
| | 58 | 0,928 | 0,57 | 21,054 | 0,022 | 9,093 | 0,239458 |
| | 68 | 0,976 | 0,67 | 22,11 | 0,024 | 9,080 | 0,268025 |
| | 128 | 0,942 | 0,718 | 21,154 | 0,027 | 9,001 | 0,300207 |

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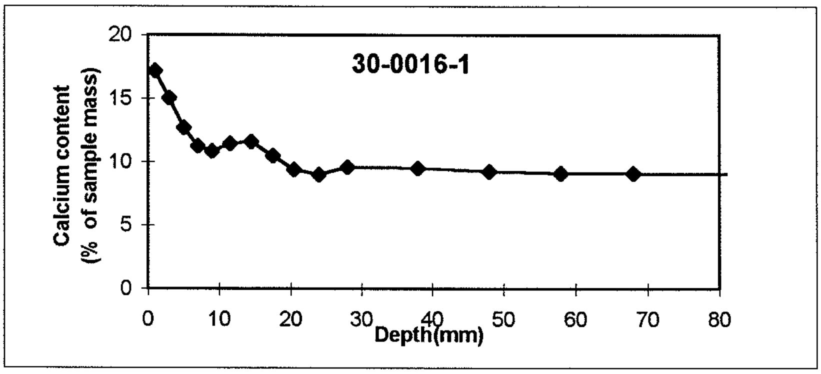


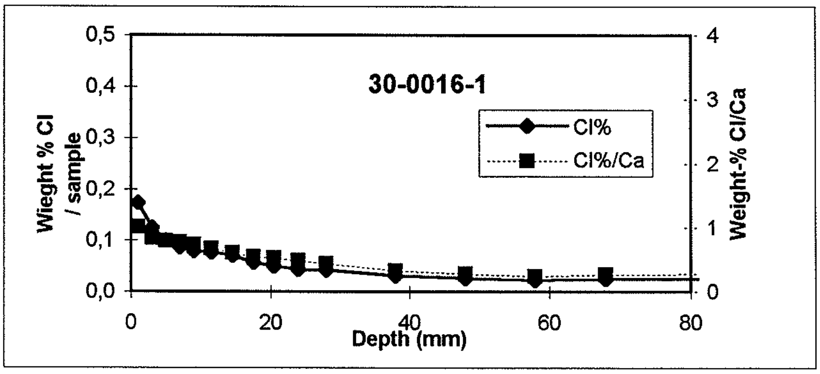

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 20-0085
Core 1

Test conducted by: NY Date 27-07-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,93 | 2,742 | 30,339 | 0,105 | 13,075 | 0,799 |
| | 3 | 0,907 | 2,168 | 28,097 | 0,085 | 12,416 | 0,682 |
| | 5 | 0,897 | 1,494 | 23,91 | 0,059 | 10,684 | 0,552662 |
| | 7 | 0,908 | 1,04 | 22,06 | 0,041 | 9,737 | 0,416981 |
| | 9 | 0,948 | 0,809 | 18,209 | 0,030 | 7,698 | 0,392962 |
| | 11,5 | 0,927 | 0,72 | 15,748 | 0,028 | 6,809 | 0,404386 |
| | 14,5 | 0,911 | 0,762 | 14,993 | 0,030 | 6,596 | 0,449526 |
| | 17,5 | 0,965 | 0,697 | 15,971 | 0,026 | 6,633 | 0,386002 |
| | 20,5 | 0,937 | 0,658 | 15,323 | 0,025 | 6,554 | 0,379814 |
| | 24 | 0,927 | 0,64 | 16,477 | 0,024 | 7,124 | 0,34355 |
| | 28 | 0,93 | 0,493 | 13,724 | 0,019 | 5,915 | 0,317727 |
| | 38 | 0,91 | 0,478 | 14,512 | 0,019 | 6,392 | 0,291333 |
| | 48 | 0,982 | 0,421 | 16,295 | 0,015 | 6,651 | 0,228516 |
| | 58 | 0,932 | 0,303 | 19,549 | 0,012 | 8,407 | 0,13709 |

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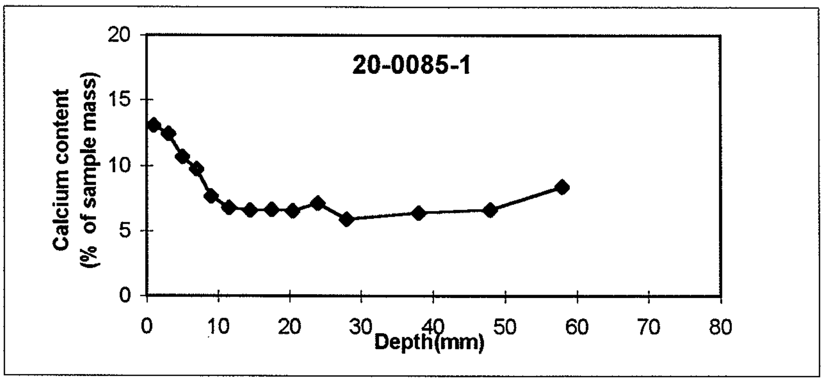


