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Chloride profiling in marine concrete

Methods and tools for sampling

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PREFACE

This licentiate thesis has been made at the division of Building Materials, Lund Institute of Technology, in collaboration with Skanska Sverige AB, Skanska Teknik. This project is called *Methods and Tools for Determining the Present State of Concrete Harbour Structures* and is a part of the research area *Durability and Service Life* at the division of Building Materials. The development fund of the Swedish Building Industry, SBUF, the Road Bridge Tunnel Consortium, VBT, and my employer Skanska Sverige AB are gratefully acknowledged for funding this project.

I would like to thank Professor Björn Täljsten, now at Denmark's University of Technology, for opening the contact with Professor Lars-Olof Nilsson who has been my supervisor during my studies and who has been a great support during these years. I would also like to thank my colleagues at the division and the technical staff, especially Stefan Backe and Bengt Nilsson, who have helped me with both field investigations and work in the laboratory. My colleagues at Skanska Teknik in Malmö are also acknowledged for helping me finishing this work.

Finally I would like to express my love to my family, Charlotta and Ellinor ☺, who has been most loving, understanding and helpful in all ways throughout the project.

ABSTRACT

This project focuses on how to determine the chloride content in concrete structures exposed to marine environment in an accurate way. When analyzing dust from dry drilling in concrete, it is very often a fact that the chloride profiles show extensive variations even if the sampling has been performed within a very concentrated area with the sampling points close to each other. Several authors have observed this phenomenon in earlier research and some of these are referred to in this thesis. The aim of this project has been to find reasons to these extensive variations and to find inspection methods that decrease the variations. Both laboratory studies and field studies have been performed within the line of this work. The laboratory study has consisted of concrete sampling by dry drilling and by profile grinding 100 mm cores on a concrete slab that had been submerged in saline water in the laboratory. The chloride profiles from the cores have been used as a reference to all other samples collected on the slab.

The study shows that profile grinding of cores is the most accurate method to perform sampling on concrete with the purpose of analyzing the chloride content, and that when using small bore diameters the sampling should be performed as mixed samples from several bore holes. In all cases, samples should not only be analyzed for chloride but also for binder content. The results from the dry drilling in laboratory shows that the binder content becomes over estimated in the dust samples compared to the analyzed cores on the same concrete slab. This means that the analyzed dust samples seams to contain a higher chloride content than the cores analyzed by profile grinding. This phenomenon became obvious when simulating chloride profiles using data from EPMA. Most probably the drilling follows an easy path between the large aggregate particles.

One field study has been performed in the port of Trelleborg in southern Sweden and another one in the port of Malmö, also in southern Sweden within some 50 km distance but facing the open sea in different directions. The field study in Trelleborg has consisted of an inventory of existing concrete structures in the harbour and climate studies of the wind and temperature in the area followed by a more detailed inspection including sampling on selected parts of a quay. This study shows that the exposure to open sea clearly influences the chloride content in concrete structures exposed to marine environment more than the main wind direction. The field study in the port of Malmö also confirms this finding. The conclusions of this work is that when sampling concrete on structures in marine environment it is important not only to study the surrounding environmental loads such as the dominating wind direction, but also the exposure of the structure to the open sea which has shown to be of great importance in the field studies.

If it is possible, the sampling should be performed by profile grinding cores. The studies in the laboratory have shown that sampling cores gives small variations in the analyzed chloride content. If dry drilling is used, the diameter of the drill bit should not be smaller than 20 mm. In all cases the analyzes should include the binder content, since it is the binder who contains chlorides. Presenting the chloride content in % by binder content has been shown to give the smallest variations in this study.

SAMMANFATTNING

Detta projekt fokuserar på hur man på bästa sätt bestämmer kloridprofiler i marina betongkonstruktioner. När borrmjöl från provtagning på marina betongkonstruktioner analyseras, är det inte ovanligt att de olika kloridprofilerna varierar oerhört mycket även om provtagningspunkterna ligger mycket nära varandra inom ett område med till synes homogen betong. Syftet med projektet har varit att hitta förklaringar till de extrema variationer i kloridinnehåll som beskrivits ovan, samt att hitta undersökningsmetoder som minskar dessa variationer.

Laboratoriestudierna har bestått i provtagningar på en betongplatta som har stått helt nedsänkt i saltlösning en längre tid i laboratorium. Provtagningarna på denna platta har dels utförts genom uttagning av borrmjöl samt genom kärnborrning med 100 mm kärnor. Borrmjölet har tagits ut med borr av olika storlek för att kunna se om borrdiametern inverkade på resultatet vad gäller spridningen i kloridinnehåll. De kloridprofiler som erhållits från kärnorna har använts som referens för alla borrmjölsprover. Studien visar att svarvning av kärnor är det absolut bästa sättet att ta prover på, med hänsyn till spridning i kloridinnehåll. Studien visar också att om mindre borrdiametrar används vid uppsamling av borrmjöl, så skall detta borrmjöl tas som blandprov från ett flertal intilliggande borrhål. Oavsett hur proverna tas så skall analysen av dessa också inkludera cementinnehållet i proverna. Att redovisa resultaten som klorid i förhållande till cementinnehåll ger mindre variationer mellan proverna jämfört med om kloridinnehållet bara bestäms som andel av själva provet.

Under projektets gång har två fältstudier utförts, en i Trelleborgs hamn och en i Malmö oljehamn, båda i södra delen av Sverige. Fältstudien i Trelleborgs hamn har omfattat en inventering av alla kajkonstruktionerna i hamnen, en klimatstudie över området med avseende på vindhastighet och vindriktning samt vattenstånd och temperatur följt av en mer detaljerad undersökning med provborrningar i en utvald kaj. Studien visar att exponeringen av betongkonstruktionerna ut mot öppet hav klart påverkar kloridupptagningen i konstruktionerna mer än den förhärskande vindriktningen. Även fältstudien i Malmö oljehamn visar samma resultat. Slutsatsen av dessa studier är att betongprover tas från konstruktioner i marin miljö så är det viktigt att inte bara studera den omgivande miljön såsom den förhärskande vindriktningen utan att även ta hänsyn till hur konstruktionen eller konstruktionsdelen är exponerad för öppet hav.

Studierna i laboratoriet visar också att om möjligheten finns så skall provtagningen genomföras genom att ta borrkärnor, eftersom resultaten av kloridanalyserna uppvisar minst spridning med denna metod. Om det inte är möjligt att ta ut kärnor, så är minsta rekommendabla borrdiameter 20 mm. Laboratoriestudierna visar att när så små borrdiametrar som 8 mm används, så måste proverna tas ut som samlingsprover från flera närliggande borrhål för att minimera spridningen i kloridinnehåll. Oavsett hur proverna tas ut så skall även cementinnehållet i provet analyseras samtidigt. Eftersom svensk ballast normalt utgörs av kristallint urberg och således inte binder klorider till sig, så kan spridningen i kloridinnehåll mellan olika provtagningspunkter minimeras genom att redovisa kloridinnehållet i vikts-% av cementinnehållet.

THE PAPERS INCLUDED

Paper I
Initial Survey of Concrete Structures in Swedish Harbours - A Case Study in the Port of Trelleborg. H. Wall and L.-O. Nilsson, *Proceedings of the International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR) 2005, Cape Town, South Africa.*

Paper II
Chloride Profiling in Concrete Harbour Structures - A Study of Extensive Variations. H. Wall and L.-O. Nilsson, *Proceedings of the 2nd International Symposium on Advances in Concrete through Science and Engineering 2006, Quebec City, Canada.*

Paper III
A Study on Sampling Methods for Chloride Profiles - Simulations Using Data from EPMA. H. Wall and L.-O. Nilsson, *Submitted to Materials & Structures in April 2007.*

Contents

INTRODUCTION

The total length of the quays in Sweden today is about 200 km and approximately 100 km of these quays are handled by the Swedish communities and technical services [1]. In Sweden the dominating materials used in quay structures are steel and concrete. Older quay structures could also be built of timber and natural stone. The majority of the structures found in Swedish harbours contains or is built completely of reinforced concrete which are affected by the chlorides from sea water. Most of the harbours in Sweden have reached an age that exceeds the original design life time which in theory means that the existing concrete structures should be replaced by new ones. Despite this, the structures are in many places still working as they should but the problem is that no one knows for how long. Therefore we need accurate and precise methods to perform inspections of these structures in order to determine their remaining service life and to be able to plan the maintenance efforts needed to keep them up to date.

This work is a part of a research project on *Methods and tools for determining the present state of concrete harbour structures*, and the aim of this work has been to improve existing inspection and sampling methods within this area. It is a well known fact that the results from chloride sampling, which is the most important tool in determining the status of concrete exposed to marine environment, show a large scatter. This is also true even if the sampling is performed within a very small area and in apparently homogeneous concrete without any visible defects or climatic variations.

The most common deterioration mechanisms in concrete exposed to the marine environment are undoubtedly reinforcement corrosion and damages caused by frost. When searching the literature for deterioration of concrete in the marine environment, the reinforcement corrosion seems to be the main deterioration factor, which is also stated by de Rooij and Polder [2]. A lot of research has been done in the field of reinforcement corrosion. In [3] Tuutti presented a model for reinforcement corrosion in concrete. The model is built up on two stages, one initiation stage followed by a propagation stage. During the initiation stage the concrete carbonates gradually and chlorides penetrate the cover, finally depassivating the reinforcing steel. In the propagation stage the reinforcement corrosion is initiated and continues until an unacceptable damage level of the structure is reached. The corrosion rate in the propagation stage is dependent on the available amount of oxygen at the cathode and on the electrical resistance of the concrete.

Tuutti [4] states that it is only the free chlorides in the pore system of the concrete that contribute to the initiation of reinforcement corrosion. Local attacks of corrosion is assumed to be able to appear if the factor $[Cl^-]/[OH^-]$ exceeds 0.6.

In many cases inspections of reinforced concrete structures are performed in an often too uncertain way, mainly as visual inspections. When performing visual inspections, traces of corroding reinforcement, cracks and damages on the concrete surfaces are detected. The problem is that when these signs are visible to the naked eye, it is often already too late. The reliability of the structure is already too low by then. The focus when performing inspections for preventive maintenance of reinforced concrete structures should be on concrete without visible signs of deterioration.

The service life of a reinforced concrete structure could be defined in several ways depending on what changes of the function of the structure that is accepted over the years. Schematically the changes of the work capacity of such a structure proceeds as shown in figure 1.

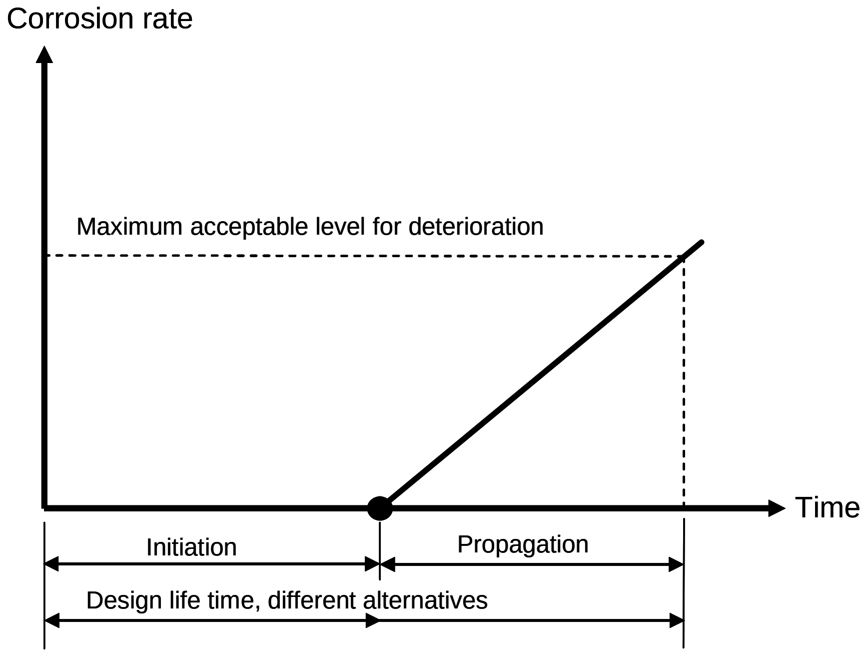

Figure 1: Initiation and propagation of reinforcement corrosion, after [4]

During the initiation phase the performance of the structure is not considerably changed. In fact, the strength of the concrete itself can actually increase due to the hardening. The surrounding climate makes it possible for carbon dioxide and chlorides from sea water or de-icing salts to penetrate into the concrete surface. The initiation phase is over when the carbonation or a critical chloride content has reached through the concrete cover resulting in initiated corrosion. After this stage the propagation phase is starting. At the end of the initiation phase and the start of the propagation phase, the cross section of the reinforcement bars starts to decrease and the developed corrosion products creates a pressure which after a certain time could result in cracking and spalling the concrete cover. This means that when the propagation stage is reached, the load-carrying capacity of the structure decreases with time.

The service life of important structures is often defined by the initiation phase. When the initiation phase has reached its end, the remaining service life of the structure is zero. The methods for maintenance and upgrading the structures during the initiation phase are much cheaper and much more reliable than if such efforts are done during the propagation phase. For this reason the determination of the state of the structure should be done during the initiation phase before any signs of corrosion or visible changes could be observed during a visible inspection. With respect to reinforcement corrosion the purpose of the determination of the status of the structure is mainly to verify how far the ingress processes have gone and how much of the initiation phase that is remaining.

The determination of the present state of a given concrete structure could be divided into six steps:

1) Description/documentation of the influence of the surrounding climate on the structure
2) Documentation of the response from the structure by the surrounding climate
3) Determination of the properties of the materials in the structure
4) Analysis of existing changes of the structure till today
5) Prognosis on future changes without any maintenance actions
6) Prognosis on future changes with maintenance actions

The main parts of the project have consisted of field studies in two harbours in southern Sweden and a study in the laboratory at the Lund Institute of Technology on concrete specimens submerged in a saline solution. The field work has been concentrated on concrete super structures in and above the splash zone. The sampling in the field studies have been performed by dry drilling, and the sampling in the laboratory has consisted in both sampling by dry drilling and profile grinding.

This project was started by a state-of-the-art literature study on the subject *inspection of concrete in marine environment* and the results from this work are stated in the following chapter. Simultaneously a study of wind and water data for southern Sweden was going on with the purpose of detecting possible patterns between the environmental load and chloride ingress when performing the case study in the Port of Trelleborg, which is described in section 2.1.

1. PREVIOUS RESEARCH IN INVESTIGATING MARINE CONCRETE

Most of the literature published within the area of marine concrete deal with the influence of marine environment on different concrete compositions. A few references, however, includes case studies and inspection methodology. These are summarized here, limited to literature that best fits under the criteria *Inspection and determination of the state of concrete structures in marine environment.*

Over the years several more or less advanced calculation models for predicting chloride ingress into concrete have been presented. Most of these models uses Fick´s second law of diffusion and are quite alike in many aspects. Input for these calculation models is among other things values on chloride content measured in existing concrete structures. The sampling methods used for collecting this data and the selection of sampling points are of great importance on how the result of the calculations becomes.

There is no lack of methods for predicting the future chloride ingress into concrete, c.f. [5]. However, for existing structures we need to decrease the uncertainties by more accurate inspection and sampling methods.

1.1. Case Studies on Marine Concrete Structures

There are numerous studies on specimens exposed to marine environment. Common for these studies is that most of them are on small specimens casted with different kind of concrete mixes submerged in harbours in order to evaluate the influence of chloride exposure. The literature does not contain any significant number of case studies on real structures and the studies that are found are often quite general, missing detailed information on how the sampling was performed. Most results published on investing concrete exposed to salt and saline solutions, are from road bridges and tunnels. Unfortunately many results from investigations of marine concrete structures are unpublished because the investigations have been performed by private companies not willing to share these results with competitors.

Durability of Reinforced Concrete Wharves in Norwegian Harbours

Gjørv [6] performed an investigation of most of the existing Norwegian harbours with the purpose of determining the present state of the concrete structures in this kind of marine environment. In total 719 different concrete structures where investigated. A detailed inspection was performed on 170 of the structures.

The inspections showed that the most dominating deterioration mechanisms were reinforcement corrosion. The parts of the concrete structures that were situated above the highest high water table showed mainly signs of ongoing reinforcement corrosion, while frost damages were observed as the dominating deterioration factor on the structures situated in the splash zone. Those parts of the structures which were constantly submerged were almost intact and no larger signs of deterioration could be observed with the naked eye at the time of inspection. It was also noted that the influence of the wind on the structures were of great importance with respect to service life.

Durability of a 60-year-old reinforced concrete pier in Oslo Harbour

During 1986 a 60 year old reinforced concrete pier in Oslo Harbour was demolished. Gjørv and Kashino [7] performed field studies at the time of the demolition with the purpose of investigating the state of the concrete structures.

Visual inspections on site were performed together with sampling for laboratory analysis. About 25 % of the reinforcing steel showed signs of ongoing corrosion while the remaining 75 % where found to be in excellent condition. The most extensive corrosion damages were found in the concrete slabs on the quay deck and on the supporting beams.

Durability of Concrete Structures Along the North Sea Coast of the Netherlands

Wiebenga [8] presented the results from investigations of 64 concrete structures of varying age along the North sea coast of the Netherlands. Most of the investigated concrete structures contained blast furnace slag. The conclusions were:

1) The carbonation depth was small even in the oldest structures
2) Reinforcement corrosion is mainly caused by chloride
3) Reinforcement corrosion was observed only in those structures which had been exposed for chlorides for a long time together with a thin concrete cover. No correlation between cement content and reinforcement corrosion could be detected.
4) The maximum depth of penetration of chlorides was caused by the exposure time and the porosity of the concrete.
5) The degree of weathering of the concrete surface did not correlate with its age or cement content.

Sixty-Year-Old Concrete in a Marine Environment

Ozaki and Sugata [9] presented the results from investigations of a 60 year old breakwater. The breakwater was built as an 11 m wide and 8 m high caisson made of reinforced concrete with an 1.7 m thick upper deck which also was made of reinforced concrete. At the side of the breakwater on the bottom of the sea foot protection blocks where situated to prevent erosion. The following parameters were measured:

- compressive strength of the concrete
- porosity of the concrete
- salt concentration
- carbonation depth
- corrosion level on the reinforcement

The results from the analyses showed that the compressive strength of the concrete has not decreased even after 60 years of exposure to sea water. The pore sizes were generally smaller than would be expected for ordinary concrete, but the total porosity was as expected. The carbonation depth was generally very small except in the foot protection blocks which was made of lower concrete quality than the caisson. The salt content near the concrete surface was high, varying between 0.3 and 0.6 % by weight of concrete. At a depth of some 80 mm, the salt content was found constant around 1 %. Tests showed that the corrosion of the bars was minimal, despite the high salt content in the concrete.

Case studies of concrete deterioration in a marine environment in Portugal

Costa and Appelton [10] performed case studies on three different types of reinforced concrete structures, all of them located in marine environment in Portugal. The case studies focused on reinforcement corrosion, which was the most common deterioration mechanism. The investigation included three dry docks of 30 years of age, four 30 years old quays or wharfs and one arch bridge 35 years old.

- **Dry docks** - At the time of the design of the docks, no service-life analysis was performed to control the expected service life of the structures. The poor concrete quality together with poor workmanship during the casting have resulted in an extremely fast deterioration of the reinforced concrete. The corrosion process started already 4 to 5 years after the docks were built. Macro-cell corrosion was detected on the dock walls that were exposed to direct sun light. The two main factors that accelerated the corrosion process were high temperature and the good access of oxygen due to the drying concrete.
- **Quays** - No durability criterion was considered during the design of the quays. Two grades of degradation were observed along the wharves. The upper parts of the wharves just above the splash zone showed large areas of spalling of the concrete cover caused by reinforcement corrosion, while the degradation within the splash zone seemed to be more moderate.
- **Bridge** - No larger maintenance efforts had been done on the bridges since it was built 35 years earlier. The damages that could be detected on the bridge were primarily spalling concrete cover on the deck beams over the arch. The authors mean that in this case the reason for the high degradation level is bad workmanship during casting. Poorly made construction joints were also a common observation on this structure. The investigation showed that the concrete cover was less than 20 mm along significant areas of the beams.

The conclusion was that the main reason for the extensive degradation of the investigated structures is chloride induced corrosion because of poor workmanship together with lack of knowledge of the deterioration mechanisms for the materials. This leads to insufficient planning and wrong estimation of environmental effects such as strong sun light together with high access to oxygen which accelerates the corrosion process.

Deterioration of Concrete of Coastal Structures In Japan

About 30 structures made of reinforced concrete along the Japanese coast have been inspected and are described by Seki [11]. Typical structures investigated were sea walls and wharfs which had been exposed to marine environment for a time period of 15 to 40 years.

The field investigations were performed both visually by inspecting the concrete surfaces, and with non destructive methods as Schmidt hammer and ultra sonic method as well as with core sampling. The cores were sampled from the upper part of the structures and were analyzed in the laboratory in order to determine the density of the concrete, water absorption, depth of carbonation, salt content, compressive strength and the mix proportions of the concrete. The depth of carbonation varied between 10 and 37 mm and no relationship between the age of the structures and the depth of carbonation was found.

The author concluded the following:

- Most deteriorated areas were located at the cold joints. No obvious relationship was found between the level of deterioration and age of the structures at the time for the investigations. This could mean that one of the most important factors when casting concrete in the marine environment is quality control with respect to the deterioration of the concrete.
- It is likely that the degree of deterioration is primarily a function of the water cement ratio provided that the structures are built with good construction practices with quality control.

Torshamnen, Oil Pier, Damaged Concrete Structures

The reason why the investigation of the oil pier in Torshamnen, Gothenburg, was performed was that signs of deterioration of the concrete had been spotted. The investigations have mainly consisted of measurements of chloride ingress into the different parts of the pier and the results are concluded in [12]. The author has performed service life predictions of the remaining service life of the pier based on the results from the chloride analyses. The predictions were performed both for the case when no maintenance procedures were used and for the repaired structures. The chloride profiles for the structure were determined with analyzes of dust sampled from dry drilling and from core grinding of 100 mm cores. The variations in chloride content were extensive especially in 10 sampling points on the upper quay deck. The 10 samples were collected along a line less than one meter on concrete that seemed homogeneous at visual inspection. About 25 mm below the concrete surface the chloride content varied between 0.4 and 1.9 % by weight of cement without any obvious explanation.

1.2. Methodology for performing inspections

Concrete in marine environment is exposed to an extreme climate. The structures in a harbour are exposed to chlorides and, in the northern countries, also to frost. These facts set strong demands on both the concrete itself and on the workmanship when casting the structures. In order to be able to detect possible damages on these structures in time, it also sets demands on accurate inspection methods for determining the present state of the structure. The literature contains several papers on case studies and sampling on concrete at site, with the purpose of using the data from chloride profiling in service life predictions. However, it is often a fact that the sampling itself is not described in detail due to the interest in the results only. The focus lies on the use of the chloride profiles and it seems sometimes that how the sampling is performed is not of interest. In the final report from REHABCON [13] an evaluation of alternative repair and upgrading options for concrete is presented together with a description of different sampling methods on concrete structures. However, the report contains no special recommendations for how to perform inspections on concrete structures exposed to marine environment.

Nilsson et al [14] described the different exposure zones in marine environment. The report also discusses the influence of wind action on structures within this area. For this reason the results from Grimsøystraumen Bridge in Norway was used where among other things the surface chloride content has been evaluated for the box girder of the bridge in several points. The influence on the surface chloride content of the dominant wind direction is therefore discussed in this section of the report.

In the following text in this chapter, the papers and reports that best fit into the subject of *Inspection of marine concrete* is presented.

Determination of the present state of harbour structures owned by the Swedish Communities

The Swedish municipalities have made a survey with the purpose of making an inventory of quays and wharves in Sweden [1]. In the published compilation the most common quay and wharf types in Swedish harbours are presented with respect to age and structural design type. Detailed inspections have been executed on structures in five of the harbours with an investigation method which has been developed in Stockholm. The method for determining the present state of the investigated structure is divided into four steps:

1) **Zero inspection** - a general description of the inspected quay containing data on the age of the structure and how it was designed. The Zero inspection also includes a visual inspection.
2) **Main inspection** - an inspection that is performed with the purpose of finding those type of damages on the quay structures that could affect the load bearing capacity of the structure within a 10 year period. In this step the quays are divided into groups called TK 0 to TK 3 depending on the state of the structure. TK 3 is the most serious state. Sampling from the concrete structures is performed with the purpose of determining the chloride content and the

carbonation depth. The compressive strength of the concrete, its frost resistance and composition is analyzed in laboratory.

3) **General inspection** - preferably performed once a year in order to follow up and register the deterioration process of the quay
4) **Special inspection** - done of those parts of the structure that has been classified to one of the higher groups TK 2 and TK 3. This inspection could be performed on selected parts only and does not necessarily include the whole quay.

Inspection, Maintenance and Repair of Maritime Structures Exposed to Damage and Material Degradation caused by a Salt Water Environment

The scientific organization PIANC-AIPCN has through a working group, WG 17, written a State-Of-The-Art report over inspection, maintenance and repair of marine structures [15]. The report includes structures of timber, natural stone walls, concrete and steel. A description of common deterioration factors is given for each type of material and quay, which is followed by recommendations for inspection methods and for maintenance and repair.

The report is summarised by giving references for inspection, maintenance and repair divided into material groups (steel, wood, concrete etc.).

Inspection of Concrete Offshore Structures

An inspection program suitable for oil rigs built of reinforced concrete was created by Browne et al [16]. The inspection program is divided into two parts:

1) Planning of frequent major general inspections.
2) Execution of the inspection by visual observations and testing of the concrete with non destructive methods.

Due to the size of the platform, probabilistic methods are used to choose suitable so called “critical points” for spot tests. Using a probabilistic method it is possible to consider the uncertainties of the environmental loads on the structure like wind direction and the influence of the wave action. In its simplified form, the execution of the inspection is described in a table: “Standard of inspection adopted for different areas of inspection”. The inspection is divided into three classes, where class 1 describes the most detailed inspection and class 3 is the most general of the inspections.

Diagnosis and repair of marine structures - Towards a unified approach

In this article Browne et al [17] discuss different approaches for determining the present state of a marine concrete structure. A financial approach is presented for determining the cost efficiency of possible actions to restore the structures. The testing methods are not presented in detail, but the authors recommend monitoring corrosion rate at site. The content in this article is quite general.

It is claimed that the low chloride content at the concrete surfaces when doing analyses in field, is not due to washing out chlorides or leaching. It is suggested that this phenomenon is due to carbonation at the surface. Concrete's capacity to bind chlorides is severely reduced by carbonation. Carbonation releases bound chlorides, allowing them to diffuse further into the cover zone.

Analysis of structural condition from durability results

In 1983 a conference on Corrosion of reinforcement in concrete construction was held in London. In the conference proceedings [18] Browne et. al. presented how to perform a survey of an existing concrete structure and how to evaluate the results and how to choose repair method. The authors state that the existing methods for undertaking inspections of concrete structures are too limited, and are often relying on visual inspections only. Furthermore the authors also commented that the used techniques of repair in many cases are ineffective.

In short the survey presented in this paper could be divided into the following steps:

- *The structure's History and Environment* in which the original design data for the structure together with general climate information for the area where the structure is located is collected.
- *The Field Specification* consists of a planning document describing the survey objectives, methods and scope.
- *The Global Survey* provides information for the whole structure and normally consists of a visual inspection and photographic survey together with the usage of non-destructive-test measurements.
- *The Detailed Survey* contains both non-destructive-testing and concrete sampling for analysis in laboratory. The sampling is usually performed as dry drilling collecting dust or core sampling with 100 mm cores preferably.

Preliminary inspection of pier structures

Wesselink & Harley [19] presented a model for inspection of quays. The model has been developed at Exxon. The inspection consists of four parts:

1) General inspection
2) Detailed inspection
3) Damage analysis
4) Suggestions for repair actions

The contents of the paper focus mainly on the general inspection. The authors present a table containing common construction parts in quays and piers together with descriptions of where the most common damages on the structures usually appears.

1.3. *Chloride in structures - large variations*

When performing sampling on concrete structures in marine environment, a frequent problem is the extensive variations in chloride content between different sampling points on the same structure.

Figure 2 shows an example from an inspection of a quay deck in a harbour in western Sweden. The 10 sampling points are located on a line with a length of less than one meter.

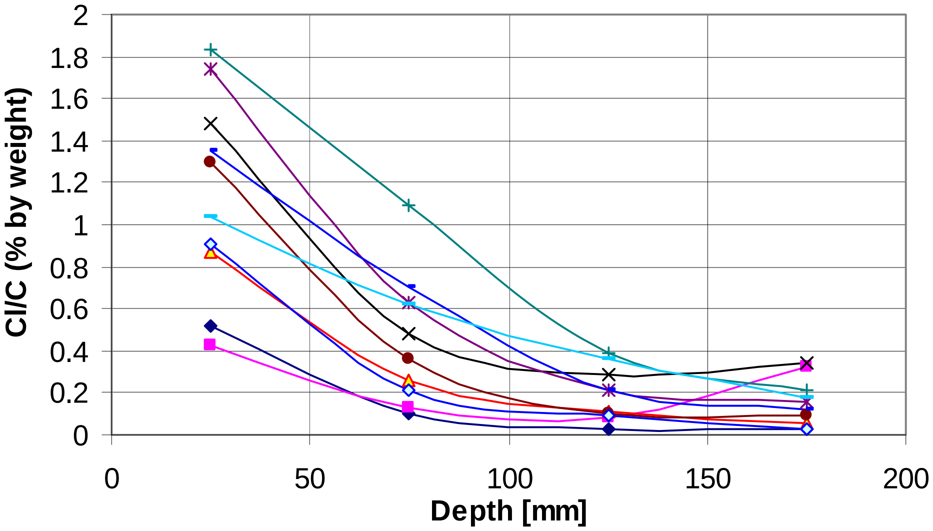

Figure 2: Example from chloride profiling, after [12]

No obvious explanation to the differences in the analyzed chloride content was found at site. The concrete surface, from which the samples were taken, showed no signs of cracks or cavities that could explain this phenomenon.

In [14] recommendations for sampling are given, and it is also stated that core grinding or grinding at site gives more accurate results than dust sampling by dry drilling. No other methods for decreasing the extensive variations seen in figure 2 are given in the report except only to use dry drilling when the examined concrete contains aggregates with a size smaller than 16-20 mm, which in practice rules out most concrete structures in marine environment.

Variation of chloride profiles in homogeneous areas

A paper by Goltermann [20] presents the results from an investigation of variations in chloride content in apparently homogeneous concrete. The sampling for analyzing chloride content has been performed on the bridge columns in a road bridge in Denmark. Both core sampling and dust sampling by dry drilling have been performed. The diameter of the cores sampled varied between 75 and 100 mm and for the dust sampling a 20 mm drill was used. Close to every sampling point for core sampling, dust where sampled from three bore holes. The dust from every equal interval in the three holes was mixed and formed one sample. In the laboratory the chloride content, cement content and moisture content was determined. The sampling was performed in areas on the bridge columns that consisted of apparently homogeneous concrete. The cores and the dust were sampled in small areas in order to be able to compare the sampling methods.

The results from the laboratory analysis showed no correlation between the chloride content and the moisture content in the samples. A good correlation was however found between the moisture content and the cement content. The coefficient of variation of the measured chloride content in the dust samples was larger than for the collected cores. This was shown to be of minor importance when estimating the remaining service life of the structure. For this estimation a calculation model based on Fick's second law was used.

The paper finally concluded that when using dust from dry drilling with the purpose of determining the chloride content in the concrete, the number of drilling holes situated close to each other should consist of not less than 4 or 5 in order to get more accurate results compared to when mixing dust from only 3 holes.

Probabilistic Approach for Local Chloride Heterogeneity near Reinforcement.

de Rooij & Polder performed sampling by core drilling in the eastern Scheldt storm surge barrier [2]. The sampling was performed on eighteen year old concrete with a core diameter of 50 mm. In total six cores where collected about nine meters above mean sea level within an area less than 0.5 m^2. The chloride profiles from the analysis showed extensive variations down to about 35 mm beneath the concrete cover. No explanation for this behaviour was found other than the heterogeneity of concrete at a micro structural level.

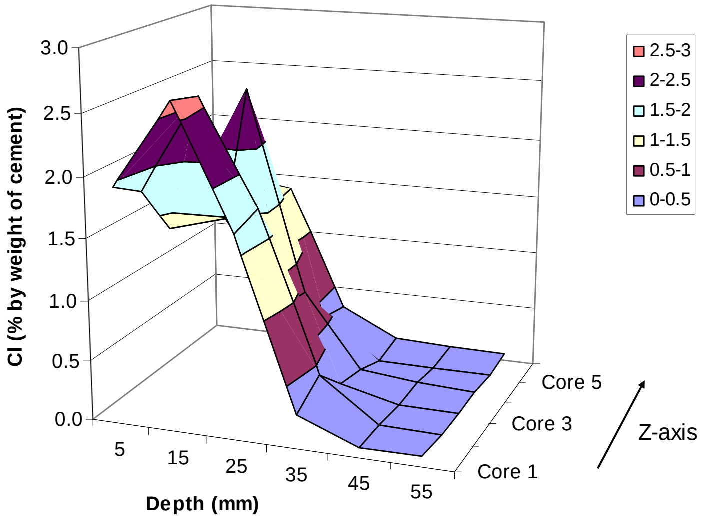

Figure 3: Chloride profiles along a 1.2 m long line which is indicated by the Z-axis, after [2]

1.4. Chloride - Sampling Methods

Very few references have been found to literature where chloride sampling methods have been evaluated.

Measurements of chlorides in concrete - sampling techniques

Farstad et al [21] performed a study of two different ways to perform sampling on concrete for chloride analysis. The methods used were core drilling by a 98 mm water cooled core sampler and dry drilling for sampling dust with a hand held drilling machine.

Concrete with known content of chloride was used in the tests. The chloride content in the analyzed concrete samples was 0.0%, 1.0% and 3.0% by weight of concrete respectively. In order to get a more accurate result from the dry drilling sampling, the dust have been collected as mixed samples from five bore holes placed near each other representing one sample. The mean values from these five bore holes were used for comparison with the chloride profiles from grinding the collected cores nearby.

The analysis showed that the determined chloride content from the collected cores agrees with the known chloride content in the concrete. Even the correlation between the different cores is good. The measured chloride content in the dust samples gives less accuracy than the cores. It is concluded in the report that when sampling dust it is necessary to use a drill diameter that exceeds the maximum aggregate size in the current concrete in order to get accurate results on the chloride content.

Other recommendations on how to collect samples of concrete for chloride analysis are given by RILEM Technical Committee, TC-178 in [22]. Also in this report, the recommendation is to refer the chloride content to the concrete mass.

2. CASE STUDIES

2.1. Case Study 1 - The Port of Trelleborg (Paper I)

In the late summer of 2005 an opportunity of executing a case study on real concrete structures in the Port of Trelleborg, a harbour in southern Sweden, was given. Before the field work started, an archive study on drawings of the existing concrete structures was performed together with a study of existing climatic data in the region. About 30 years of data on wind speed and wind direction together with air and water temperature, was analyzed statistically in order to be able to see if these parameters had influenced the chloride ingress into the existing concrete super structures. The climatic data was collected by the Swedish Meteorological and Hydrological institute at the weather station in Falsterbo, about 20 kilometres west of the port of Trelleborg. The results from this study are presented in paper I.

The climatic study showed that the mean wind direction coincides with the opening of the port entrance which of course affects the structures that lies in this direction inside the docks. The study of the variations of the temperature, which is measured three times per day, also showed that there is very little risk for frost in winter looking at the mean temperature.

The pier that was chosen for detailed inspection is a pile sheet wall with a head beam of reinforced concrete, see figure 5. It was built around 1955, which means that it had reached its design life at the time of inspection. No obvious signs of extreme deterioration were, however, found at the initial visual inspection. The pier, which is about 200 m long, is located in the circle in figure 4. The top beam of the pier is made of reinforced concrete which is exposed to the local climate in three directions, west, south and east.

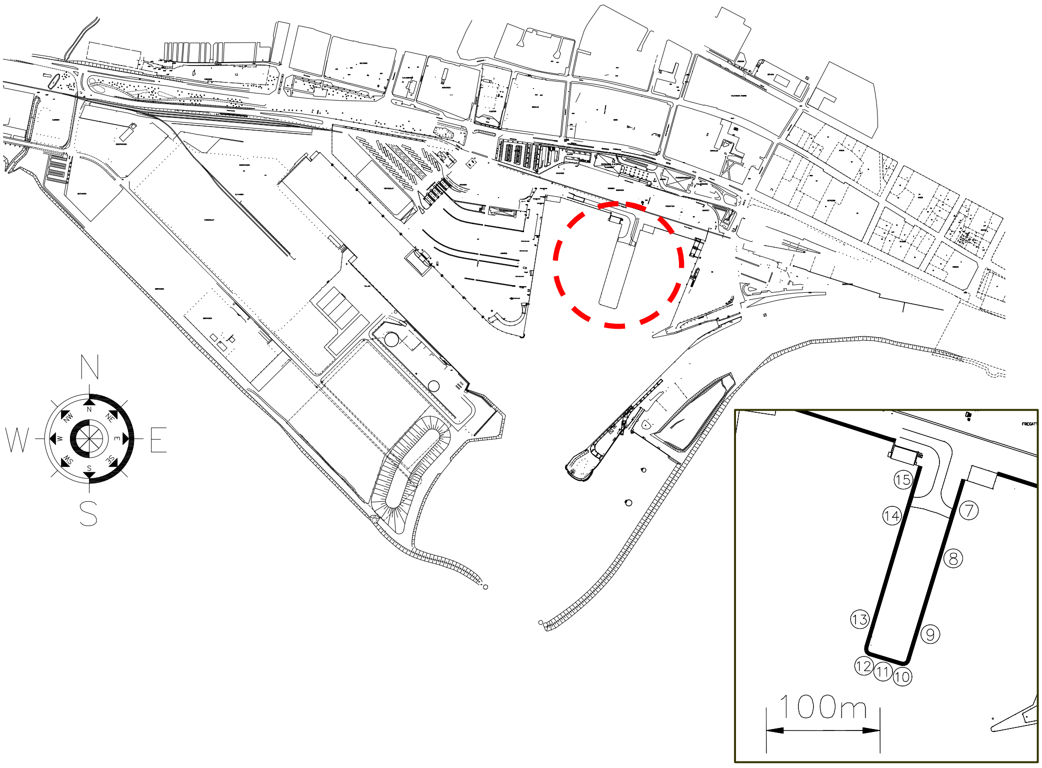

Figure 4: Plan over the Port of Trelleborg showing the inspected pier. The small figure on the right shows the location of the sampling points.

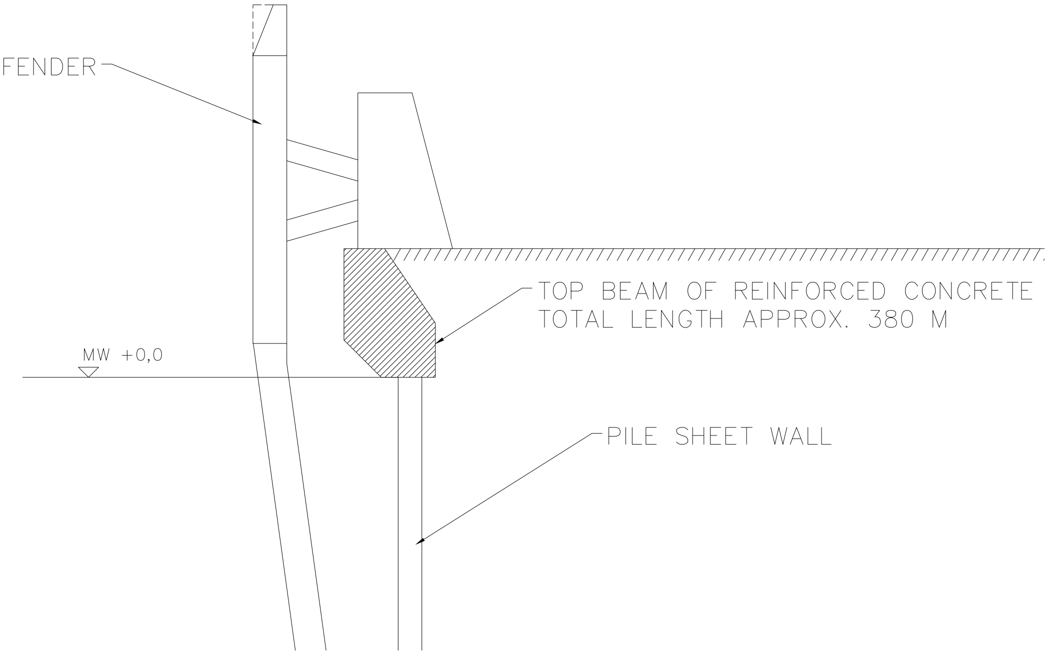

Figure 5: Section through the inspected top beam

The detailed investigation of the head beam was performed by dry drilling and sampling dust along the head beam of the pier. The samples where all taken on the same level on the head beam of the quay about 1 m over mean sea level, and the diameter of the bore was 20 mm. Nine sampling holes where drilled on each side in groups of 3, that is 27 holes in total, down to a depth of 100 mm. The bore holes where chosen so that it shouldn't be disturbed by cracks or other anomalies, and were organized in such a way that in every sampling point three holes were drilled in order to be able to see differences between the results when the dust had been analyzed. The distance between the bore holes in every sampling point numbered 10 to 15, is less than 200 mm. The sampling depth interval was set to 10 mm between the depth of 0 and 40 mm and to 20 mm between 40 mm and 100 mm depth. Between every interval, the holes where cleaned with a small brush and by a hand held air blower.