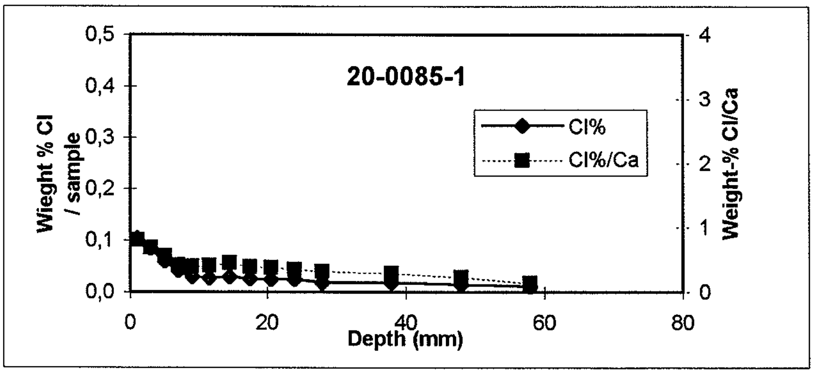

# DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 20-0085
Core 3

Test conducted by: NY Date 26-06-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,927 | 2,874 | 29,877 | 0,110 | 12,918 | 0,851 |
| | 3 | 0,904 | 1,994 | 29,055 | 0,078 | 12,882 | 0,607 |
| | 5 | 0,945 | 1,215 | 24,988 | 0,046 | 10,598 | 0,430 |
| | 7 | 0,935 | 0,751 | 20,94 | 0,028 | 8,976 | 0,317 |
| | 9 | 0,916 | 0,8 | 18,645 | 0,031 | 8,158 | 0,380 |
| | 11,5 | 0,952 | 1,306 | 18,396 | 0,049 | 7,745 | 0,628 |
| | 14,5 | 0,949 | 1,81 | 16,722 | 0,068 | 7,062 | 0,957 |
| | 17,5 | 0,92 | 1,861 | 16,471 | 0,072 | 7,176 | 0,999 |
| | 20,5 | 0,973 | 1,907 | 17,121 | 0,069 | 7,053 | 0,985 |
| | 24 | 0,927 | 1,597 | 17,519 | 0,061 | 7,575 | 0,806 |
| | 28 | 0,898 | 1,205 | 15,873 | 0,048 | 7,085 | 0,671 |
| | 38 | 0,942 | 0,819 | 16,7 | 0,031 | 7,105 | 0,434 |
| | 48 | 0,9 | 0,689 | 19,235 | 0,027 | 8,566 | 0,317 |
| | 58 | 0,925 | 0,518 | 14,965 | 0,020 | 6,484 | 0,306 |
| | 68 | 0,942 | 0,471 | 18,65 | 0,018 | 7,935 | 0,223 |

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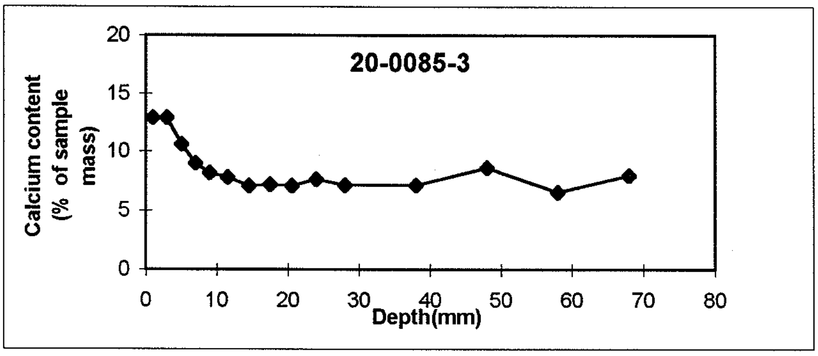


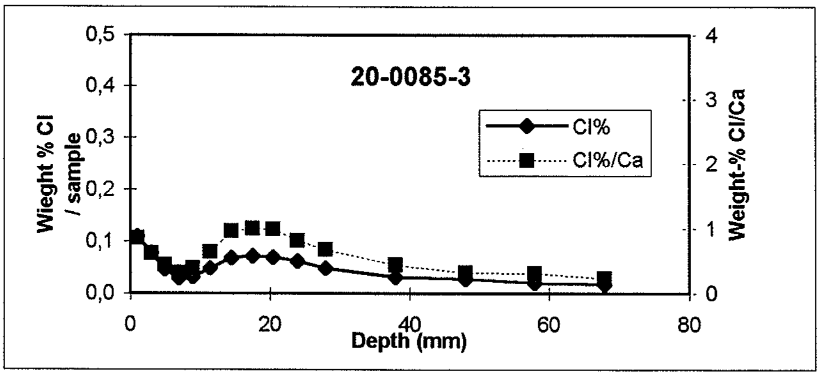

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS
Chalmers University of Technology

Bridge 20-0085
Core 4

Test conducted by: NY Date 04-07-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,929 | 5,341 | 27,396 | 0,204 | 11,820 | 1,724 |
| | 3 | 0,914 | 4,212 | 24,384 | 0,163 | 10,693 | 1,528 |
| | 5 | 0,987 | 3,906 | 24,09 | 0,140 | 9,782 | 1,434 |
| | 7 | 0,907 | 2,777 | 18,629 | 0,109 | 8,232 | 1,318 |
| | 9 | 0,925 | 2,167 | 17,446 | 0,083 | 7,559 | 1,099 |
| | 11,5 | 0,923 | 2,024 | 16,983 | 0,078 | 7,375 | 1,054 |
| | 14,5 | 0,939 | 2,403 | 18,969 | 0,091 | 8,097 | 1,120 |
| | 17,5 | 0,926 | 2,592 | 17,931 | 0,099 | 7,761 | 1,279 |
| | 20,5 | 0,922 | 2,464 | 17,355 | 0,095 | 7,544 | 1,256 |
| | 24 | 0,916 | 2,366 | 19,508 | 0,092 | 8,536 | 1,073 |
| | 28 | 0,927 | 2,026 | 20,067 | 0,077 | 8,676 | 0,893 |
| | 38 | 0,949 | 1,233 | 20,536 | 0,046 | 8,673 | 0,531 |
| | 48 | 0,94 | 0,831 | 20,6 | 0,031 | 8,783 | 0,357 |
| | 58 | 0,975 | 0,593 | 18,096 | 0,022 | 7,439 | 0,290 |
| | 68 | 0,91 | 0,415 | 16,411 | 0,016 | 7,228 | 0,224 |
| | 78 | 0,915 | 0,319 | 17,375 | 0,012 | 7,611 | 0,162 |

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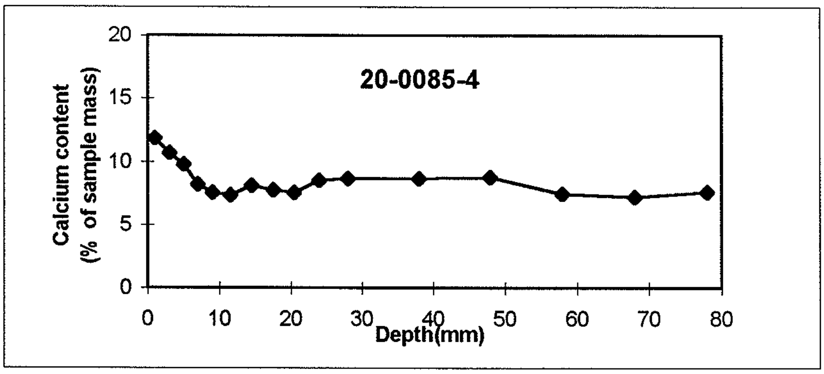


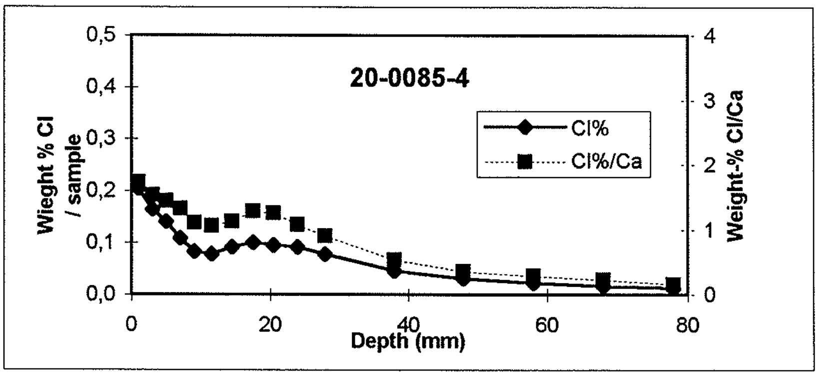

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 40-0004
Core "20"

Test conducted by: NY Date 08-07-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,927 | 8,697 | 37,6 | 0,333 | 16,257 | 2,046 |
| | 3 | 0,998 | 7,233 | 27,497 | 0,257 | 11,043 | 2,327 |
| | 5 | 0,956 | 4,478 | 19,968 | 0,166 | 8,372 | 1,984 |
| | 7 | 0,91 | 4,389 | 23,048 | 0,171 | 10,151 | 1,684 |
| | 9 | 0,945 | 4,664 | 27,731 | 0,175 | 11,761 | 1,488 |
| | 11,5 | 0,933 | 3,218 | 19,748 | 0,122 | 8,483 | 1,441 |
| | 14,5 | 0,944 | 2,473 | 18,2 | 0,093 | 7,727 | 1,202 |
| | 17,5 | 0,909 | 1,951 | 16,076 | 0,076 | 7,088 | 1,073 |
| | 20,5 | 0,962 | 1,822 | 18,459 | 0,067 | 7,691 | 0,873 |
| | 24 | 0,92 | 1,426 | 19,909 | 0,055 | 8,673 | 0,634 |
| | 28 | 0,954 | 1,083 | 21,185 | 0,040 | 8,900 | 0,452 |
| | 38 | 0,905 | 0,608 | 19,23 | 0,024 | 8,516 | 0,280 |
| | 48 | 0,906 | 0,323 | 21,262 | 0,013 | 9,406 | 0,134 |
| | 58 | 0,912 | 0,263 | 17,758 | 0,010 | 7,804 | 0,131 |
| | 70 | 0,546 | 0,22 | 15,63 | 0,014 | 11,473 | 0,124 |

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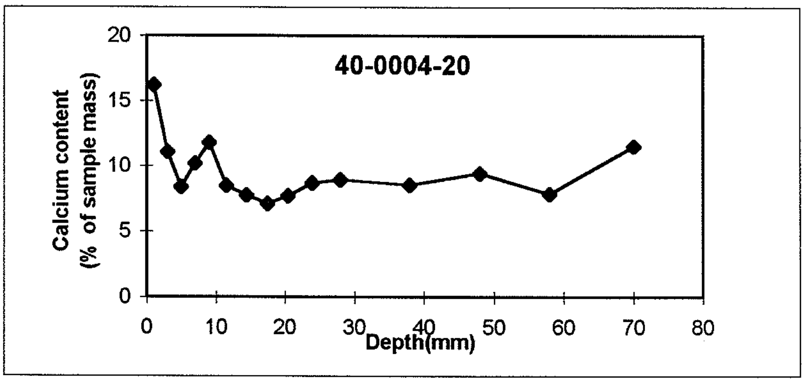


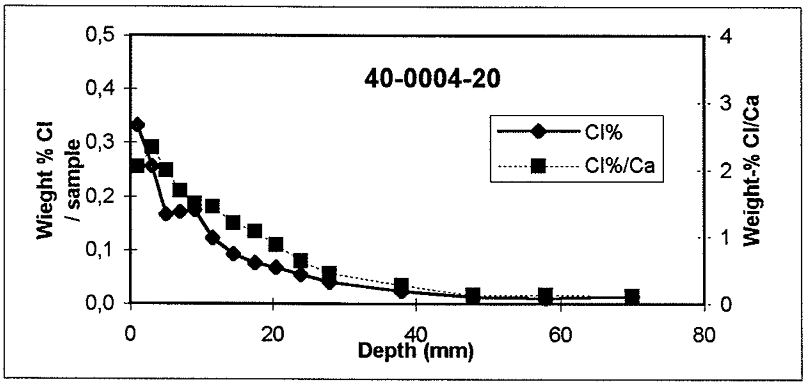

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 40-0004
Core "33"