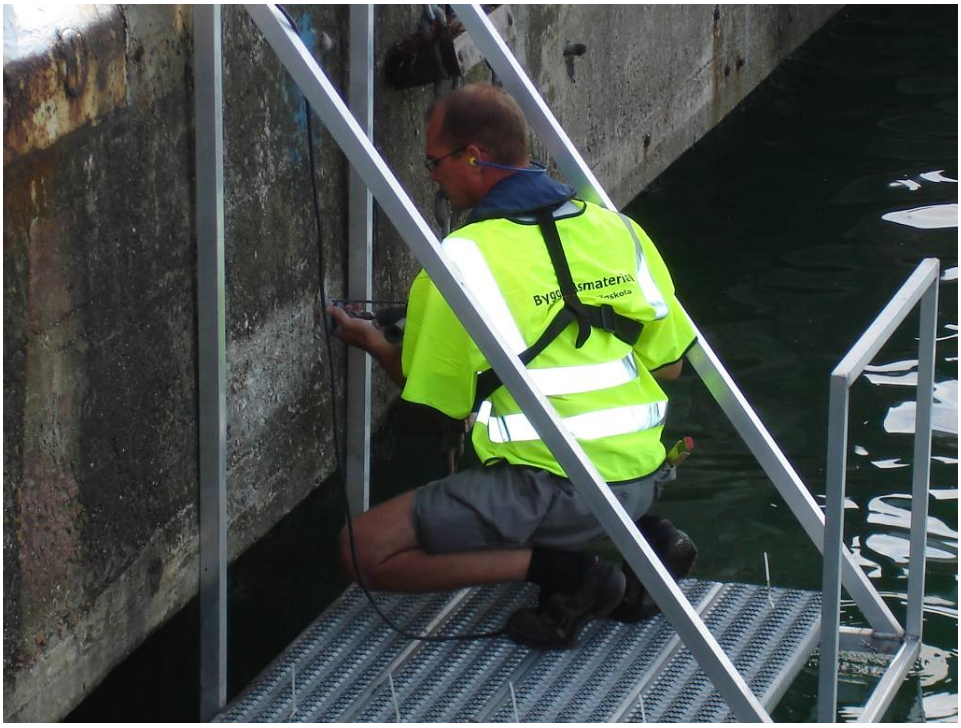

Figure 6: Dry drilling with a hand held drilling machine

From the analysis of the collected dust it is seen that the tip of the pier is the most exposed one with respect to chlorides. 15 mm below the concrete surface the chloride content varied between 0.7 and 4.2 % by weight of cement. The chloride content in the east and west side of the head beam was about 0.5 % by weight of cement as an average value, see figure 7.

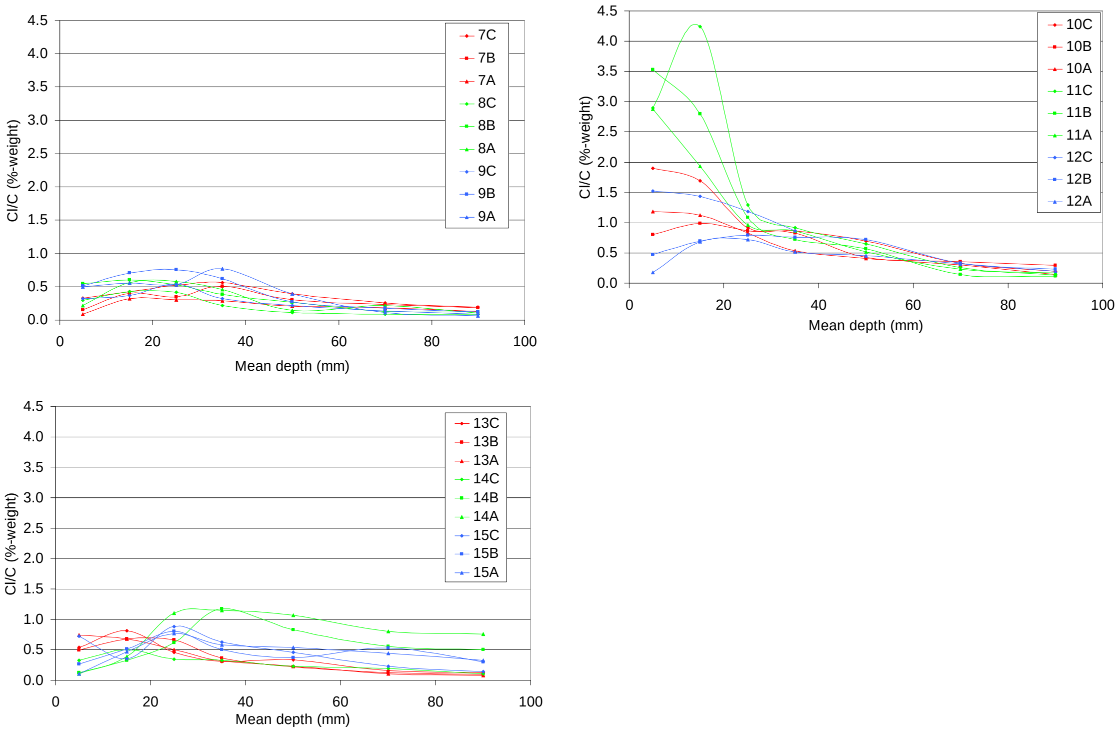

Figure 7: Chloride profiles from the east, south and the west side respectively

No obvious reason for the variations in the results in the samples collected from the south end of the pier has been found. A possible explanation to the high chloride levels at the tip of the pier is that it has been exposed to cyclic wetting and drying caused by the waves coming in from the Baltic Sea since the direction of the pier coincides with the main wind direction in the harbour. The east and west side of the pier are more sheltered from the wind and from the open sea and the moisture content in the concrete is probably more constant here. Another factor to be concerned is that the highest surface chloride values in single sampling points seems to be in those sampling points taken near the location of the bow thrusters of the vessels trafficking the harbour at the ferry berths as seen in figure 8.

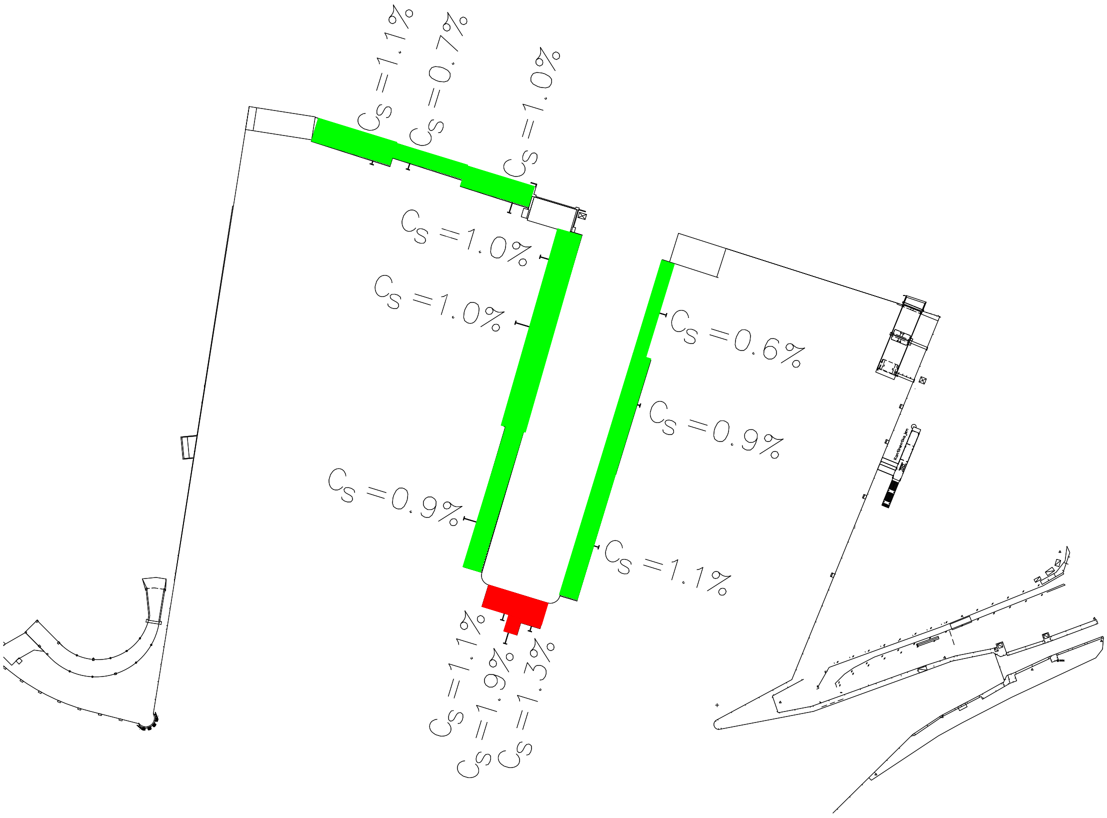

Figure 8: Surface chloride contents determined by curve fitting, around the pier and on the quay besides the pier.

2.2. Case Study 2 - The Port of Malmö

In the autumn of 2005 an inspection of an oil pier in the port of Malmö in southern Sweden was performed with the purpose of determining the remaining service life of the structure. The pier was built in the late fifties and the design life was reached at the time of inspection. The pier is exposed to the open sea from the north. Figure 9 shows a photo and a plan over the investigated pier.

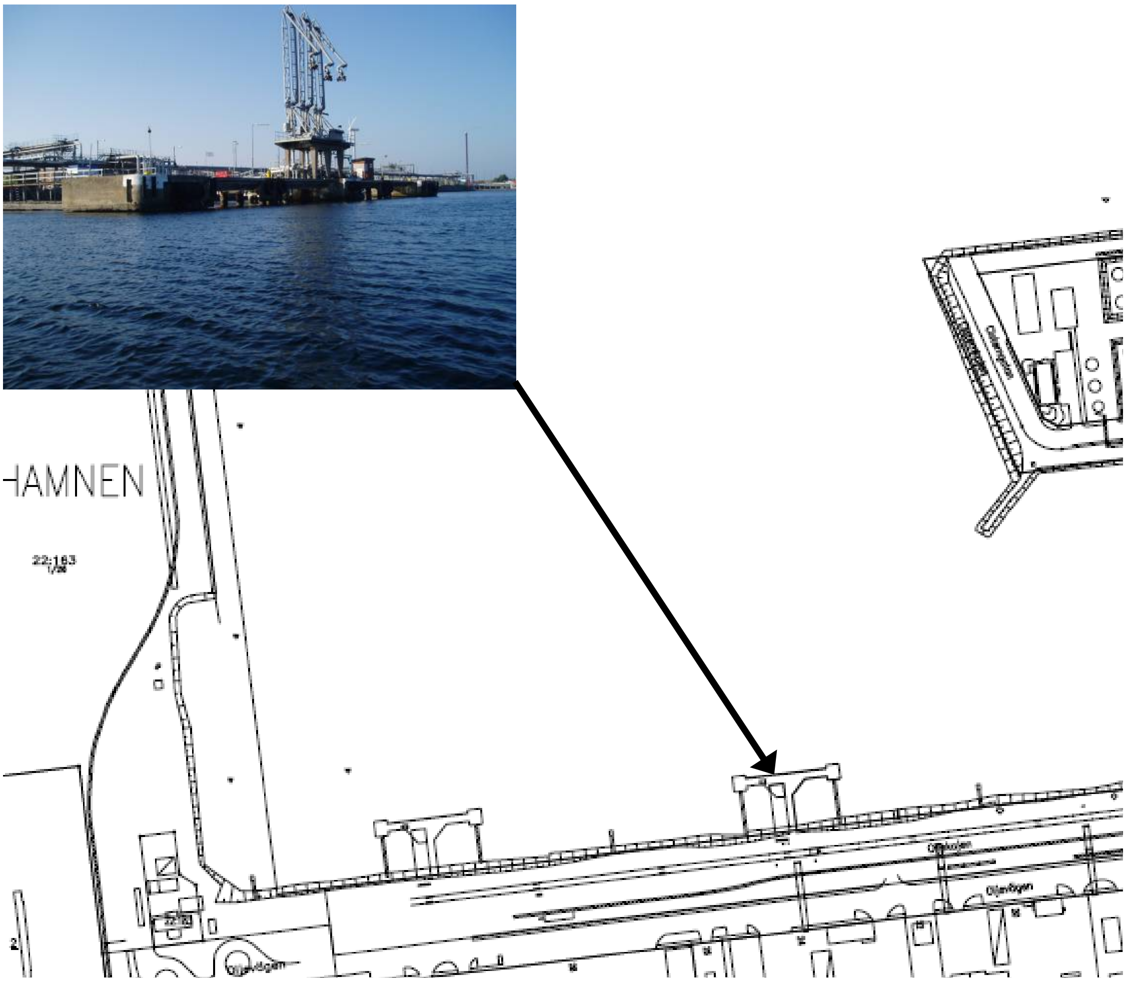

Figure 9: Pier 1004 in Malmö Oil Harbour, facing the open sea at north.

In total five sampling points on the structure were selected for dust sampling by dry drilling, see figure 12. Sampling points 1 to 3 are located at the vertical surface of the west caisson about 2 m above mean sea level. Sampling point 4 is located on the west side on a column on top of the deck about five m above mean sea level and point 5 is located on the bottom side of the quay deck between the caissons, about three m above mean sea level.

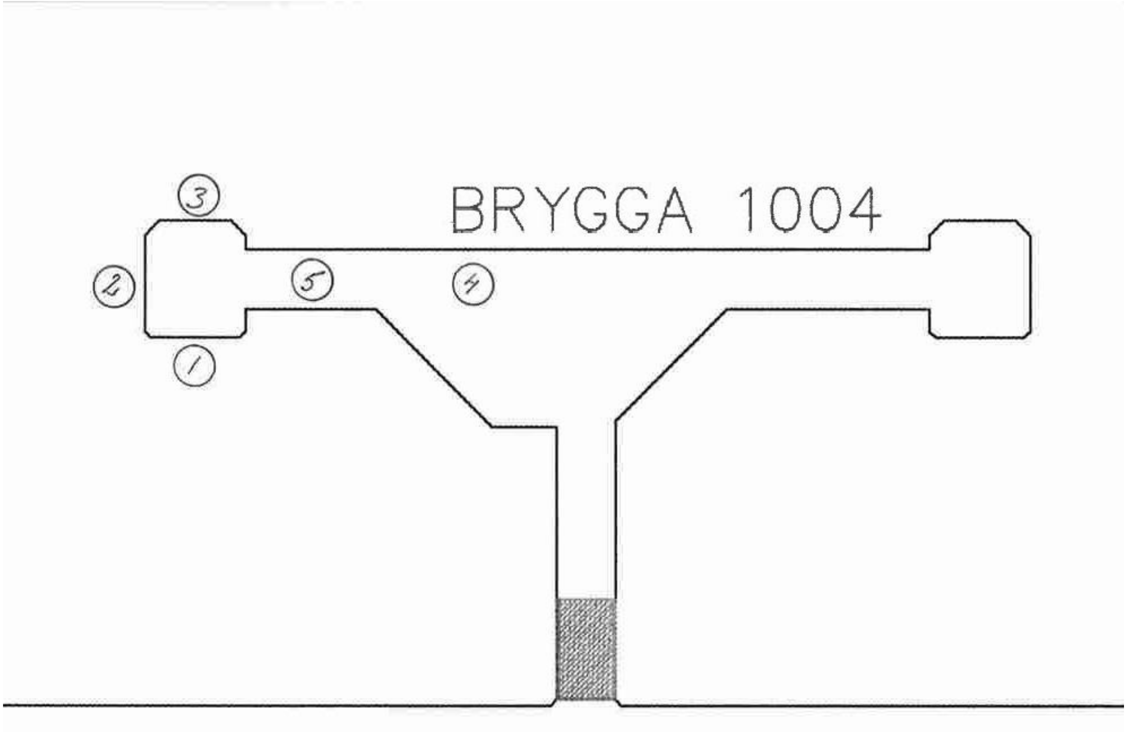

Figure 10: Schematic plan of the oil pier showing the location of the sampling points selected for inspection. Point 3 is facing the open sea from the north.

The dust sampling was performed with a hand held drilling machine, see figure 11, with a 20 mm bore and the dust sampling interval was set to 20 mm with a maximum depth of 100 mm below the concrete surface. Between every interval, the holes where cleaned with a small brush and a hand held air blower. Three bore holes were drilled in every sampling point which means 15 bore holes in total. The distance between the bore holes in every sampling point was less than 200 mm, and the location was selected in homogeneous concrete without any signs of cracks or other visual damages.

Figure 11: The equipment used when sampling dust by dry drilling in the ports of Malmö and Trelleborg

As seen from the graphs in figure 12, the variations in chloride content between the different sampling holes in each sampling point is in most cases quite small. The variations in sampling points 2 and 4 are almost negligible compared to points 1, 3 and 5. The chloride content in point 1 is quite constant throughout the investigated depth. The points 2 - 5 show chloride profiles with very different chloride levels and penetration depths.

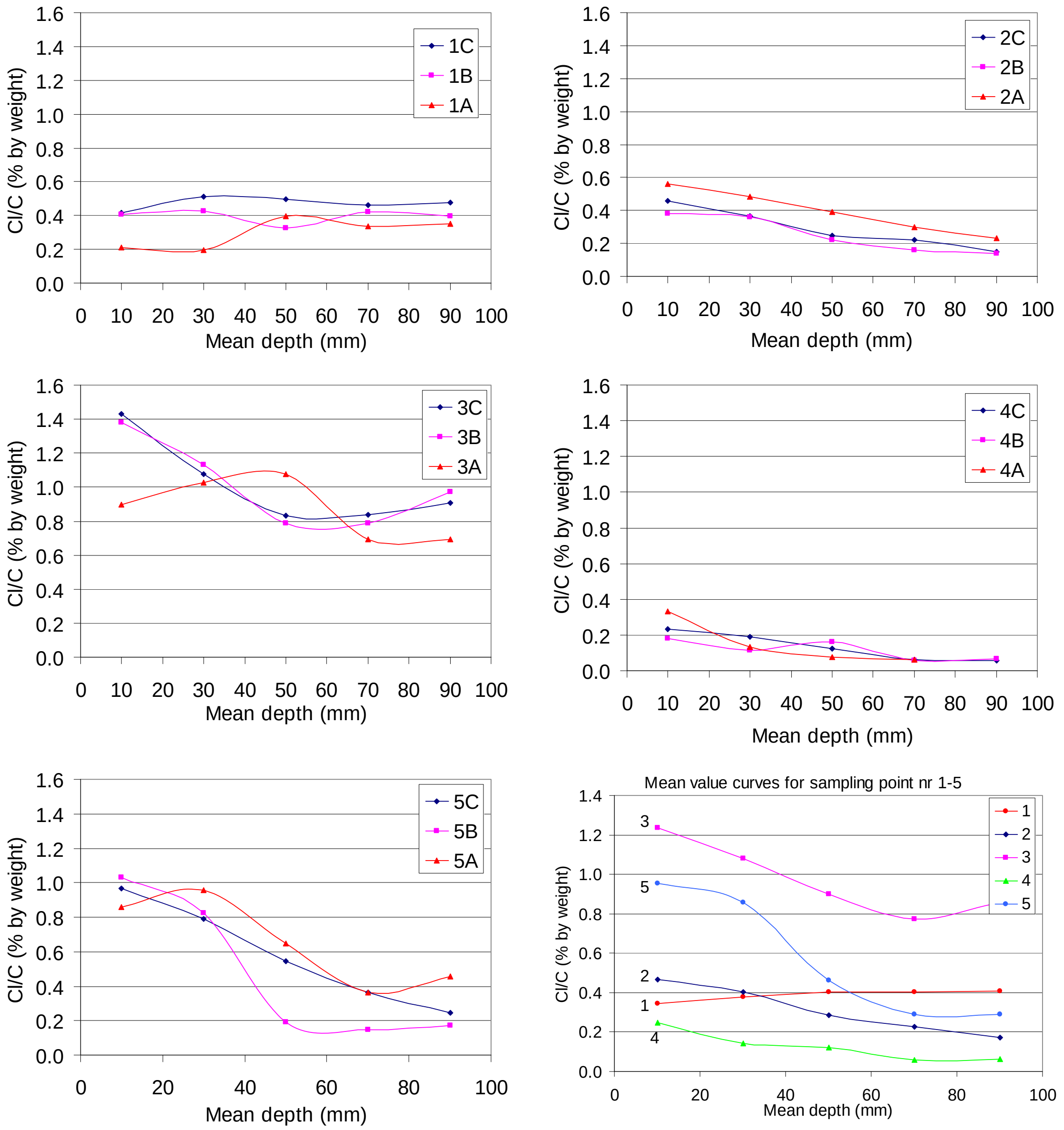

Figure 12: Chloride profiles for sampling points 1 to 5. The bottom right figure shows the mean values in chloride content for point 1 to 5.