Test conducted by: NY Date 09-07-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,608 | 4,786 | 22,82 | 0,279 | 15,043 | 1,855 |
| | 3 | 0,92 | 6,329 | 27,284 | 0,244 | 11,886 | 2,052 |
| | 5 | 0,92 | 5,411 | 23,247 | 0,208 | 10,128 | 2,059 |
| | 7 | 0,908 | 4,133 | 19,606 | 0,161 | 8,654 | 1,865 |
| | 9 | 0,91 | 2,925 | 16,878 | 0,114 | 7,434 | 1,533 |
| | 11,5 | 0,946 | 2,526 | 18,607 | 0,095 | 7,883 | 1,201 |
| | 14,5 | 0,942 | 2,536 | 21 | 0,095 | 8,935 | 1,068 |
| | 17,5 | 0,906 | 2,19 | 20,323 | 0,086 | 8,991 | 0,953 |
| | 20,5 | 0,948 | 1,763 | 18,6 | 0,066 | 7,864 | 0,838 |
| | 24 | 0,921 | 1,552 | 21,362 | 0,060 | 9,296 | 0,643 |
| | 28 | 0,978 | 1,343 | 23,813 | 0,049 | 9,759 | 0,499 |
| | 38 | 0,908 | 0,843 | 17,8 | 0,033 | 7,857 | 0,419 |
| | 48 | 0,915 | 0,648 | 20,982 | 0,025 | 9,191 | 0,273 |
| | 58 | 0,942 | 0,469 | 24,154 | 0,018 | 10,277 | 0,172 |

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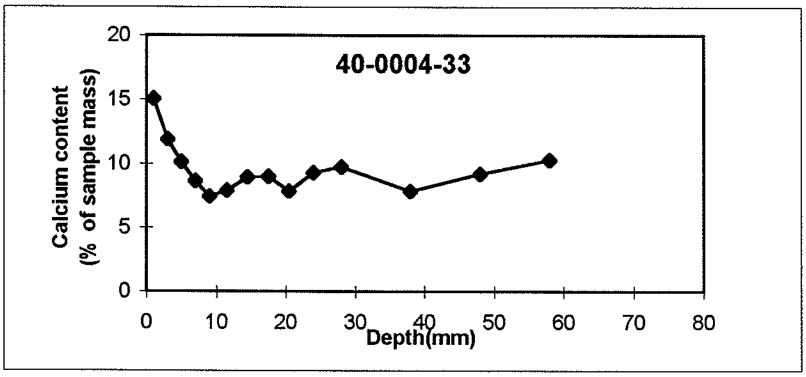


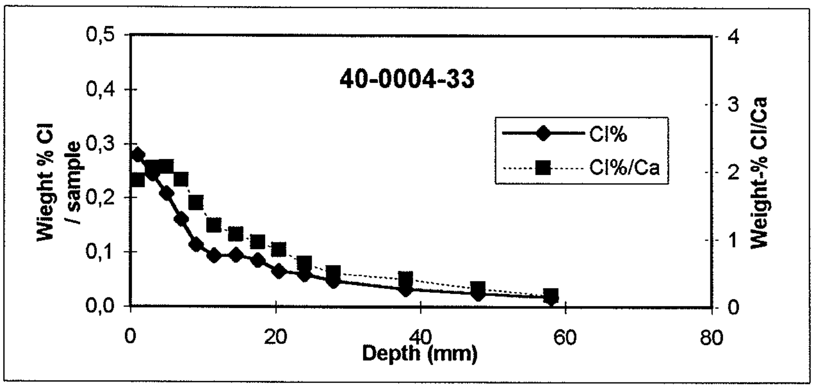

## DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS
Chalmers University of Technology

Bridge 14-0036
Core S

Test conducted by: NY Date 17-07-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,983 | 13,959 | 34,503 | 0,503 | 14,068 | 3,578376 |
| | 3 | 0,939 | 8,406 | 22,869 | 0,317 | 9,761 | 3,251103 |
| | 5 | 0,916 | 5,554 | 18,757 | 0,215 | 8,207 | 2,618973 |
| | 7 | 0,923 | 4,014 | 18,576 | 0,154 | 8,066 | 1,911233 |
| | 9 | 0,993 | 3,412 | 19,194 | 0,122 | 7,747 | 1,572288 |
| | 11,5 | 0,951 | 2,705 | 18,16 | 0,101 | 7,654 | 1,317468 |
| | 14,5 | 0,957 | 2,638 | 20,123 | 0,098 | 8,428 | 1,1595 |
| | 17,5 | 0,941 | 2,621 | 23,274 | 0,099 | 9,913 | 0,996058 |
| | 20,5 | 0,976 | 1,972 | 23,556 | 0,072 | 9,673 | 0,740447 |
| | 24 | 0,979 | 1,176 | 21,745 | 0,043 | 8,902 | 0,47834 |
| | 28 | 0,98 | 0,65 | 22,807 | 0,024 | 9,328 | 0,252077 |
| | 38 | 0,908 | 0,306 | 20,097 | 0,012 | 8,871 | 0,134672 |
| | 48 | 0,959 | 0,248 | 18,4 | 0,009 | 7,690 | 0,119213 |
| | 58 | 0,987 | 0,241 | 20,58 | 0,009 | 8,357 | 0,103576 |

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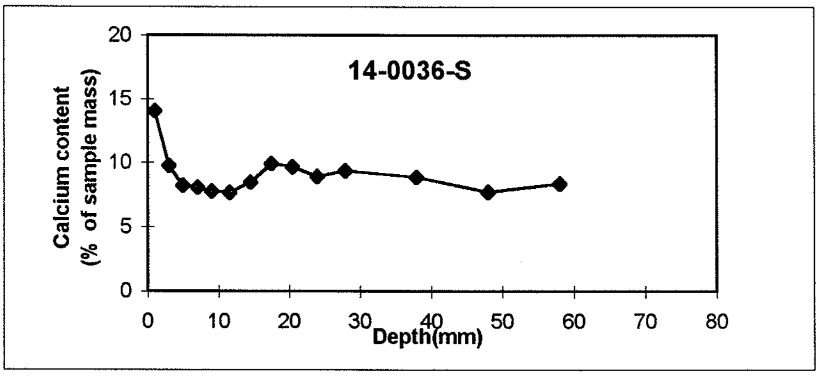


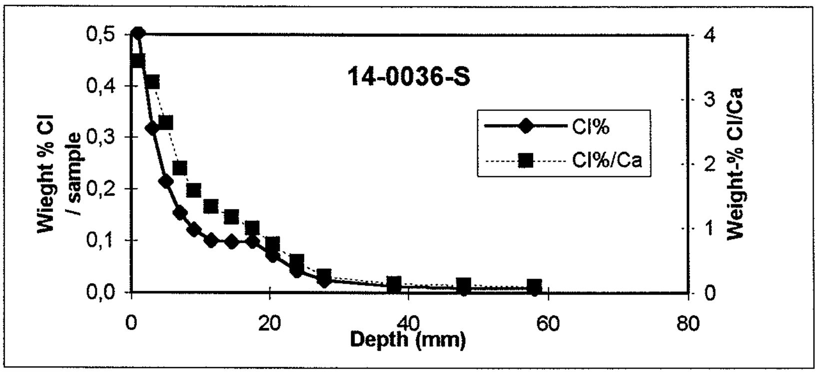

# DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS

Chalmers University of Technology

Bridge 14-0036
Core N1

Test conducted by: NY Date 15-07-96

**Method:Potentiometric titration**

(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,911 | 8,5 | 30,432 | 0,331 | 13,389 | 2,470 |
| | 3 | 0,924 | 6,606 | 28,111 | 0,253 | 12,194 | 2,079 |
| | 5 | 0,921 | 3,84 | 23,333 | 0,148 | 10,154 | 1,455624 |
| | 7 | 0,926 | 1,87 | 19,511 | 0,072 | 8,445 | 0,847716 |
| | 9 | 0,991 | 0,977 | 19,315 | 0,035 | 7,812 | 0,447392 |
| | 11,5 | 0,998 | 0,491 | 20,043 | 0,017 | 8,049 | 0,216674 |
| | 14,5 | 0,923 | 0,278 | 19,05 | 0,011 | 8,272 | 0,129074 |
| | 17,5 | 0,959 | 0,221 | 20,923 | 0,008 | 8,744 | 0,093424 |
| | 20,5 | 0,93 | 0,183 | 21,689 | 0,007 | 9,347 | 0,074628 |
| | 24 | 0,985 | 0,153 | 22,748 | 0,006 | 9,256 | 0,059489 |
| | 28 | 0,903 | 0,099 | na | 0,004 | *9,000* | 0,043184 |
| | 38 | 0,92 | 0 | na | 0,000 | *9,000* | 0 |
| | 48 | 0,944 | 0,125 | na | 0,005 | *9,000* | 0,052157 |
| | 62 | 0,948 | 0,143 | na | 0,005 | *9,000* | 0,059416 |

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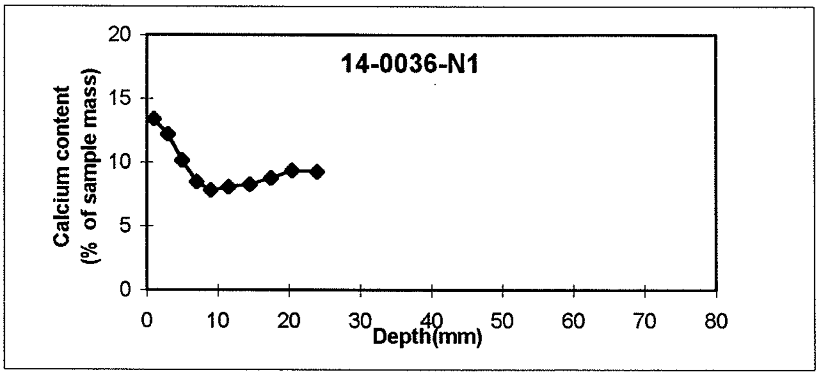


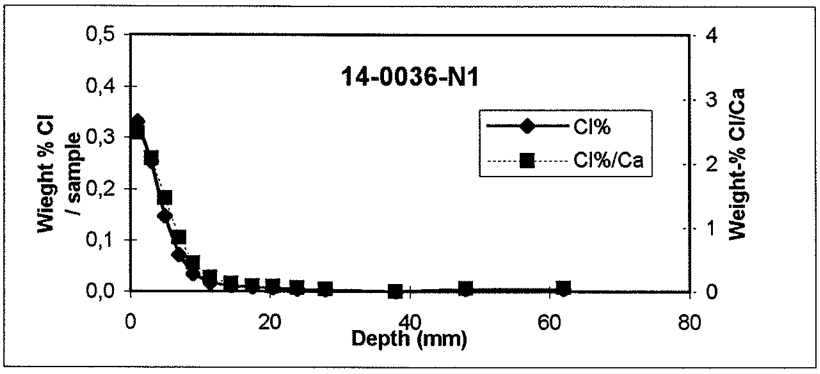

**DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS**
Chalmers University of Technology

bridge 14-0036
Core 3N

Test conducted by: NY Date 10-07-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,915 | 11,427 | 34,215 | 0,443 | 14,987 | 2,954 |
| | 3 | 0,94 | 9,117 | 27,273 | 0,344 | 11,629 | 2,957 |
| | 5 | 0,929 | 5,706 | 21,961 | 0,218 | 9,475 | 2,298096 |
| | 7 | 0,91 | 4,194 | 17,214 | 0,163 | 7,582 | 2,15494 |
| | 9 | 0,918 | 3,897 | 18,395 | 0,150 | 8,031 | 1,873782 |
| | 11,5 | 0,922 | 3,618 | 18,776 | 0,139 | 8,162 | 1,704331 |
| | 14,5 | 0,925 | 2,79 | 17,613 | 0,107 | 7,632 | 1,401069 |
| | 17,5 | 0,907 | 2,582 | 21,307 | 0,101 | 9,415 | 1,071821 |
| | 20,5 | 0,951 | 2,127 | 22,488 | 0,079 | 9,478 | 0,836576 |
| | 24 | 0,938 | 1,337 | 20,117 | 0,051 | 8,596 | 0,587837 |
| | 28 | 0,988 | 0,9 | 21,12 | 0,032 | 8,568 | 0,37691 |
| | 38 | 0,934 | 0,244 | 16,58 | 0,009 | 7,115 | 0,130165 |
| | 48 | 0,938 | 0,151 | 17,509 | 0,006 | 7,481 | 0,076279 |
| | 66 | 0,982 | 0,134 | 19,582 | 0,005 | 7,992 | 0,060525 |