As seen from figure 12, the highest values on the chlorides in the concrete are in sampling point 3 and 5. The high chloride values in point 3 confirm the observations in the earlier case study in Trelleborg, that the exposure to open sea is the main factor to chloride ingress into marine concrete super structures. The high values in point 5 on the underside of the quay deck is probably caused by splashing. This side of the structure is not exposed to cleaning by rainfall which also could explain the high chloride values at the surface. Looking at the results in point 1 and 2 it is seen that the chloride content in the concrete is quite low compared to point 3 and 5. The reason why the chloride content in point 1 is higher than in point 2 could be the lack of cleaning by rainfall, since this sampling point was located under a sheltering bridge connecting the pier with the shore. The chloride content in point 4 was extremely low with respect to the age of the structure. Since the location of the sampling point was located about 5 m above mean sea level, it is probably almost only airborne chlorides that have affected the column. This is also seen in figure 13, which shows the values of the surface chloride content determined by curve fitting. It is obvious that the north surface facing the open sea has the highest surface chloride content followed by the underside of the quay deck.

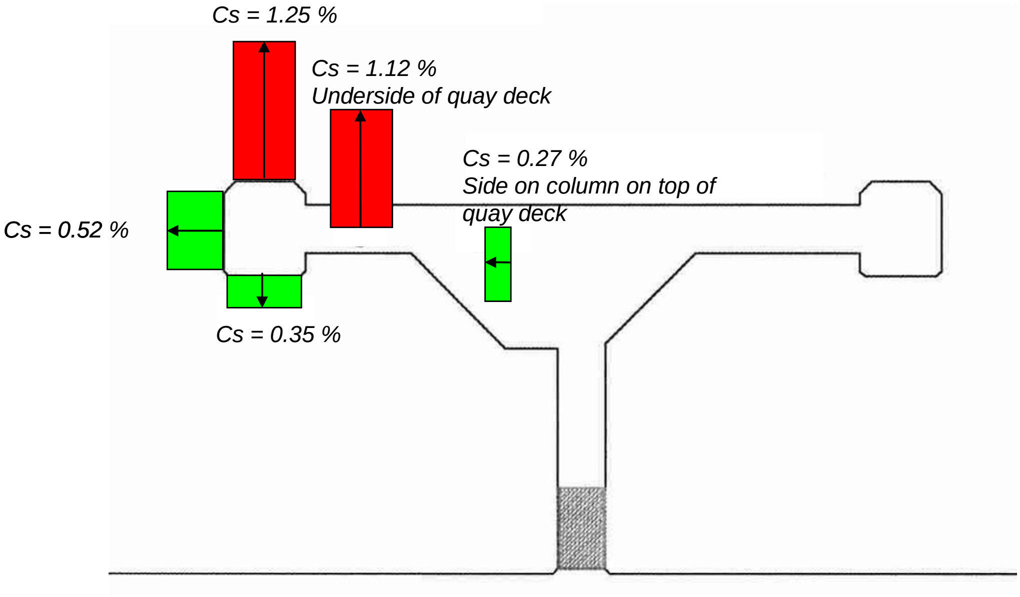

Figure 13: Cs values for the concrete in the investigated pier

2.3. Case studies - conclusions

The conclusions of the two case studies are that when inspecting a reinforced concrete structure exposed to the marine environment, all surrounding factors that influence the structure should be concerned. This means that it is not enough to select for example the oldest structure in the port or harbour when performing inspection thinking that because of its age it has to be the most damaged one with respect to reinforcement corrosion. The case studies have shown that the exposure of chlorides on the structures depends, not only on the dominating wind direction, but more on the exposure to the open sea.

In Trelleborg the dominating wind direction is from south to north. That coincides with the direction of the port entrance which could be one of the factors why the chloride content reached its highest level on the tip of the inspected pier which elongation is perpendicular to the wind direction in the harbour. This means that the south tip of the pier is exposed to wave actions from the open sea while the east and the west side of the pier coincide with the elongation of the wave direction, and are therefore not that exposed.

In the case study in the port of Malmö, a structure facing the open sea at north was inspected. Since the distance between Malmö and Trelleborg is about 50 km, it is reasonable to think that the dominating wind direction is the same in both cities. The highest chloride values in the inspected caisson in Malmö were on the north side of the caisson, while the lowest values on the same structure was found on its west and south side. A clear correlation between the exposure to the open sea at north and the chloride content could therefore be suspected.

The results from the dry drilling shows that the variations in chloride content between the different sampling holes in the sampling points decrease when presenting the chloride content in % by weight of cement instead of % by weight of sample. This effect was shown in both case studies. However, the sampling points on the tip of the pier show extensive variations even though the chloride content is expressed as % by weight of cement without any clear reason. One explanation to this behaviour could be that the tip of the pier is exposed to cyclic wetting and drying increasing the possibility of chlorides to enrich in the concrete cover.

3. CHLORIDE SAMPLING METHODS

3.1. Dry drilling and core sampling (Paper II)

With the purpose of trying to understand the reason for the extensive variations in chloride content in samples collected in field, a laboratory study was performed in the spring of 2005. The testing was performed on a concrete slab which had been submerged in a saline solution for about seven months and stored in a laboratory environment. The mix used for the concrete in the slab was composed so that it should be as near as possible to the concrete compositions used in older harbour structures in Sweden.

The sampling of concrete specimens from the slab was performed both by core sampling and by dry drilling, sampling dust. In order to imitate sampling performed by industry, personnel from the Swedish Road Administration performed the dry drilling. The main reason for this action was to investigate the effect of the sampling technique on the achieved results. To be able to investigate the influence of the bore diameter on the analyzed chloride content in the specimen, three different bore diameters was used, 8, 12 and 20 mm. The 100 mm cores were profile grinded. The dust sampling was performed in circles around the location of the sampled cores in order to be able to compare the results from both sampling methods, see figure 14. Dust sampling was performed both when the slab was in a horizontal position and vertical standing up for the purpose of detecting the influence of sampling position on the achieved results. Theoretically the chloride content should be the same in all the samples.

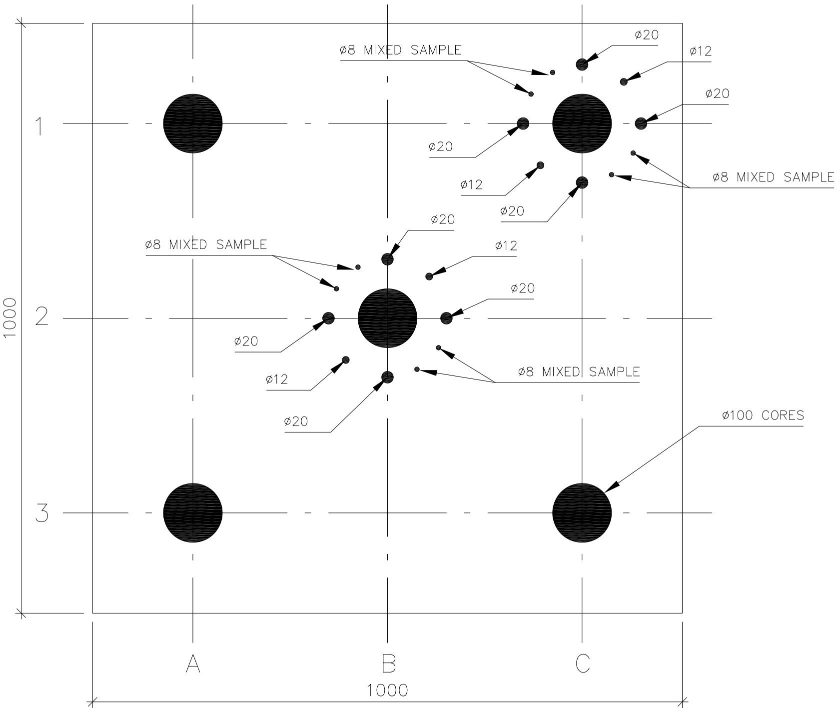

Figure 14: Sampling points for core sampling and dry drilling in laboratory

The results from this investigation showed that coring is the most outstanding method for analyzing the chloride content in concrete, at least when using such large core diameters as 100 mm. Coring gives much smaller variations in chloride content compared to dust sampling. The study also showed that when using small bore diameters, mixed samples should be used in order to minimize the variations in chloride content between different samples.

One observation from the dust sampling is that the mean value from the bore holes done with a 20 mm bore was higher than the mean value of the cores, see figure 15. This could be the effect of a systematical depth error caused by wrong measurements when drilling in intervals, or even by poor cleaning of the bore hole between the intervals resulting in transporting chlorides into the concrete giving a result on “the safe side”. No significant differences in the chloride content or cement content in the samples caused by sampling from a horizontal or a vertical surface respectively, were found when performing the dust sampling.

As seen in figure 15 the variations in chloride content become extensive even when using as large bores as 20 mm when presenting the chloride content as % by weight of sample. The dotted line represents the mean value of the five cores analyzed by profile grinding and is used as a reference curve.

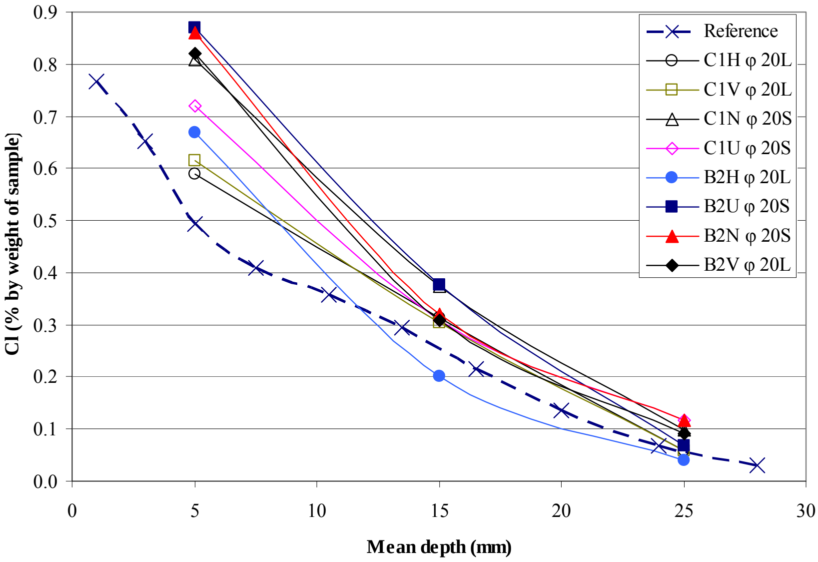

Figure 15: Results from dust sampling with 20 mm bore. Chloride presented as % by weight of sample.

When sampling dust the binder seems to become over-represented in the collected samples. This is seen in figure 16 showing the binder content in the analyzed samples. This could be due to that the drill has searched its way between the aggregates in the concrete.

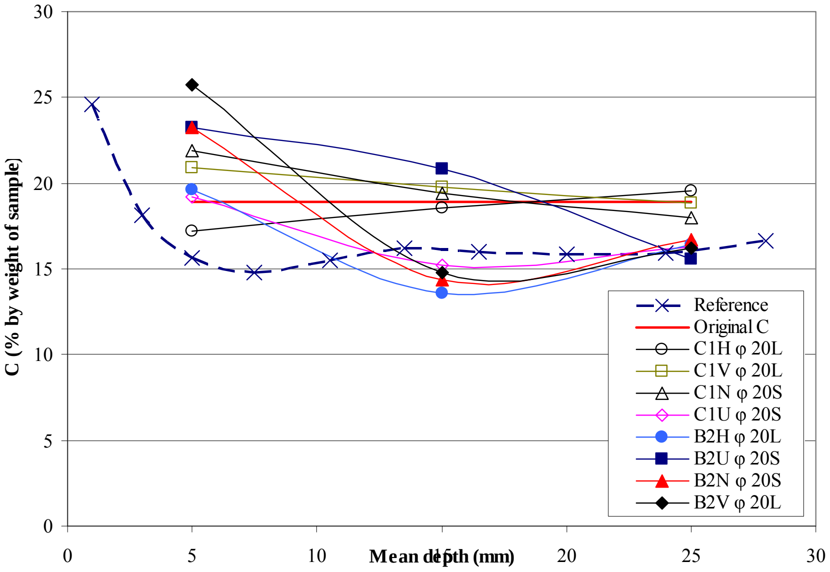

Figure 16: Cement content in samples collected with 20 mm bores.

The fact that the binder is over-represented in the samples gives too high chloride values when analyzing the dust, giving results on “the safe side”. This also means that the sample is not representative for the concrete in the analyzed structure.

The main conclusion of the study is, however, that when analyzing concrete in order to determine the chloride content, the calcium oxide should also be analyzed at the same time. Presenting the chloride content as % by weight of calcium oxide, or by weight of cement, gives much smaller variations between the different bore holes than when presenting the chloride content as % by weight of sample. The complete results from this investigation are presented in paper II.

3.2. Simulated drilling using data from EPMA (Paper III)

A sample from the same slab described in paper II was sent to Japan for EPMA analysis. The EPMA, or the Electron Probe Micro Analyzer, uses a focused beam of high energy electrons to non -destructively ionize a solid specimen surface for inducing emission of characteristic X-rays. The typical size of a sample to be analyzed by the EPMA is a slice with height*length*thickness = 50*75*10 mm. The analysis is two dimensional and the EPMA delivers values of the analyzed element in pixels with the size of 0.1*0.1 mm, one value for every pixel on the sample. Five different elements can be analyzed at the same time. The results from the EPMA, that is the values on the analyzed element or elements, are delivered as matrices with the dimension of 500 rows and 750 columns due to the size of the pixels. The elements analyzed in this study were chloride, calcium oxide, silica, potassium and sodium.

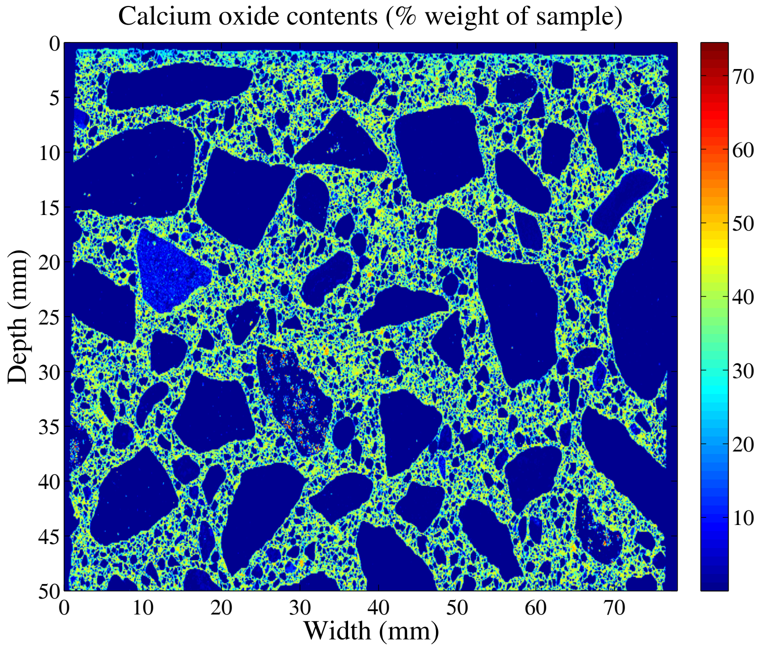

Figure 17: Calcium content in concrete specimen analyzed with EPMA

The results from the EPMA analysis have been used to simulate two dimensional drilling and dust sampling. In this study the “drill” is a strip in two dimensions, cf. figure 18. To simulate different bore diameters, different strip widths have been used. To be able to compare the results from the dust sampling, the same strip widths have been chosen as the drill diameter in the laboratory test, namely 8, 12 and 20 mm.

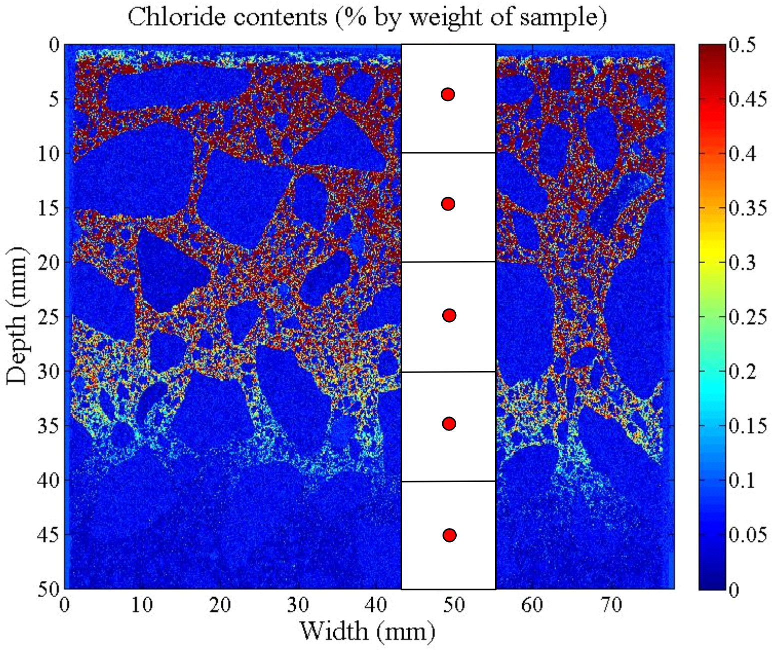

Figure 18: Chloride content in concrete specimen analyzed with EPMA showing the simulated dry drilling intervals.

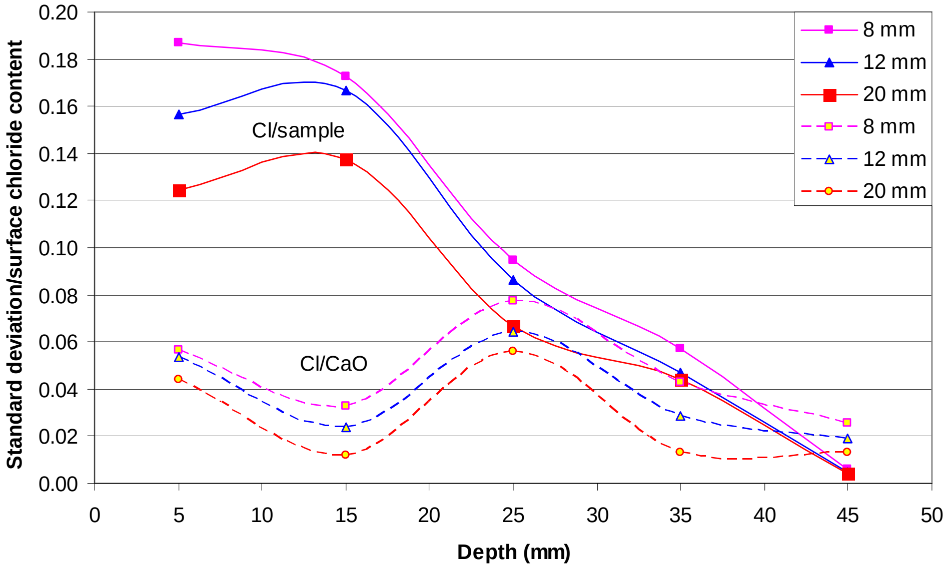

Figure 19: Standard deviation divided by surface chloride content: comparison between Cl/CaO and Cl/sample

In figure 19 the scatter in chloride content in the sampling results from the simulations are compared. The graph shows clearly that the variations in the estimated chloride content are very much higher when measuring the chloride content by weight of sample than when measuring as % by weight of binder.