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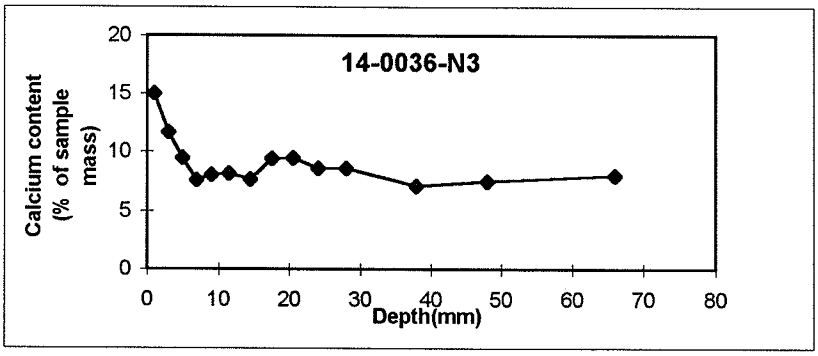


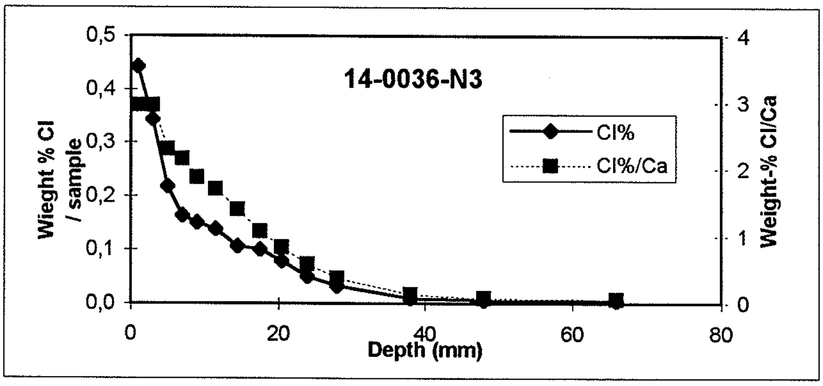

**DETERMINATION OF ACID SOLUBLE CHLORIDE AND CALCIUM CONTENTS**
Chalmers University of Technology

Bridge 14-0036
core 4N

Test conducted by: NY Date 16-07-96
**Method:Potentiometric titration**
(0,0100 N silver nitrate for chloride and 0,100N EDTA for calcium)

**Raw data and calculations**

| profile | Depth(mm) | Weight(g) | Cl (ml) | Ca (ml) | Cl% | Ca% | Cl%/Ca |
|---|---|---|---|---|---|---|---|
| | 1 | 0,935 | 6,989 | 30,32 | 0,265 | 12,997 | 2,039 |
| | 3 | 0,907 | 5,378 | 26,689 | 0,210 | 11,794 | 1,782 |
| | 5 | 0,941 | 3,414 | 25,49 | 0,129 | 10,857 | 1,184629 |
| | 7 | 0,942 | 2,318 | 24,04 | 0,087 | 10,228 | 0,85284 |
| | 9 | 0,937 | 1,741 | 22,94 | 0,066 | 9,813 | 0,671265 |
| | 11,5 | 0,91 | 1,406 | 22,408 | 0,055 | 9,869 | 0,554972 |
| | 14,5 | 0,942 | 0,964 | 23,962 | 0,036 | 10,195 | 0,35583 |
| | 17,5 | 0,952 | 0,518 | 22,096 | 0,019 | 9,303 | 0,20735 |
| | 20,5 | 0,925 | 0,359 | 24,313 | 0,014 | 10,535 | 0,1306 |
| | 24 | 0,951 | 0,291 | 25,696 | 0,011 | 10,830 | 0,100165 |

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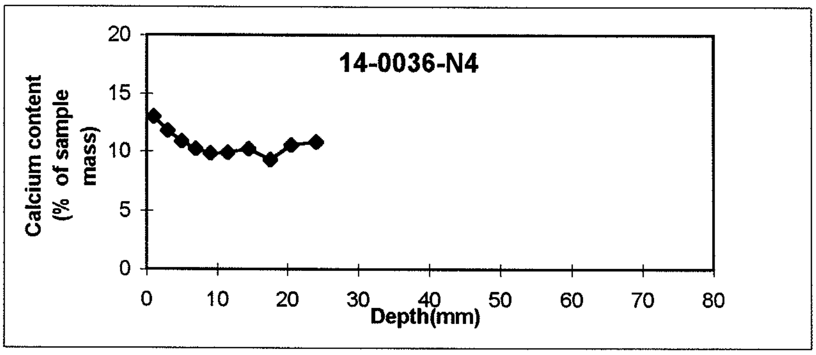
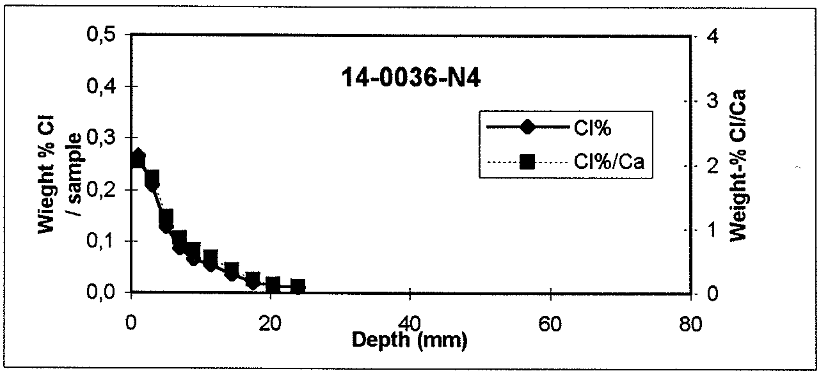


# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendix 4

Report No. 82
1996

## DEGREE OF CAPILLARY SATURATION $S_{cap}$

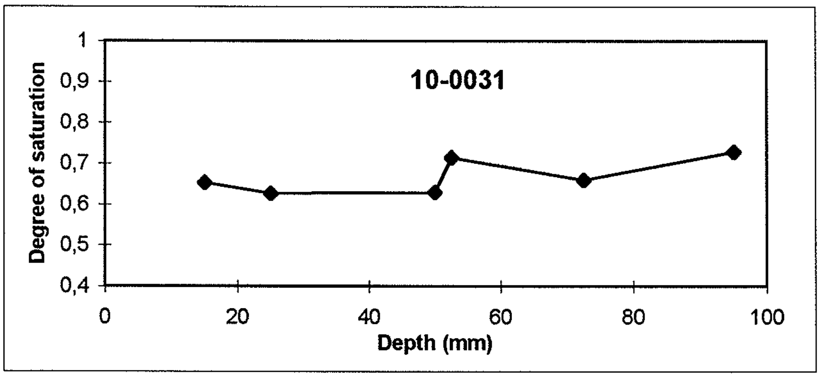
Chalmers University of Technology

Bridge 10-0031

Test conducted by: AA/MT Date 11-06-96 to 19-06-96

### Raw data and calculations

| | cm | cm | mm | gram | | | |
|---|---|---|---|---|---|---|---|
| Sample | depht from | to | mean | start | sat. | 105°C | $S_{cap}$ |
| k | 0 | 30 | 15 | 59,664 | 60,514 | 58,064 | 0,653061 |
| l | 15 | 35 | 25 | 17,444 | 17,915 | 16,655 | 0,62619 |
| d | 09-feb | 60 | 50 | 26,563 | 26,984 | 25,846 | 0,630053 |
| e | 35 | 70 | 52,5 | 66,316 | 67,49 | 63,392 | 0,713519 |
| c | 65 | 80 | 72,5 | 38,379 | 38,916 | 37,339 | 0,65948 |
| b | 85 | 105 | 95 | 78,951 | 80,01 | 76,123 | 0,727553 |



## DEGREE OF CAPILLARY SATURATION $S_{cap}$

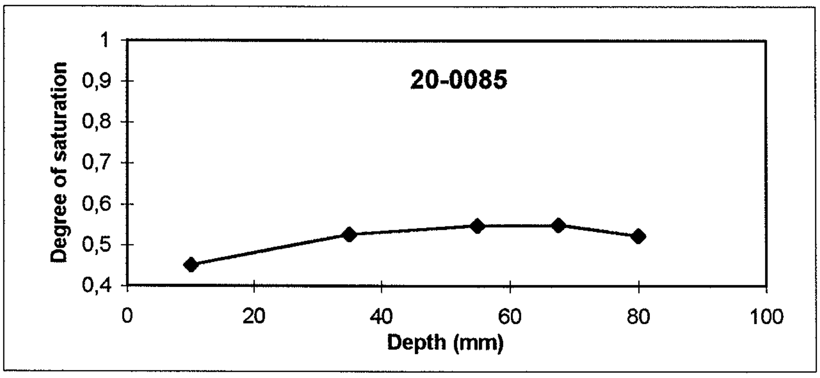
Chalmers University of Technology

Bridge 20-0085

Test conducted by: AA/MT Date 11-06-96 to 19-06-96

**Raw data and calculations**

| | cm | | | gram | | | |
|---|---|---|---|---|---|---|---|
| Sample | depht from | to | mean | start | sat. | 105°C | $S_{cap}$ |
| h | 0 | 20 | 10 | 31,906 | 32,935 | 31,057 | 0,452077 |
| d | 30 | 40 | 35 | 31,333 | 32,521 | 30,011 | 0,526693 |
| c | 40 | 70 | 55 | 34,491 | 35,496 | 33,269 | 0,54872 |
| b | 60 | 75 | 67,5 | 23,441 | 24,161 | 22,56 | 0,550281 |
| a | 75 | 85 | 80 | 19,531 | 20,144 | 18,858 | 0,523328 |



# DEGREE OF CAPILLARY SATURATION $S_{cap}$

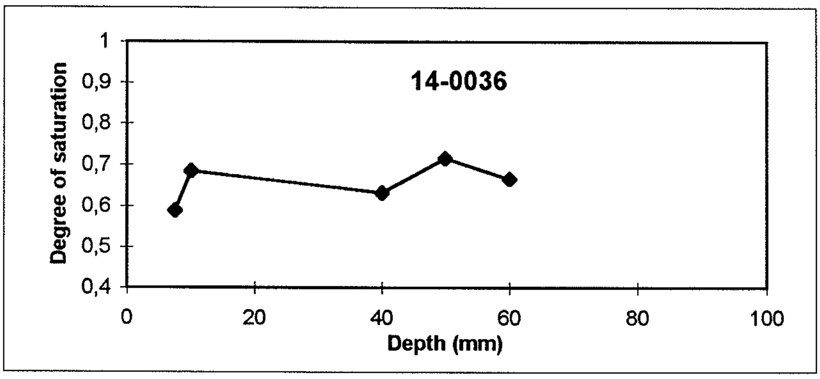
Chalmers University of Technology

Bridge 14-0036

Test conducted by: AA/MT Date 25-06-96 to 09-07-96

**Raw data and calculations**

| | cm | | | gram | | | |
|---|---|---|---|---|---|---|---|
| Sample | depht from | to | mean | start | sat. | 105°C | $S_{cap}$ |
| | 0 | 15 | 7,5 | 12,539 | 12,838 | 12,111 | 0,588721 |
| | 0 | 20 | 10 | 61,782 | 62,506 | 60,201 | 0,6859 |
| | 40 | 40 | 40 | 19,329 | 19,76 | 18,587 | 0,632566 |
| | 50 | 50 | 50 | 44,914 | 45,649 | 43,055 | 0,716654 |
| | 60 | 60 | 60 | 26,998 | 27,307 | 26,379 | 0,667026 |



# HETEK

Investigation of chloride penetration into bridge columns exposed to de-icing salt