Figures 20 and 21 show the chloride content in % by weight of binder analyzed by simulating data from EPMA and by dry drilling and core sampling in laboratory respectively. As seen from figure 20 the chloride content in the simulated bores is exactly the same as the chloride content in the simulated core. This is not the fact in figure 21. It is rather obvious in these results that the binder content is over-represented in the samples collected by dry drilling and confirms the suspicion that the bore could take a path between the aggregates when drilling. This gives results that overestimate the chloride content in the analyzed concrete which are not representative for the investigated structure.

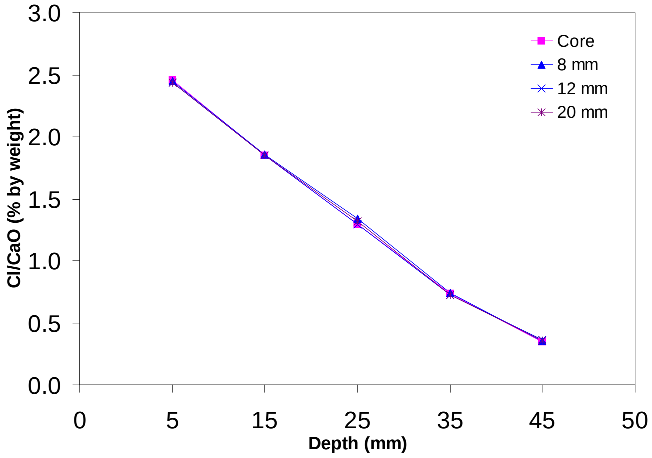

Figure 20: Chloride content in % by weight of binder from simulations on data from EPMA.

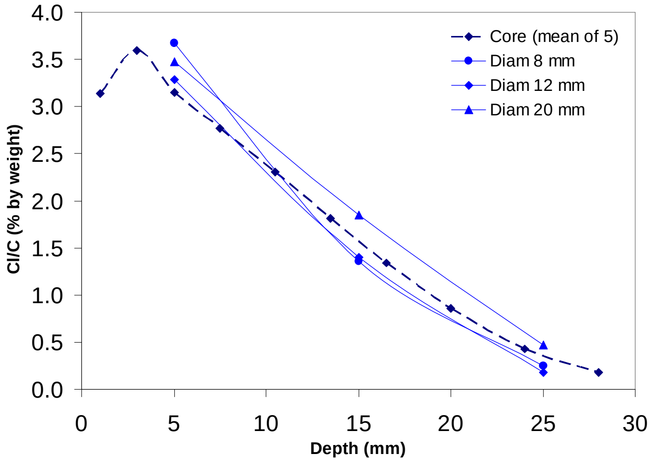

Figure 21: Chloride content in % by weight of binder from dry drilling and core sampling in the laboratory.

The results from this study mostly confirm the results from the dry drilling tests. The variations in chloride content are extensive when presenting the results as % by weight of sample independent of strip width, but a little smaller when using large widths. Presenting the chloride content as % by weight of calcium oxide gives almost no variations at all in the simulations. An interesting observation is that the mean value for the chloride content in the whole sample coincides with the mean values from the simulation with the strips. This is of course what should be expected, but it also confirms the suspicions from the results from the dry drilling that the binder content could be over represented in the collected dust samples or that chloride is transported into the concrete when performing dry drilling, in reality giving higher chloride values. The complete EPMA study is described in paper III.

3.3. Sampling methods - conclusions

The study showed clearly that the smallest variations between different samples where achieved by core sampling and profile grinding. The mean value curve from the core grinding has been used for comparison with the results from dust sampling. The dry drilling was performed both when the slab was in a horizontal direction and when it was in a vertical direction with the purpose of detecting if there was any difference on the results caused by the sampling position. No such differences could, however, be seen from the results of the analyzed dust.

The dust samples show quite extensive variations in chloride content even when as large bores as 20 mm are used. This is most obvious when presenting the chloride content as % by weight of sample. Presenting the chloride content as % by weight of cement or binder, the variations are decreasing. In order to get enough dust for the analysis, mixed samples from two holes where used when the dry drilling with 8 mm bore was performed. When comparing the results from the 8 mm bore with the ones taken with the 12 mm bores, it is seen that the variations in the results from the 12 mm bore is larger. The conclusion of this is that mixed samples are to prefer and gives smaller variations, when using small bore diameters when dry drilling.

Another effect seen in the results, especially in the results from dry drilling with 20 mm bore, is that they could be affected by a systematic error. The mean value of the dust sampling curves lies above the curve from core grinding, which means that either the measurement of depth interval is inaccurate or the chloride infected dust is transported into the bore hole between the bore intervals giving higher chloride values than expected. Another possibility that gives the same results with “too high” values on the chloride content, is that the binder is over-represented in the dust sample. If the bore searches its way besides or between the aggregates when dry drilling, it means that the sample contains more binder than what is representative for the binder content in the investigated concrete structure giving higher chloride values. This means that the results from dry drilling are not representative for the investigated structure. These errors are avoided when using data from EPMA. Simulating dry drilling on the data from the sample analyzed with the EPMA has shown almost the same results as when dry drilling in reality. It is even more clear that presenting the chloride as % by weight of sample gives very extensive variations between the simulated bore holes, than when looking at the results from dry drilling.

4. CONCLUSIONS

Finding sampling methods for determining the chloride content in marine concrete structures that give small scatter in the results, is part of the solution to the problem with getting good input data for a service-life model for the structure. This study has lead one step further on how to decrease the extensive variations in chloride content when sampling on reinforced concrete exposed to marine environment.

It should be pointed out that when measuring the chloride content it should be expressed as % by weight of cement or calcium oxide, giving much smaller scatter between different chloride profiles taken from the same structure compared to if the chloride content is determined as % by weight of sample. This is particularly important when collecting dust by dry drilling especially when using small bore diameters, since the influence of the aggregates on the achieved results seems to be the main reason to the extensive variations in chloride content.

The studies in this work have also shown that dry drilling gives too high chloride values because of the over-representation of binder in the samples. This means that the sampling is not representative for the investigated concrete.

The case studies in this work also showed the importance of how to choose sampling points on an existing structure. If a surface on a concrete structure is exposed to open sea without any sheltering barriers in front, it seems that the chloride content on this side tends to be much higher than in the surfaces facing other sheltered directions on the same structure despite of the dominating wind direction. This should be considered when evaluating the results from an investigation of the structure. Even if one side of the structure shows values of chloride content exceeding the supposed threshold value for reinforcement corrosion, it does not mean that the remaining service-life is zero for the whole structure. In this case it could be enough to perform maintenance efforts only on the most deteriorated parts of the structure to a moderate cost compared to if the whole structure should be repaired.

5. FUTURE RESEARCH

The next step in this research area should be to core sampling together with dry drilling on real marine concrete structures, with the purpose of improving the sampling methods and to study threshold values for chloride initiated corrosion at the same time. The studies in this work have shown that the exposure to open sea is of great importance regarding to environmental load on structures in marine environment. Consequently, the sampling should follow a detailed investigation of the climatic loads on the chosen marine structures.

Using sampling methods that decrease or preferably eliminate those extensive variations in chloride content, which are often the fact when sampling on marine concrete, gives us a chance to get closer to the threshold value for reinforcement corrosion. The threshold value is dependent on several parameters, for example the moisture content in the concrete, the pH-value in the concrete close to the reinforcement and on the compaction of the concrete around the steel bars, just to mention a few, and it will be easier to find the dependency of these parameters if the variations in the analyzed chloride content are small.

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APPENDIX

Paper 1 - *Initial Survey of Concrete Structures in Swedish Harbours - A Case Study in the Port of Trelleborg*

Paper 2 - *Chloride Profiling in Concrete Harbour Structures - A Study of Extensive Variations*

Paper 3 - *A Study on Sampling Methods for Chloride Profiles - Simulations using Data from EPMA*

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Initial survey of concrete structures in Swedish harbours – a case study in the Port of Trelleborg

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ABSTRACT: This paper is a case study on how to perform a survey of concrete structures in Swedish harbours. The purpose of the survey is to detect common damages and signs of deterioration on concrete structures in marine environment. The survey should consist of information about the structural design for the structures together with climatic conditions for the harbour in question, as well as documentation of existing damages on the structures. Information about the concrete mix is often found in structural drawings. If not, laboratory analysis is necessary for determining the composition of the actual concrete. In the climatic data information such as the dominant wind direction and wave action is given. The analysis of the climatic data should be combined with field studies at site for the full understanding of the climatic actions on the structures. The harbour chosen for this case study is the harbour of Trelleborg which is the second largest harbour in Sweden expressed in tonnage and has well functioning concrete structures from 1930 and onwards.

1 INTRODUCTION

Concrete entered the Swedish harbours as a dominant building material during the Second World War, which means that many of the existing concrete structures in the harbours today have reached an age of 60 to 70 years. Most of these structures suffer from severe deterioration. Corroding reinforcement due to a constant exposure to chlorides from the sea water is probably the greatest deterioration problem in marine concrete structures.

The aim of this work has been to develop a methodology on how to perform a survey of concrete structures in Swedish harbours. The purpose of the survey is to describe the present state of the concrete structures in the harbours with respect to usage, surrounding climate and deterioration, and to be a helpful tool when choosing sampling points for determining the chloride content in existing concrete structures.

The survey presented in this article is made for the Port of Trelleborg in the south of Sweden, but could easily be changed to fit any other harbour with concrete structures, all over the world.

The purpose of the survey is to give information about the conditions of the structures and the environmental actions on them. This includes determining the age of the various concrete structures, together with collecting information about the concrete mixture and, if available, to get results from earlier performed inspections. The survey report should contain copies of construction drawings for the structures in question. How the structures are affected by wind and wave action together with rain and temperature data is also information suitable for the survey report. For this reason climatic data from the Swedish Meteorological and Hydrological Institute has been analysed. The climatic data together with the construction data should form the basis for a more detailed inspection plan from which relevant sampling points should be selected for measuring chloride ingress in the concrete etc. When performing a survey it is important to visit the site at all relevant weather conditions to make observations useful for the understanding of the climatic influence on the harbour structures.

2 METHODS

2.1 *Former research*

Several papers and articles on the subject inspection of marine concrete structures have been published during the years. The main conclusion in these articles is that the corrosion of reinforcement steel due to chlorides is the largest deterioration factor for concrete in marine environment.

In the 1960s Gjørv (1968) performed an investigation of about 700 concrete structures in Norwegian harbours. Nearly 170 of these structures where investigated thoroughly on site. The main conclusions of these site investigations were that the concrete above the mean water level suffered from corroding reinforcing steel and damages due to frost, while the submerged construction parts where almost intact, even in very old structures. The author also noticed that the effect of the wind have a great effect on the deterioration of the structures.

In 2003 the Swedish Association of Local Authorities, Kommunförbundet (2003), designed a four-step inspection model for Swedish harbour structures as follows:

1 Preliminary inspection
2 Main inspection
3 Annual inspection
4 Special inspection

The report does not give any recommendations on how to choose the sampling points, when taking samples for analyzing concrete specimens.

Browne et al. (1981) constructed an inspection program for inspection of reinforced concrete oil platforms. The program is built up in two phases:

1 Phase 1: Planning
2 Phase 2: Accomplishing the visual inspection

In the program, a probabilistic approach is used for choosing the sampling points on the concrete platform because of the size of the structure. The authors also state that knowledge of the dominant wind direction and wave forces could be assigned to the inspection program.

Wesselink and Harley (1983) present a model for inspection of quays. The model is developed at Exxon and consists of four steps:

1 Preliminary inspection
2 Detailed inspection
3 Analysis
4 Repair

The model is made for terminal operators, with simple descriptions where and what to look for. In the report, only step 1 is accounted for. The procedure on how to perform a detailed inspection is not explained in the article.

It is a well known fact that the results from chloride sampling, which is the most important tool in determining the status of marine concrete, show a very wide scatter, see for instance Goltermann (2004) and Farstad et al. (1993). This is even if the sampling is performed in very small areas and in apparently homogeneous concrete without any visible defects. This is why the survey should precede the detailed inspection in order to make the right decision on how to place the sampling points.

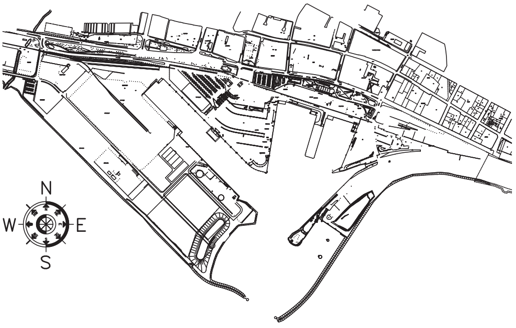

Figure 1. Overview for the Port of Trelleborg.

2.2 *Survey of marine concrete in the Port of Trelleborg*

The Port of Trelleborg is located in the south of Sweden with several daily departures and arrivals of ferries crossing the Baltic Sea between Sweden and Germany. The age of the concrete structures in the harbour varies between 0 and 75 years. An overview of the harbour is presented in figure 1.

The main structure of the performance of the survey for the harbour is as follows:

1 *Archive studying* with the purpose to find information such as structural drawings over the structures in the harbour. Results from earlier performed inspections, if available, should also be studied in this first part of the work.
2 *Analysis of climatic data* for the harbour. Parameters important for the deterioration of concrete super structures are wind direction and wind speed together with wave action on the structures and water level fluctuations.
3 *Observations of climatic actions at site* should be performed at all relevant weather conditions. Data regarding wave heights are often collected outside the harbours and will differ from the actual wave heights inside the docks.
4 *Visual damage inspection at site*. Anomalies and existing damages are recorded and photographed.
5 *Final report* with description of the influence of the climate on the concrete structures, together with recommendations for sampling points in a future detailed inspection with respect to the present state of the structure and the results from the climatic analysis.

3 RESULTS

3.1.1 *Archive studying*

In many cases it could be a genuine detective work to find structural drawings and other vital information

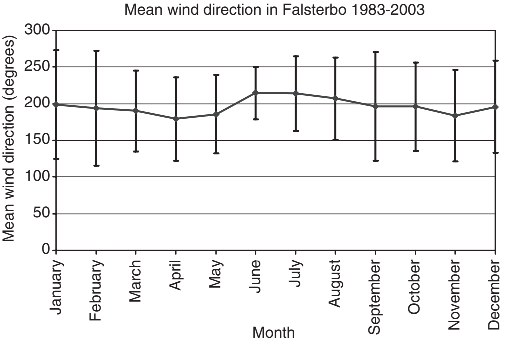

Figure 2. Mean wind direction for Falsterbo. Monthly mean values for 1983 to 2003.

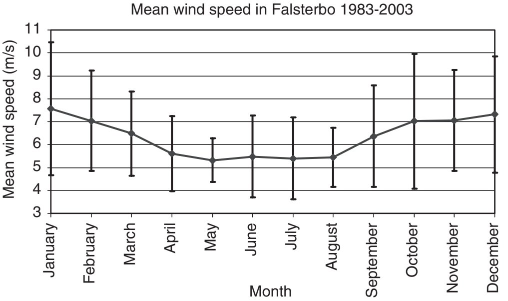

Figure 3. Mean wind speed for Falsterbo. Monthly mean values for 1983 to 2003.

especially regarding older structures. In this case structural drawings are available for almost every structure built after 1955. The knowledge about the design and age of the structures has been helpful in the searching for anomalies on them, and for the understanding of the anomalies when found.

Even though good data on the structures are available, it should not be trusted blindly. It is a fact that the actually built structure often differs from the described design on the drawings. However, the information gives one a hint of what to expect in reality.

3.1.2 *Analysis of climatic data*

Meteorological data has been collected from the Swedish Meteorological and Hydrological Institute. The meteorological station for wind and temperature measurements is located in Falsterbo, 15 km west of Trelleborg. Even though the climatic data is not collected in Trelleborg, it should still be relevant for describing the climate in the Port of Trelleborg. Analysis of the data states that the mean wind direction is about 196° with 0° being wind from the north with positive direction turning clock wise, and that the main wind speed over the year is about 6.3 m/s. The evaluated data with two times the standard deviations, which represents the 95% confidence interval, is presented in figure 2 and 3.

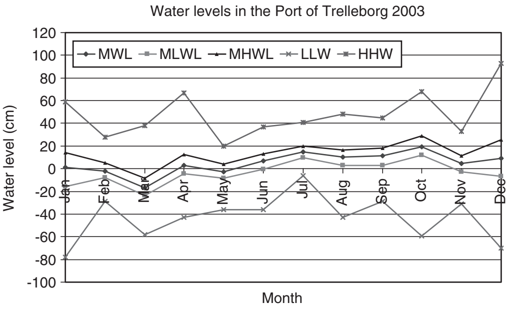

Figure 4. Water levels for 2003, monthly mean values.

The data in figure 3 shows the trend observed in field studies that storms mostly occur in springtime and in late autumn.

The water level is measured between three and eight times per day in the Port of Trelleborg. The available water level data for the year of 2003 has been used for determining the dominant water levels in the harbour. The fluctuation of the water level for the year of 2003 is shown in figure 4.
The abbreviations in figure 4 means as follows:

- **MWL**: Mean Water Level
- **MLWL**: Mean Low Water Level
- **MHWL**: Mean High Water Level
- **LLW**: Lowest Low Water
- **HHW**: Highest High Water

In the Nordic countries the action of frost on the concrete structures is in many cases a large deterioration factor. Frost actions on concrete surfaces could cause softening and scaling of the surfaces, which in turn could increase the amount of chlorides penetrating into the concrete. It is therefore of importance to study the temperature variations in the area. In this case temperature measurements from 1973 and onwards for Falsterbo where used for determining the frost risk. The temperature has been measured three times a day, and is presented as a mean value over twenty-four hours. The twenty-four hour means have been used to calculate mean temperature values over the months and the results are presented in figure 5.

As shown in figure 5 neither the mean temperature of the air nor the mean temperature of the surface water, falls below 0°C. The 95% confidence interval presented in the figure indicates though that the mean air temperature could pass zero degrees during January and February.

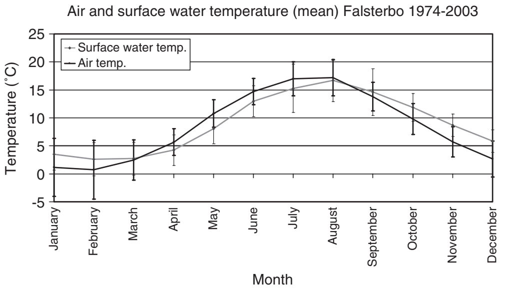

Figure 5. Mean values of air temperature and surface water temperature from 1974 to 2003.

Figure 6. Wave action on breakwaters. Wind direction about 200 degrees.

3.1.3 *Observations of climatic actions at site*

For the understanding of the environmental actions on the structures in the harbour, a visual inspection at site is necessary. The visual inspections should be performed at all weather conditions for a full comprehension of the environmental loads on site.

It is seen from field studies at stormy days that the breakwaters serves their purpose. This means that even when stormy weather occurs and when the wind direction is straight in line with the harbour entrance, no significant waves occur inside the docks. This observation is indicated in figure 6.

The fact that no significant waves occur inside the docks means that most of the chloride content in the concrete structures inside the harbour, has its origin in airborne chlorides.

The concentration of NaCl in the sea water in the south of the Baltic Sea is about 1% NaCl. The salt content was measured inside the docks with a hand held recfractometer, and the results agreed with the expected value.

3.1.4 *Visual damage inspection at site*

The visual damage inspection of the concrete super structures has been performed by foot and by boat. In total, approximately 2500 m of quay length was investigated visually. The inspection was performed in October 2004 and was documented by notes and photographs.

The quay structures in the Port of Trelleborg are dominated by pile sheet walls with head beams of reinforced concrete, except for the "Norra Kajen", which is a 340 m long quay made mainly of prefabricated reinforced concrete. Norra Kajen is located in the north part of the harbour facing the south and was built in 1958.

The underside of the concrete head beam on the pile sheet walls coincide, in several cases, with the mean water level and none of the head beams have their underside below this level. This fact means that no parts of the concrete super structures are continuously submerged into the sea water, but that parts of the structures are exposed to wetting and drying, which is very harsh for reinforced concrete.

Very few signs of corroding reinforcement where observed during the visual inspection. In most cases the only visual corroding steel in the head beams, were form ties left in place when the structure was built. The corroding ties had not, however, caused any damage to the surrounding concrete.

Typical damages, or more correct anomalies, on the concrete head beams are vertical cracks, probably caused by shrinkage. Even though the concrete is cracked, no sign of corroding reinforcement in the form of rust stains was observed. However, in several cases, the cracks seemed to have self-healed by leaching calcium hydroxide, as shown in figure 7.

The concrete in figure 7 is from 1957 and is generally in good shape. The distance between the vertical cracks on the front side of the head beam follows a settled pattern with a uniform distance between centres, and seems to have been caused by shrinkage.

Another type of damage often seen on the concrete super structures is traces of collisions. In most cases only the concrete cover is lost and the damage is concentrated to a very small area. Even though these damages are small and not widely spread, the reinforcement in these locations is often exposed directly to the marine atmosphere, which leads to an accelerated corrosion rate. A typical example of this kind of damage is shown in figure 8.

In critical sections this type of damage and deterioration could, within a short time, lead to a collapse if the damage is not repaired in time.

The quay deck in Norra Kajen where bored through with a core drill with a diameter of 100 mm, in order to be able to inspect the underside of the quay deck. The thickness of the quay deck was approximately 300 mm and the inspection was performed

Figure 7. Typical vertical crack with signs of leaching calcium.

Figure 8. Local damage with corroding reinforcement.

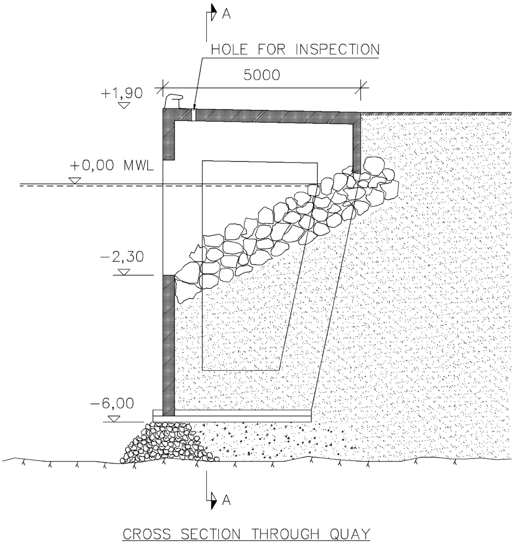

Figure 9. Section through Norra Kajen.

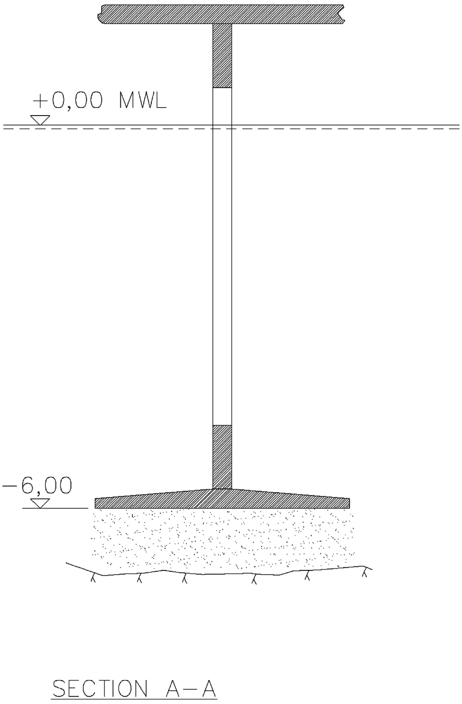

Figure 10. Section through Norra Kajen.

with a digital camera lowered down the bore hole. The principal design of Norra Kajen is shown in figure 9 and figure 10.

It seems as if the deterioration of the concrete on the prefabricated parts of the quay beneath the quay deck was more pronounced than on the visible surfaces on the outside of the quay. The quay deck itself showed none or very small signs of deterioration, but the prefabricated vertical elements had traces of rust stains on the sides and calcium leakage in the connection between the in situ casted quay deck and the prefabricated vertical elements as indicated in figure 11.

Figure 11. Rust stains and traces of calcium leakage on the side of a prefabricated vertical plate element.

This kind of damage indicates that the deterioration of the concrete structure has reached a critical state. It is however at this stage not possible to determine the exact status of the concrete without further detailed inspections. It should also be noted that this sampling point represents only 4 to 5 m of about 340 m of quay length.

4 CONTINUED INVESTIGATIONS

The results from the visual inspection and the results from the climate data that has been analyzed will be used in order to choose sampling points for the detailed inspection.

The detailed investigations will be concentrated to Norra Kajen and Mittelbron, see the thick line in figure 12. The reason for choosing this area is that the two docks shown in the figure containing ferry berth 3 to 6, are the most frequently used. The quays are built in the same year, 1955 to 1956, and with the same concrete mix, according to Skoglund January (2005), and they are facing three directions. This makes it possible to study variations of the chloride ingress in the concrete between samples taken in different directions but in the same lateral level. With knowledge about the climatic actions on these structures, it should be possible to establish a correlation with the chloride content in the concrete. The results from this study will be published in a forthcoming paper.

A systematic selection of sampling points for analyzing chlorides in the existing concrete super structures will be performed. The final sampling will be performed with a core drill and the chloride ingress will be determined in laboratory by profile grinding.

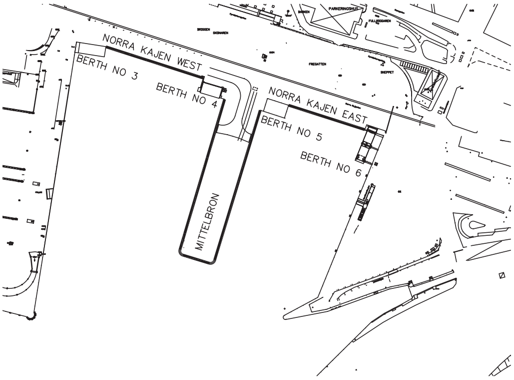

Figure 12. Area for detailed inspection.

For determining the depth of the chloride ingress, the sampling of cores will be preceded by a sampling of drill cuttings along Norra Kajen and Mittelbron.

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CHLORIDE PROFILING IN CONCRETE HARBOUR STRUCTURES – A STUDY OF EXTENSIVE VARIATIONS

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Abstract

The aim of this work is to try to explain why chloride profiles differ significantly even though the samples are taken in a homogeneous concrete, and within a small area. As a first step in this study, different sampling methods have been used to investigate the influence of the sampling method on the achieved results.

Slabs were submerged in a 13.5 % NaCl solution for about six months. Two different sampling methods for collecting concrete specimens for chloride profiling were used, collecting dust by dry drilling and by water-cooled drilling of cores and profile grinding. The sampling of concrete dust was performed with a handheld drilling machine with bore diameters of 8, 12 and 20 mm. The sampling of dust was performed with the slab in both horizontal and vertical position with the purpose of detecting influence on results due to sampling position.

The results from this study show that the chloride profiles from the analyzed cores show little scatter, but also that sampling with a 20 mm bore gives quite accurate results compared to the cores and sampling with smaller bores.

1. INTRODUCTION

Concrete entered the Swedish harbours as a dominant building material during the Second World War, which means that many of the existing concrete structures in the harbours today have reached an age of 60 to 70 years. Most of these structures suffer from severe deterioration. The owners of the harbours must therefore make a decision on when and whether to repair the existing concrete structures or replace them with new structures. To be able to make these decisions, an inspection of the structure has to be performed. This, in turn, sets demands on the inspection with respect to the selection of sampling (location, quantity and sampling method). In harbour structures extreme variations are frequently found in measured chloride ingress, without obvious explanation.

The most dominating factor of deterioration of reinforced concrete in marine environment is undoubtedly reinforcement corrosion caused by chloride ingress into the concrete. Several empirical and physical prediction models for chloride ingress into concrete have been developed during the years, see for instance [1]. The common denominator for these two types of calculation models is that they have to be calibrated with actual results from reality to be able to be used in calculations for predicting the remaining service life for the concrete in question. In many cases the different parameters in the calculation models are dependent on each other, which complicate the usage of this kind of models even more. To be able to use these models with the purpose of giving a statement about the remaining service-life for a concrete structure, input for the model has to be prepared. The input data in order to calibrate the model could for example consist of climate data for the region in which the structure is located, the age of the structure and data about how far the chloride ingress in the concrete has advanced.

It is, however, a fact that the chloride profiles from samples taken with the same sampling method on real structures in field studies, show extensive variations even though the sampling has been concentrated to a very small area and to apparently homogeneous concrete, see also [2]. Figure 1 shows an example on the variations of 10 chloride profiles. The samples have been taken from the horizontal upper surface of a quay deck along a line shorter than one meter. The level of the upper surface of the quay is about four meters above mean sea water level. No cavities or visible cracks on the deck where observed at the time the sampling was accomplished. No obvious differences in climatic actions along this line are expected. The quay in question is located in a major harbour located at the Swedish west coast.

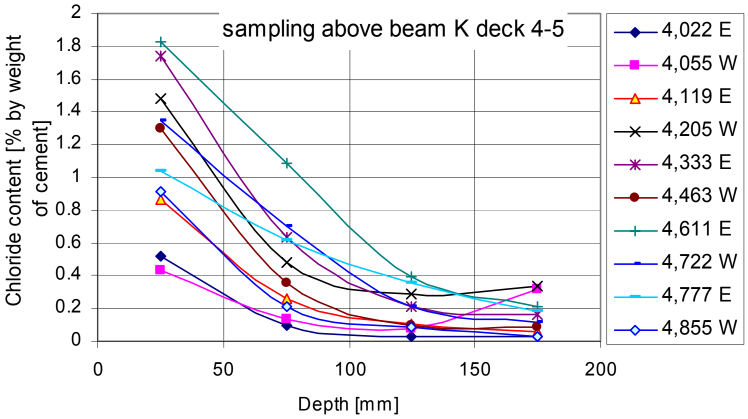

Figure 1: An example of variations of chloride profiles from samples from a small area in homogeneous concrete, after [3]

A major field investigation performed earlier within this research project in the port of Trelleborg in Southern Sweden, shows that the dominating wind direction together with the traffic load from the vessels trafficking the harbour have large influence on the chloride content in concrete super structures. The results from this investigation are partly presented in [4].

The aim of this ongoing research project is to try to explain why the chloride profiles differ even though the specimens are taken in a homogeneous concrete, and within a small area. If an explanation is found, it could be a helpful tool for the selection of inspection methods and for selecting the location and quantity of samples when performing chloride measurements in concrete structures.

1.1 Previous research

The phenomenon that the chloride content in concrete specimens sampled in field shows extensive variations is well known, and has been studied by among others Goltermann (2004) [5] who has performed chloride tests on concrete core samples from columns in Danish road bridges.

The reasons for these variations can be several. One example is for instance micro cracks in the concrete, which are not visible with the naked eye. Another example is that the workmanship in the casting of the concrete when the structure was built was of bad quality, which may have influenced the compaction of the concrete resulting in a poor porosity distribution. A third example is normal variations in the local microclimate.

One of the most important parameters in this matter is, however, what sampling method that is used, and how the sampling itself is performed. Farstad et.al. (1993) [6] performed sampling on several concrete specimens prepared in the laboratory with known chloride content. The chloride content in the concrete was expressed as chloride weight to concrete weight. The purpose of this investigation was to determine the influence of drill diameter on the analyzed chloride content when performing sampling by collecting dust from dry drilling. The aim was to find a drill diameter giving the same accuracy and precision in measured chloride contents as the results from grinding cores. The conclusion of this investigation was that when sampling by dry drilling the diameter of the drill has to exceed the maximum aggregate size.

2. METHOD

2.1 Concrete slabs

With the purpose of investigating the influence of sampling method and the execution of the sampling when sampling on concrete for determining chloride profiles, four concrete slabs, 1.0x1.0x0.1 m^3, have been cast with the same concrete mix at the concrete laboratory of the Lund Institute of Technology, see figure 2. The slabs have been submerged, standing in a 13.5 % NaCl solution at room temperature.

The concrete mix used in the laboratory is similar to the concrete mixes used before 1995 when casting marine concrete structures in Sweden, see table 1. The concrete quality is C40, with an intended cylinder strength of 40 MPa, and the water cement ratio is 0.45. The amount of water in the mix description was reduced to compensate for the moisture content in the aggregate and the water content in the plasticizer before mixing.

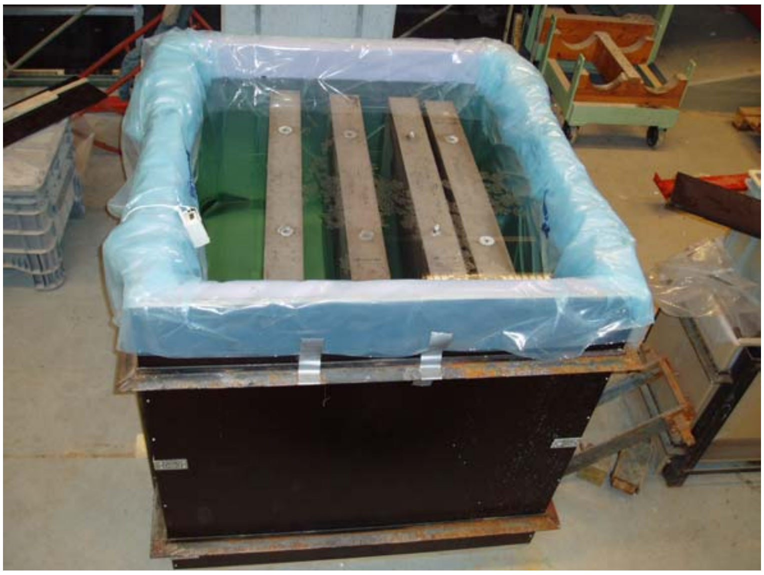

Figure 2: Concrete slabs submerged in saline water in the laboratory

Table 1: Recipe for the concrete mix used in the laboratory experiments

Ingredient	Aggregate size (mm)	Weight (kg/m^3)
Cement	-	422
Water	-	190
Sand	0-8	866
Gravel	8-11	433
Stone	11-16	432
Plasticizer	-	2.7

When casting the concrete slabs the remainder of the concrete was used for casting small concrete specimens in the purpose of determining the compressive cube strength of the concrete. Three concrete cubes with the standard size of 150x150x150 mm^3 were casted for each of the three first made slabs, in total 9 test cubes. The cubes where stored in water for 28 days whereupon the compressive strength was tested. The mean value of the compressive strength of the concrete was 62.0 MPa and the variation was ± 5.2 MPa in the 95% confidence interval, which corresponds to twice the standard.

To be able to inspect the chloride ingress into the concrete without spoiling the full scale slabs, four test slabs with the dimensions length x width x height = 150x150x100 mm^3 were also casted with the remainder of the concrete from the four full scale slabs. Both the full scale slabs and the minor slabs were submerged into the salt solution in July 2004. The depth of the chloride ingress was controlled by grinding in the centre of one of the smaller test slabs in November 2004 and the chloride content was determined by a Rapid Chloride Test, RCT according to [7]. The chloride content of each sample was recalculated to chloride content by weight of cement by using the data on the known cement content in the original mix.

The result from the chloride analysis of the first test cube is shown in figure 3. The graph shows that the chlorides have penetrated about 20-25 mm into the concrete in approximately 4 months.

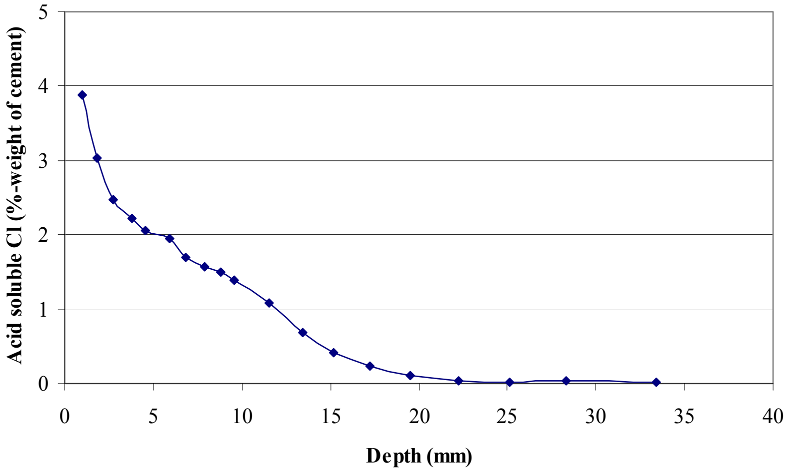

Figure 3: Chloride ingress in the test slab from profile grinding analyzed with the RCT-method

The result from the first test cube indicated that a chloride penetration depth of more than 20 mm was to be expected in the slabs. Therefore it was decided to start sampling from the slabs.

2.2 Sampling program for laboratory specimens

To be able to quantify the effect of the sampling methods used in industry a drill programme has been prepared for the slabs. The sampling has been executed as follows:

1. Sampling by dry drilling with a 20 mm bore with the slab in a vertical position
2. Sampling by dry drilling with a 12 mm bore with the slab in a vertical position
3. Sampling by dry drilling with a 8 mm bore with the slab in a vertical position
4. Sampling by dry drilling with a 20 mm bore with the slab in a horizontal position
5. Core drilling with a core diameter of 100 mm with the slab in a horizontal position. Sampling of dust from profile grinding.

In order to simulate reality, the dry drilling was performed by the staff from a laboratory of The Swedish Road Administration, who often performs this kind of investigations on road bridges in Sweden. All sampling was made from the same slab surface, the upper trowelled surface during casting. The location of the different sampling points on the slab is shown in figure 4.

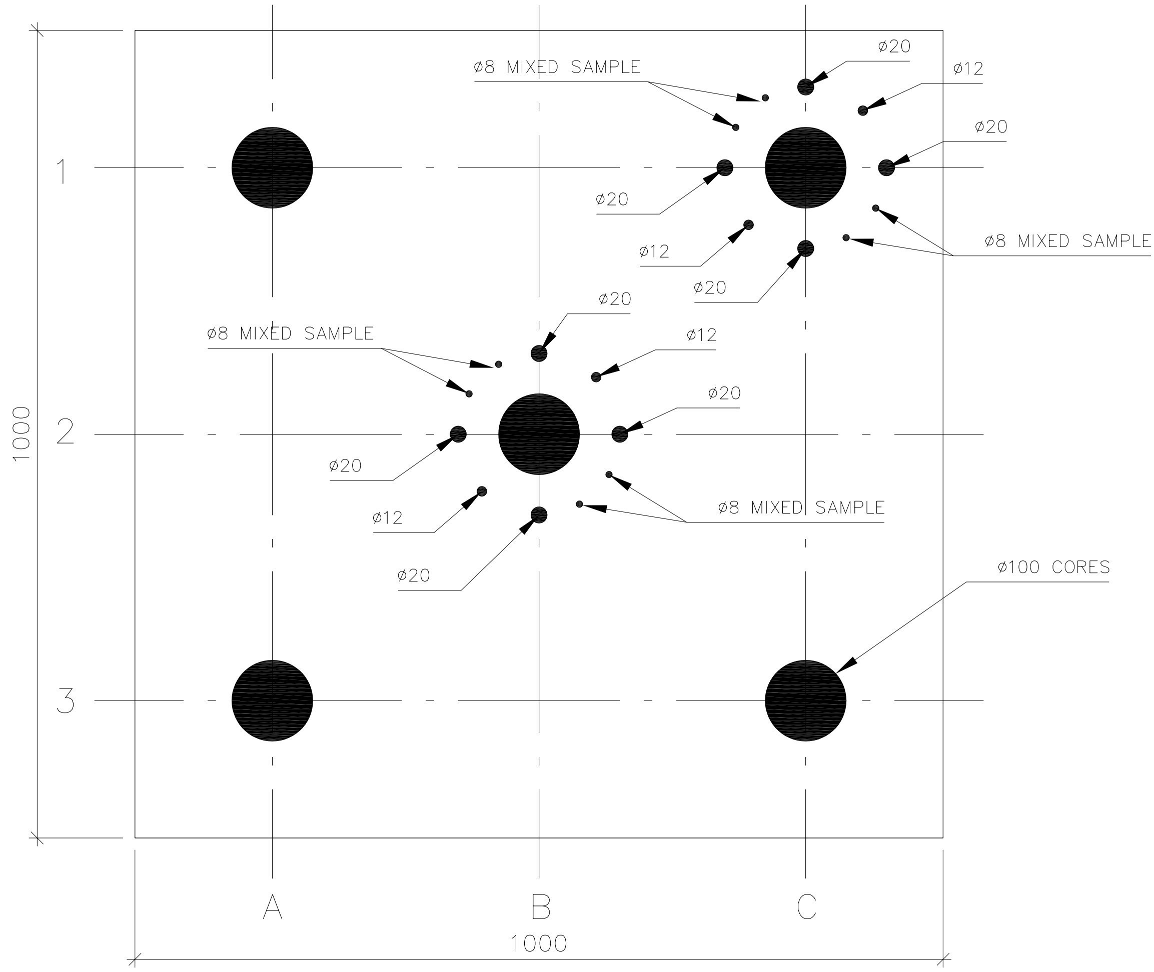

Figure 4: Sampling points on the concrete slab in laboratory. All numbers in mm.