# Appendix 5

Report No. 82
1996

**Relative humidity**

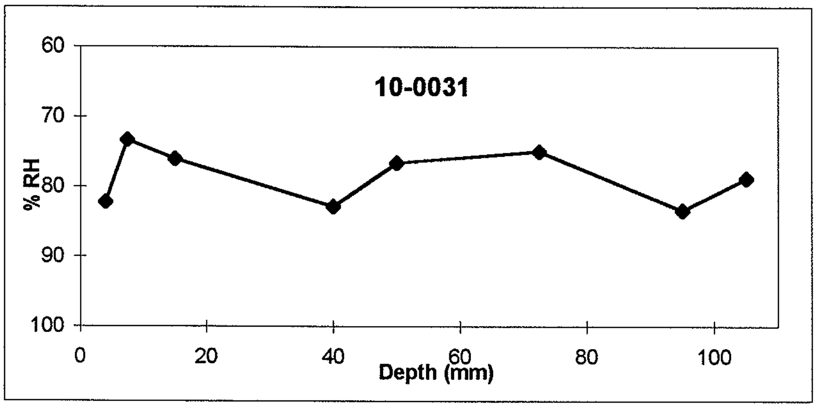
Chalmers University of Technology

Bridge 10-0031

Test conducted by: JA/AA Date 09-07-96

**Raw data and calculations**

| number | (mm) depth | (cm) rem. | %RH corr. |
|---|---|---|---|
| I4-G | 4 | 0,0-0,8 | 82,2 |
| I4-J | 7,5 | 0,0-1,5 | 73,4 |
| I4-H | 15 | 1,0-2,0 | 76,1 |
| I4-F | 40 | 4 | 82,8 |
| I4-D | 50 | 4,0-6,0 | 76,7 |
| I4-C | 72,5 | 6,5-8,0 | 75,1 |
| I4-B | 95 | 8,5-10,5 | 83,4 |
| I4-A | 105 | 10,0-11,0 | 78,9 |



## Relative humidity

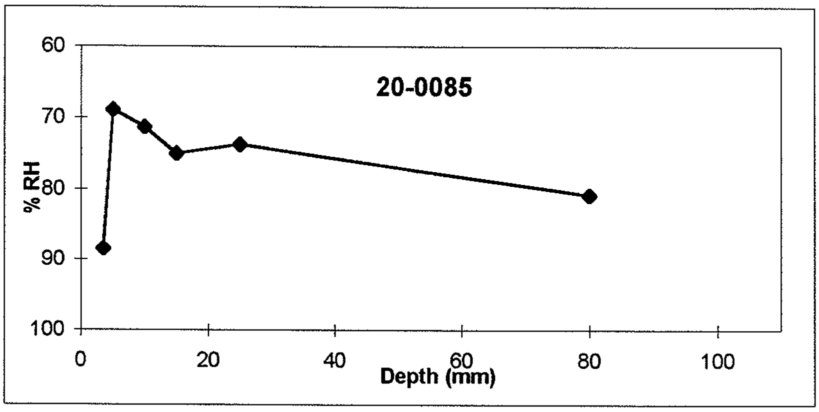
Chalmers University of Technology

Bridge 20-0085

Test conducted by: JA/AA Date 09-07-96

### Raw data and calculations

| number | depth (mm) | rem. | %RH corr. |
|---|---|---|---|
| S2-2G | 3,5 | 0,0-0,7 | 88,5 |
| S2-2I | 5 | 0,0-1,0 | 68,9 |
| S2-2J | 10 | 0,5-1,5 | 71,3 |
| S2-2F | 15 | 1,0-2,0 | 75,0 |
| S2-2E | 25 | 2,0-3,0 | 73,8 |
| S2-2A | 80 | 7,5-8,5 | 80,9 |



**Relative humidity**

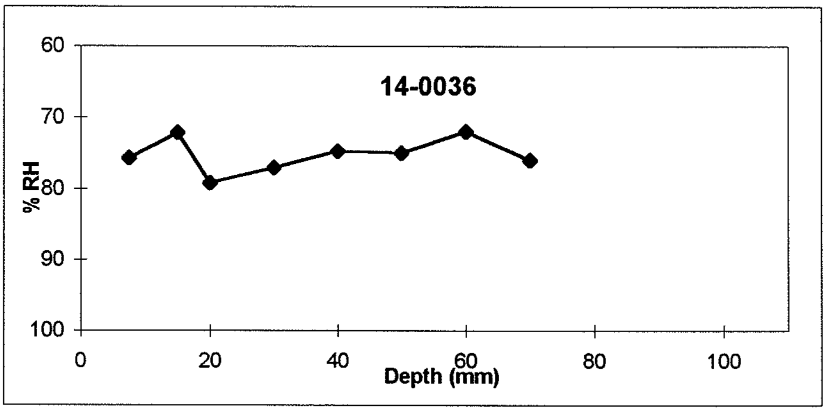
Chalmers University of Technology

Bridge 14-0036

Test conducted by: JA/AA Date 09-07-96

**Raw data and calculations**

| number | (mm) depth | rem. | %RH corr. |
|---|---|---|---|
| 0,0-1,5 | 7,5 | | 75,7 |
| 1,0-2,0 | 15 | | 72,1 |
| 2 | 20 | | 79,2 |
| 3 | 30 | | 77,1 |
| 4 | 40 | | 74,8 |
| 5 | 50 | | 75,0 |
| 6 | 60 | | 71,9 |
| 7 | 70 | | 76,0 |



**Relative humidity**

Chalmers University of Technology

Bridge 30-0016

Test conducted by: JA/AA Date 09-07-96

**Raw data and calculations**

| number | depth | (cm) rem. | %RH corr. |
|---|---|---|---|
| su-0.5 | 2,5 | 0,0-0,5 | 70,8 |
| 0-1 | 5 | 0,0-1,0 | 70,7 |
| 4-5 | 45 | 4,0-5,0 | 72,6 |
| 4-5 | 45 | 4,0-5,0 | 75,5 |
| 5-7 | 60 | 5,0-7,0 | 78,4 |