After collecting the samples, the cores and the dust have been sent to Chalmers laboratory of building materials in Gothenburg for profile grinding and analysis. The chemical analysis included the total chloride content and calcium oxide content of each dust sample, from the drilling and the profile grinding. The results from the laboratory are expressed as % by weight, the cement content as % by weight of each sample and the chloride content of each sample expressed as % by weight of cement, calculated from the known CaO-content of the cement. This was possible since the aggregate contained no $CaCO_3$ at all.

3. REFERENCE DATA FROM CORE GRINDING

In order to compare the different sampling methods (core drilling and dry dust drilling) the results from the analysed dust from grinding cores have been used as a reference to the other results. The names of the curves in the following diagrams refer to the sampling grid in figure 4. Figures 5 to 7 show the results from the profile grinding of the five 100 mm cores shown in figure 4. The straight horizontal line in figure 5, named Original C, shows the known cement content in the mix, which is 18.9 % by weight of concrete.

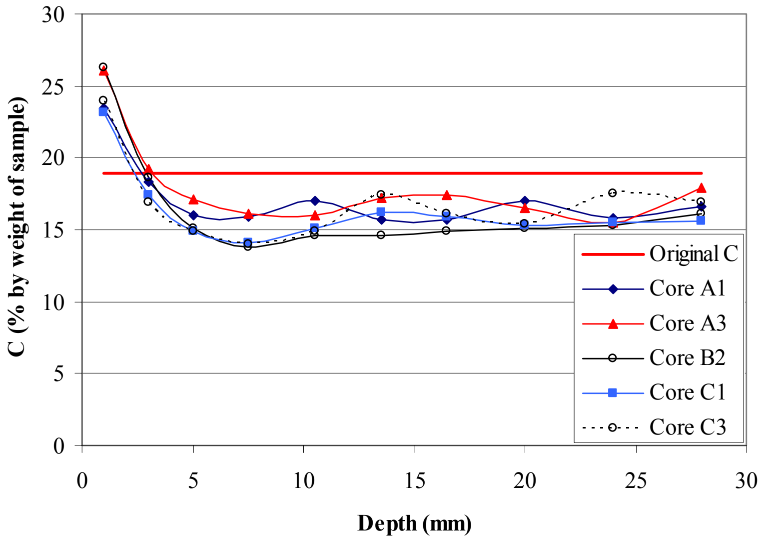

Figure 5: Profiles of cement content in the profile grinded cores.

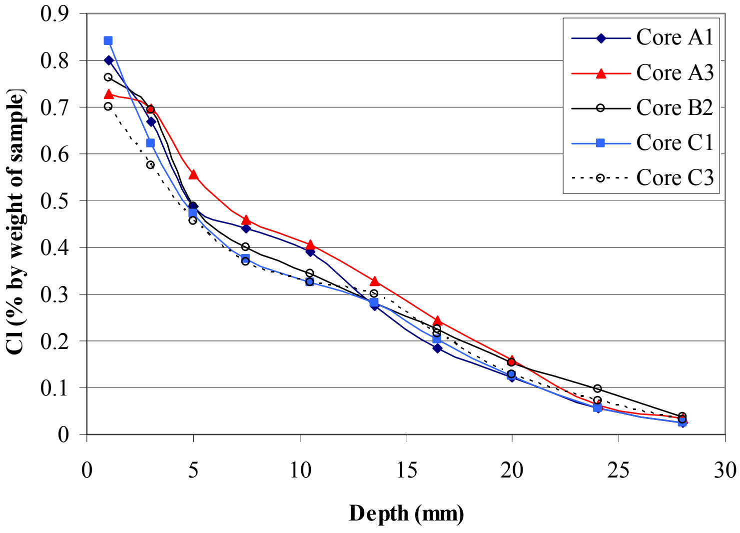

Figure 6: Chloride content in analysed cores expressed in % by weight of sample.

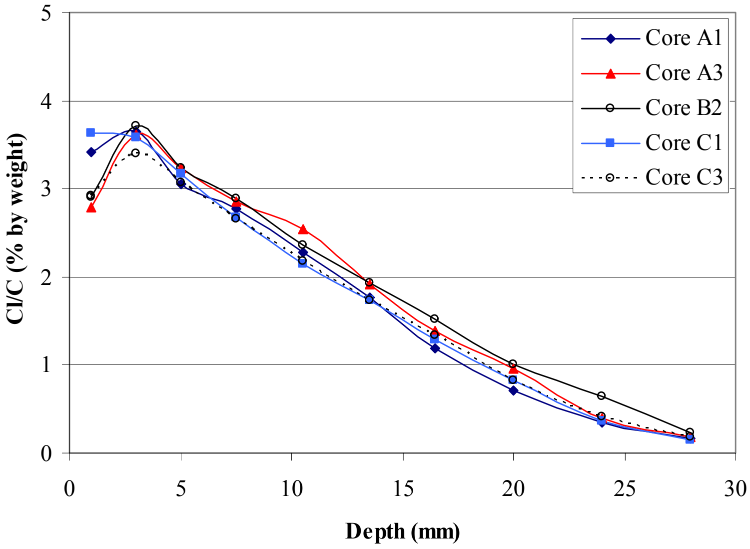

Figure 7: Chloride content in analysed cores expressed in % by weight of cement content.

As seen from picture 5 to 7, the variation between the cores is quite small and indicates that this sampling method is possibly as accurate as it can be when performing destructive sampling on existing concrete structures. The mean value of the chloride content in the cores has been used to compare with the results from the dust samples taken with 8, 12 and 20 mm bores respectively.

The cement content profiles show the "normal" appearance, with a significantly higher cement content closer to the surface, due to the "wall-effect". The cement content is higher because there is no space for the largest aggregate particles. For the same reason there is a minimum cement content at a depth equal to half the maximum size of stones.

No quantitative explanation has been found to why the measured cement content shown in figure 5 deviates as much as it does from the real cement content in the mix. When studying the holes from the core drilling it is seen that the upper most 30 mm of the slab contains much more large aggregate than expected. Consequently, the cement content could be lower than the average because of that.

The chloride profiles expressed as % by weight of sample show a clear effect of the cement content profiles. The shape at depths between 3 and 11 mm follows from the minimum in cement content in that depth interval. When expressed as % by weight of cement, cf. figure 7, this shape is no longer present.

4. RESULTS - PROFILE GRINDING VS. DUST SAMPLING

The sampling of dust has been performed in 10 mm intervals down to 50 mm below the upper surface of the slab. The chloride content and the cement content is presented as the mean value in every interval, that is at 5, 15 and 25 mm depth. The samples from 35 and 45 mm had a chloride content close to zero and are not shown. The curve named "reference" in the figures below refers to the mean value of the analysed cores in figure 5 to 7.

4.1 Results from dry drilling with 8 mm bore - mixed samples

Figure 8 to 10 show the results from dry dust sampling with an 8 mm bore. Because of the limited amount of dust available when using this small size bore, mixed samples from two boreholes in every sampling point had to be taken.

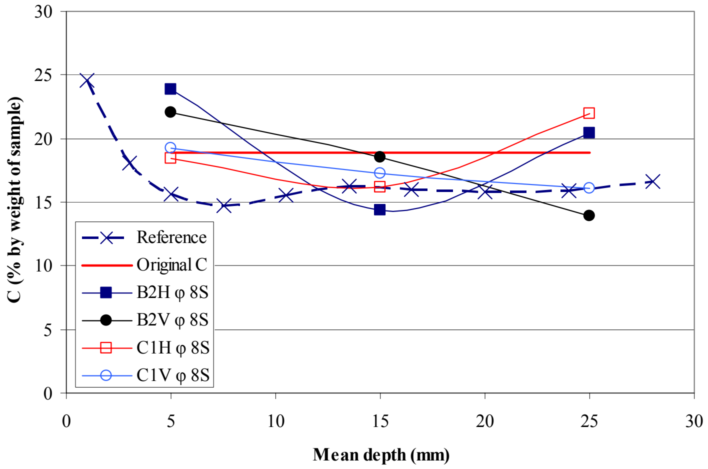

Figure 8: Cement content in % by weight of sample, dry drilling with 8 mm bore. Each point represents two mixed samples

From figure 8 it is seen that the cement content in the samples shows extensive variations both compared to the reference curve and when comparing the different dust samples. When using 8 mm no obvious pattern in the deviations between the samples is seen. The average cement content, however, seems to be higher than in the cores, indicating a certain "preference" of the bore to enter between aggregate particles.

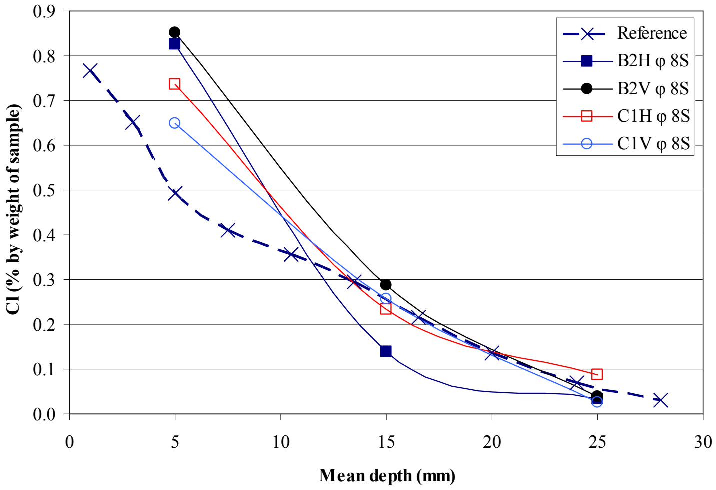

Figure 9: Chloride content in % by weight of sample, dry drilling with 8 mm bore. Each point represents two mixed samples

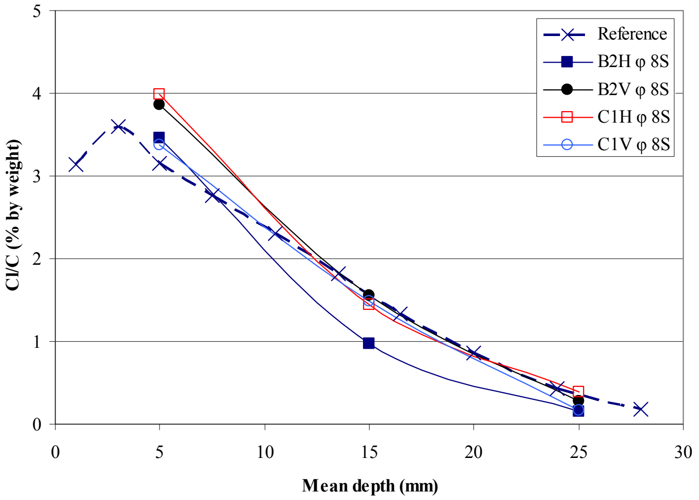

Figure 10: Chloride content in % by weight of cement, dry drilling with 8 mm bore. Each point represents two mixed samples

In figure 9 there is a clear difference between the measured chloride contents in the cores and the dust. The measured chloride content in the dust samples is quite higher than the chloride content in the cores from the concrete surface down to approximately 15 mm into the slabs. From the depth of 15 mm down to 45 mm the results from core grinding and dust sampling are quite similar. Most of this difference can be explained by the difference in cement content of the samples, cf. figure 10.

When comparing the curves in figure 9 and 10 it is clearly seen why it is important to relate the chloride content to the cement content in the analysed sample, instead of comparing the chlorides directly to the concrete weight. Using the curves in figure 9 when for example determining the remaining service-life of an existing structure, gives results on the safe side. In this case there is a great risk of misjudging the remaining capacity of the examined structure. The curves in figure 10 show less scatter when presenting the chloride content in % by weight of cement. The values from the dust sampling are somewhat higher at the 5 mm level than those from the core grinding, but should still be considered accurate to use.

4.2 Results from dry drilling with 12 mm bore

The cement content profiles in figure 11, showing the results from 12 mm bores, have a similar pattern as in figure 8, with an even larger scatter. Here, the points represent only one sample, with the smallest amount of dust. An interesting point noted from the results in figures 12 to 13 is the results at the depth of about 15 mm behind the surface of the analysed concrete. The maximum aggregate size in this composition is 16 mm and it could be a possibility that a shadowing aggregate particle just close to the concrete surface influences the chloride front, giving a lower chloride content. A large stone at a depth of around 20 mm would give the opposite effect, with a higher chloride content in sample taken there.

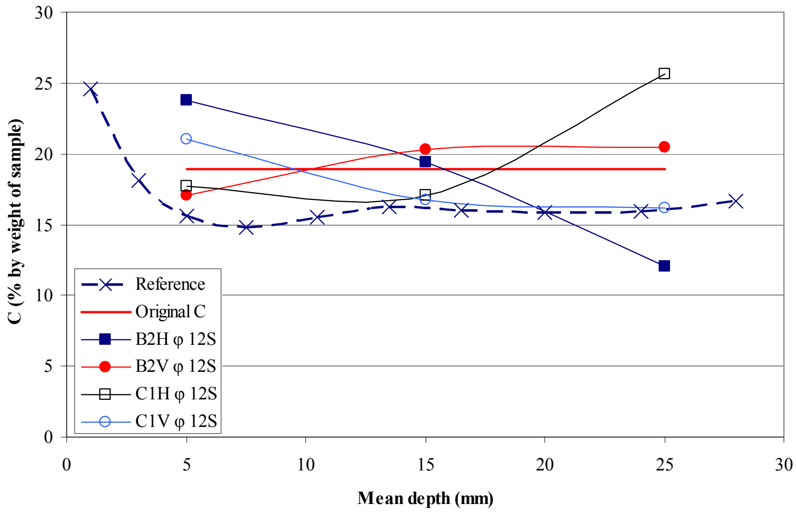

Figure 11: Cement content in % by weight of sample, dry drilling with 12 mm bore

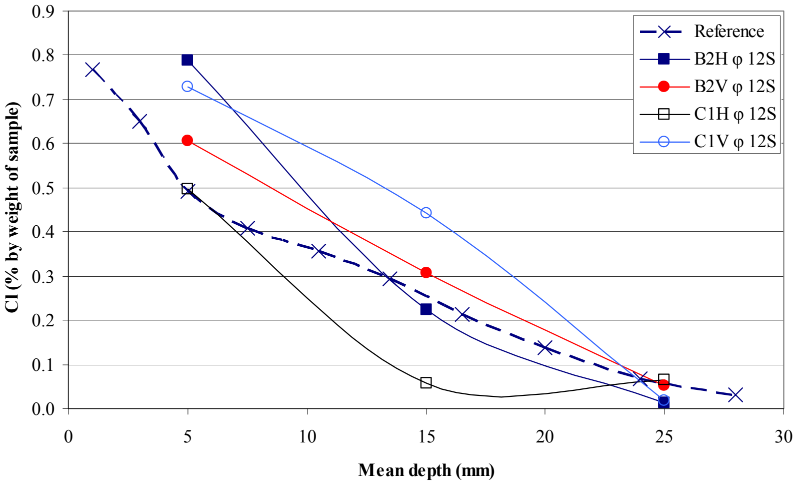

Figure 12: Chloride content in % by weight of sample, dry drilling with 12 mm bore

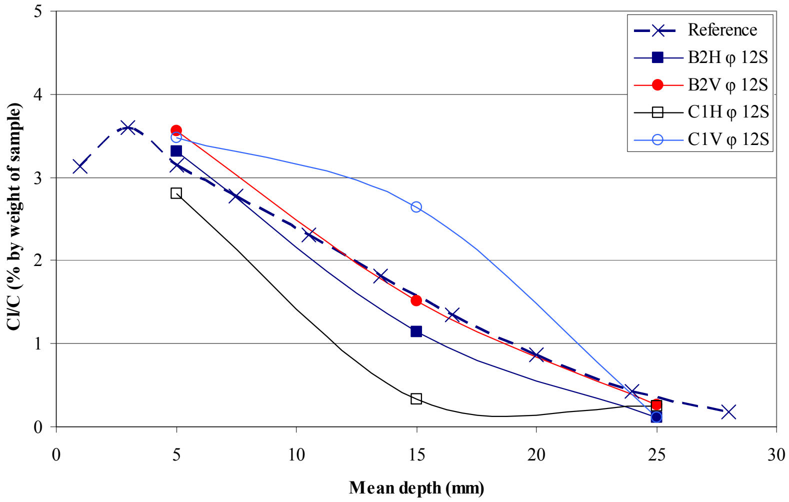

Figure 13: Chloride content in % by weight of cement, dry drilling with 12 mm bore

The pattern seen in figure 9 and 10 is also shown in figure 12 and 13. The chloride content when presented as % by weight of concrete is much higher than the reference curve at small depths. When the chloride content from the dry drilling is presented as % by weight of cement the difference compared to the reference curve decreases.

The variations in chloride content between the different samples seen in figure 10 to 12, clearly shows that the precision is very low when sampling dust with small-bore diameters. The dust sampled with 8 mm bores actually shows less variation in chloride and cement content than the dust sampled with 12 mm bore. An explanation to this finding is probably that the dust sampled with 8 mm bore is a mixed sample, which was not the case when the 12 mm bore was used. This indicates that when performing dust sampling with small bore diameters, mixed samples gives more accurate results than sampling dust from a single hole.

4.3 Results from dry drilling with 20 mm bore

Figures 14 to 16 show the results from dust sampling with a 20 mm bore. The capital letters L and S at the end of the notation on the sampling curves means that the sampling has been performed with the slab in horizontal and vertical position respectively. No significant difference in chloride content or cement content due to sampling from a horizontal versus a vertical surface could be detected from these analyses. Also with a 20 mm bore, giving more than three times as much dust in each sample, there is a significant scatter in cement contents of each sample. At the first depth interval there is also a significantly higher cement content than in the cores. The curves in figure 15, that is the chloride content presented in % by weight of concrete, is quite higher than the reference curve, which is also the case when using smaller bore diameters as shown in the figures above. Here, however, all of that effect can be explained by the systematically higher cement content in the samples.

The curves in figure 16, showing the chloride content in %-weight of cement content, are quite close to the reference curves from the core grinding. The mean value of the results from dust sampling gives slightly higher chloride content values than the reference, but it is very well comparable to profile grinding of large cores when using the result for determining the present state of a structure exposed to a saline environment.

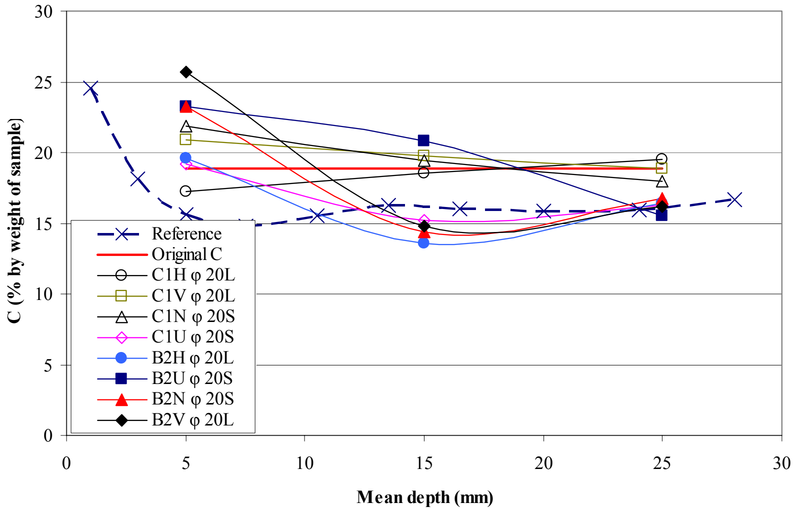

Figure 14: Cement content in % by weight of sample, dry drilling with 20 mm bore

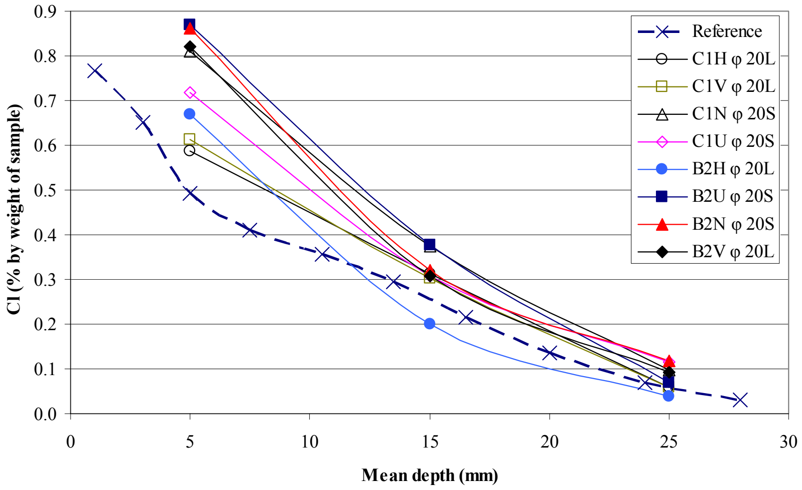

Figure 15: Chloride content in % by weight of sample, dry drilling with 20 mm bore

The samples taken as dust with 20 mm bore seem to contain more cement and less signs of aggregates compared to profile grinding which is seen in figure 14. When studying the curves in figure 16 it is, however, clear that dust sampling with a 20 mm bore gives almost as accurate results as profile grinding, when the chloride content is expressed in % by weight of cement.

One must also remember that when sampling dust, the results are actually a mean value of the cement and chloride content in selected intervals. When performing dry drilling there is also a risk of “moving” chloride contaminated material further into the hole from smaller to larger depths during sampling. It is therefore important to clean the hole between every sampling step.

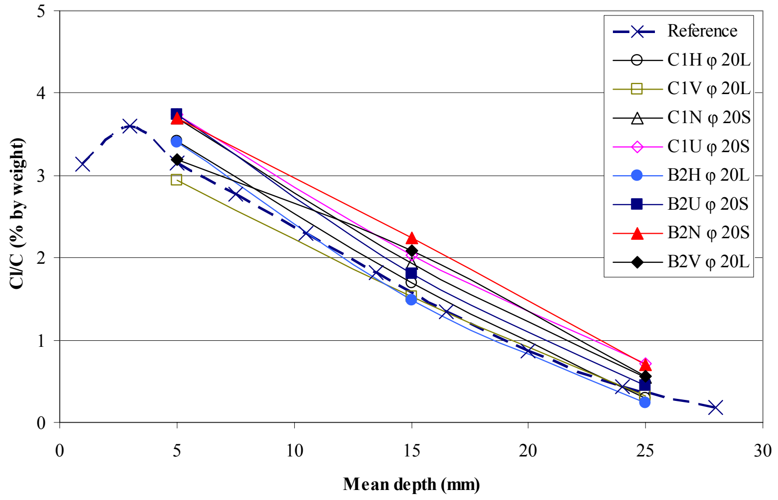

Figure 16: Chloride content in % by weight of cement, dry drilling with 20 mm bore

5. DISCUSSION AND CONCLUSIONS

When determining the chloride content in cores by grinding, the representative surface of the sample is almost as large as the core area, which in turn means that the deviations between different samples should be at a minimum if the core diameter is large enough. In this study only one core diameter was used when sampling, but it is reasonable to assume that smaller core diameters gives larger deviations between samples when analysing the cores in order to determine the chloride content. Collecting concrete sampling by dry drilling with a hand held drilling machine is a quicker and a less expensive method compared to core drilling, which demands heavy equipment. It is, however, not possible to perform core drilling on every site due to limited space and resources, why a simpler sampling method like dry drilling and sampling dust is the only alternative to get concrete specimens for analysis. It would therefore be preferable to find a method for performing dry drilling, which gives nearly as accurate results according to chloride content as core grinding.

In this study the 20 mm bore gives almost the same result as profile grinding, when the chloride content is presented as % by weight of cement. The results from the 8 mm mixed samples are closer to the reference cores than the individual results from the 12 mm bore, but both of them deviate significantly from the reference. Consequently, sampling dust by a 20 mm bore, in 10 mm intervals, is the preferred sampling method after profile grinding of cores.

No significant differences in the chloride content or cement content in the samples caused by sampling from a horizontal or a vertical surface respectively has been found. This study also indicates that mixed samples gives less variation in the analysed chloride content when performing dust sampling by dry drilling with small bore diameters.

Farstad et. al (1993) showed in their experiments that when performing dry drilling and collecting dust, the diameter of the bore has to be larger than the maximum aggregate size in order to get the same or almost the same results in chloride contents as when sampling cores. They related the chloride content to concrete weight, which is shown in this study to give results on the safe side.

The results presented in this article clearly show the importance of referring the chloride content to the cement content in the sample and not to the weight of the concrete. When referring the chloride content to concrete weight it is seen from all the experiments performed in this study that the chloride content is quite higher at the surface of the concrete down to approximately 20 mm when compared to the reference curve from the collected cores. This means that if the results from the dry drilling sampling expressed as chloride content in % by weight of concrete are used to predict the remaining service-life of an existing structure, it gives a result on the safe side.

ACKNOWLEDGEMENTS

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A STUDY ON SAMPLING METHODS FOR CHLORIDE PROFILES – SIMULATIONS USING DATA FROM EPMA

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ABSTRACT

Investigating marine concrete by determining the chloride profile is a common way for making a prediction of the remaining service life of a structure. The most common methods of sampling concrete for this purpose is dust sampling by dry drilling or sampling cores which are analyzed by profile grinding in a laboratory. Now, a similar study has been performed, by simulating different sampling techniques in data from EPMA. The results from the simulations of the concrete specimen analyzed with the EPMA, confirm the results from earlier performed dry drilling tests in laboratory and shows the same extensive variations when chloride content is presented as % by weight of concrete instead of as % by weight of calcium oxide. Comparing the results from the earlier performed sampling by dry drilling with the results from the EPMA simulations, it is seen that the dry drilling probably is afflicted with a systematic error by "movement" of dust into the sampling holes when drilling. This study also shows effects of large aggregates in small bores even though the cement content is referred to. However, no signs of "shadowing" by the aggregates was detected when the simulations where performed. Even "horizontal" drilling was simulated in order to be able to detect this possible effect of the aggregates on the chloride ingress into the concrete.

RÉSUMÉ

Examinant le béton marin en déterminant le profil de chlorure est une façon commune pour faire une prédiction de la durée d'utilisation restante d'une structure. Les méthodes les plus communes d'essaie le béton est à cet effet la poussière essaie par entraîner sec ou essaie des noyaux qui est analyse par meuler de profil dans un laboratoire. Maintenant, une étude similaire a été exécutée, en simulant différent essayer des techniques dans les données de EPMA. Les résultats des simulations du spécimen concret analysé avec le EPMA, confirment les résultats d'entraîner les tests secs plus tôt exécutés dans le laboratoire et montrent des variations vastes pareilles quand le contenu de chlorure est présenté comme % par le poids de béton au lieu de comme % par le poids d'oxyde de calcium. Comparer les résultats du plus tôt exécuté essaient par entraîner sec avec les résultats des simulations de EPMA, il est vu que l'entraîner sec est probablement affligé avec une erreur systématique par le « mouvement » de poussière dans l'essaie des trous en entraînant. Cette étude montre aussi des effets de grands totaux dans les petits raseurs bien que le contenu de ciment est référé à. Cependant, aucuns signes de « shadowing » par les totaux ont été détectés quand les simulations où exécuté. Entraîner même « horizontal » a été simulé afin d'être capable de détecter cet effet possible des totaux sur l'entrée de chlorure dans le béton.

1. INTRODUCTION

Reinforced concrete is by far one of the most common building materials in marine structures, and has been so during the last century. Since many of the existing structures have reached an age which exceeds the original structural design life time, it is important for the owners of these structures to determine their condition according to deterioration to be able to plan future investments.

In Sweden, structures such as harbours and harbour equipment, are often own by the communities. The costs for the maintenance of these structures tend to be quite high, since several of them are beyond the limit for repair. The most dominating factor for deterioration of reinforced concrete in the Swedish marine environment is by far reinforcement corrosion caused by chloride ingress into the concrete. The problem with this kind of deterioration process is the "invisible" corrosion process under the concrete cover, which is not seen until it is too late. If the corrosion process has gone so far that one can see rust stains with the naked eye at the concrete surface, it is often too late to perform any repairs that are guaranteed to last. It is therefore of great importance to investigate existing marine concrete structures in order to determine their present state with respect to deterioration. To be able to follow the process of the chloride ingress, and to be able to plan the future reparation works with the costs that are bound to them, the owner of these kind of marine harbour structures should prepare an investigation program even for new structures.

The most common sampling methods for concrete with the purpose of evaluating the chloride ingress, are dust sampling by a hand held drilling machine or core sampling. When performing sampling by dry drilling, the bore diameter has to be quite large in order to get representative samples, see for instance [1] and [2]. This sampling method is quite simple to perform and does not require any heavy equipment, which has made it popular among people performing concrete sampling in industry. The risk of errors is, however, quite high using this method. Systematical errors when measuring the depth when drilling in intervals, seems very likely to appear particularly when drilling in small intervals. Another error is that dust from shallow intervals is transported into the concrete when drilling, giving results on "the safe side" when evaluating the chloride ingress. Cleaning of the sampling hole between the different drilling intervals is also a source of possible errors when evaluating the collected dust.

The purpose of this study has been to improve the understanding of the extensive variations in chloride content that often appears when performing concrete sampling on marine concrete structures, which is also discussed in [3]. In an earlier study, described in [1], extensive variations in chloride profiling were investigated experimentally by comparing dust sampling from drilling holes with different sizes. The effect of how the sampling is executed has been shown to be of great importance and the study clearly showed that when performing dust sampling with small bore diameters, mixed samples should be used in order to minimize the variations in the results referring to the chloride content in the sample. Goltermann [4] also made the same observations regarding the variations in chloride content on samples collected from Danish road bridges exposed to deicing salts. In 2003 an investigation of a quay deck in a harbour on the Swedish west coast was performed. Samples for chloride profiling by collecting dust where performed on a very small area, and the results shows extensive variations in chloride content between the different samples. No obvious explanation was found to these variations. The results from this investigation are presented in [5].

Earlier studies presented in [6] and in [7] have also shown that the wind direction and the access to open sea have great importance for the chloride ingress into the concrete super structures in harbours. This is also a factor of great importance when selecting sampling points for determining the chloride content in the structure despite which sampling method chosen.

Now, EPMA-analysis has been used to simulate sampling by drilling with some of these factors excluded.

2. MATERIALS

The specimens analyzed in this study was sawn from a concrete slab with dimensions 1 x 1 x 0.1 m. At the time of sampling, the slab had been submerged in a strong saline solution for almost two years. Both the form side and the cast side of the slab had been exposed to the saline water. The concrete mix used for this study was composed in order to simulate concrete used in Swedish harbours before 1995. The cement used in the mix is ordinary Portland cement, OPC, with 12 % lime-stone filler. The maximum aggregate size used in the concrete mix is 16 mm. The aggregates in the concrete is nearly 100 % quartz. The recipe for the mix is shown in table 1.

Table 1. Concrete mix for the slabs

Ingredient	Aggregate size mm	Weight kg/m^3
Cement	-	422
Water	-	190
Sand	0-8	866
Gravel	8-11	433
Stone	11-16	432
Plasticizer	-	2.7

The sample used for the EPMA analysis was collected in a way to avoid the influence of three dimensional chloride ingress near the edges of the slab. The cut out sample was taken from the inner part of the slab. The sample was then divided in to two parts with the height of 50 mm each which is half the slab thickness. The part of the sample with the cast side exposed to the saline water was sent to Taiheiyo Cement Corp. in Japan for the EPMA analysis.

3. EPMA

The EPMA, the Electron Probe Micro Analyzer, uses a focused beam of high energy electrons to non destructively ionize a solid specimen surface for inducing emission of characteristic X-rays [8]. The analyze method is two-dimensional, and when analyzing concrete specimens, it is the plane surface of the concrete that is analyzed.

The EPMA can analyze several different elements in one sample at one time. This means that one can analyze for instance chloride, calcium, sodium, potassium and silica directly from one sample. The size of the analyzed sample was a slice with the dimensions length x height x thickness = 75 x 50 x 10 mm. The EPMA scans the surface and presents the analyzed elements as values in pixels with the size of 0.1 x 0.1 mm. This means that every data file from the 50*75 mm sample is a matrix with 500 rows and 750 columns presenting the analyzed element as % by weight of sample. An example of the results from the EPMA for CaO is shown in figure 1. The exposed surface on the sample is the one on top at depth zero in the figure.

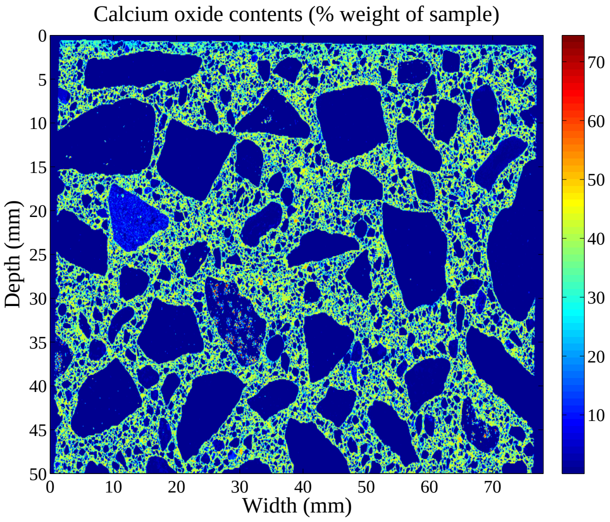

Fig. 1 - Calcium oxide content in the concrete specimen analyzed with the EPMA

4. SIMULATING DRILLING AND CORING WITH EPMA DATA

Figure 2 shows a plot of the chloride content expressed as % by weight of concrete in the sample analyzed with the EPMA. The figure shows that the chlorides are bound to the cement paste in the specimen and not to the aggregates. The fact that Swedish aggregates do not normally contain calcium oxide and that the aggregates do not contain chlorides, is an advantage when analyzing specimens for chloride contents. Consequently, the calcium oxide contents is a measure of the cement content.

Using a computational program in the evaluations of the results from the EPMA, it was possible to simulate "dry drilling" within the size of the specimen analyzed with the EPMA. The results can, when interpreted to the computer program, be used over and over again to test anomalies in the sample and their effects on the analyzed chloride content in the sample. Values on chloride and calcium oxide content are given in one matrix for each element analyzed. The matrices are then used for presenting, for example, the chloride content expressed in % by weight in calcium oxide, by dividing the values in the chloride matrix with the values from the calcium oxide matrix.

The "boxes" in the figure represents the depth interval and width ("bore diameter") used when performing sampling. The dot in each box marks the location in depth of the average content of every dry drilling interval representing the sample.

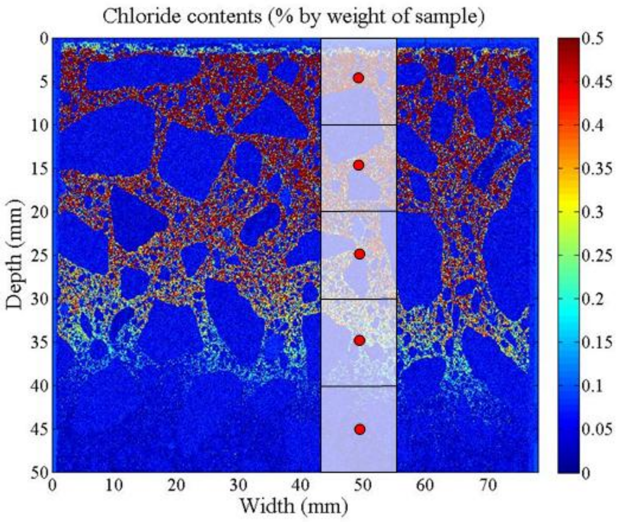

Fig. 2 - Plot showing the chloride content in % by weight of concrete in the sample analyzed with the EPMA. The upper surface is the exposed surface.

The results from the EPMA analysis have been used for simulating dry drilling and dust sampling with different "bore diameters". The "bores" are represented by two-dimensional strips at different locations along the EPMA sample, cf. the five "boxes" in figure 2, in order to study the variations in the results which are compared to those from the dust sampling performed in an earlier study.

Three different strip widths have been used in the simulations, 8, 12 and 20 mm, representing two-dimensional bore holes with the same diameter. The x-coordinate is given by the horizontal axis at the bottom of figure 2 and goes sideways from the left at zero to the right as shown in the figure. To simulate coring, a 70 mm strip has been used.

5. RESULTS

Figure 3, 4, 5 and 6 show the results from the data simulations of dry drilling with the different widths of the strips described above, representing two-dimensional bores. The simulated dust sampling depth interval is 10 mm which is also indicated in figure 2. The legends in the graphs below refer to the x-coordinate of the centre of the simulated bore hole. The graphs in figure 3, 4, 5 and 6 shows the chloride content both in % by weight of concrete and expressed as % by weight of calcium oxide.

Presenting the chloride content as % by weight of concrete gives large variations between the different samples despite which strip diameter used. This yields for all of the used strip widths representing bores. The variations decrease somewhat when using a 20 mm strip width compared to the 8 and 12 mm strips. However, the mean value curve for the chloride content presented as % by weight of concrete, seems to be almost the same for all of the three strip widths. The mean value curves are also very similar to the simulated strip in figure 3, representing the whole EPMA sample. Presenting the chloride content in % by weight of calcium oxide, gives much smaller variations for all the used strip widths.

The result from the EPMA analysis has also been used to find out if the large aggregates decrease the chloride ingress locally behind the large particles. Theoretically there is a possibility of accumulation of chlorides in front of the aggregates while lower values of chloride content behind the aggregates would be expected compared to if the chlorides only would have penetrated pure cement paste to the same depth. This phenomenon was studied by “sampling” horizontally but could, however, not be observed in the sample analyzed in this study. By the visual appearance of the out data in figure 2 it seems that the chloride front is distributed uniformly over the analyzed concrete surface, and simulations with strips through the location of the aggregates showed the same results.

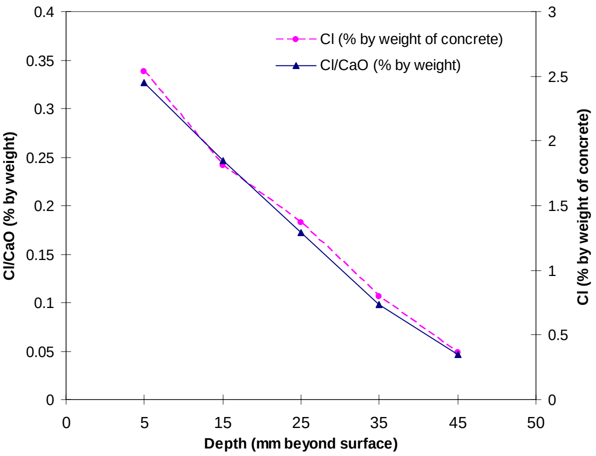

Figure 3: Chloride profile from simulations with a 70 mm strip, expressed in two different ways.

6. DISCUSSION AND CONCLUSION

Finding a sampling method that decreases, or preferable, eliminates the extensive variations in chloride content, which is often shown when performing sampling of concrete on existing structures, is the first key to get a useful tool for determining the present state of a structure. Eliminating the variations in the analyzed samples makes it possible to use the results for better life time predictions of the investigated structure. The condition is, of course, that the threshold value for reinforcement corrosion is known.

The simulations show the same results as in [1], that the variation in presented chloride content is extensive when the chloride content is measured as % by weight of concrete, even when using as large strips as 20 mm. It is also seen in the diagrams that when using small bores as 8 and 12 mm, the variations is higher than when using larger bores as 20 mm. When the chloride content is measured as % by weight of calcium oxide, the variations between the results decrease and the simulations show almost the same results with all the three strip widths. The conclusion of this observation is that when measuring the chloride content as % by weight of calcium oxide, the variations between the different samples are much smaller compared to when measured as % by weight of sample. The simulations of dry drilling in two dimensions using the results from the EPMA, make it possible to study the influence of the location of the aggregates in the sample on the achieved chloride profiles and the variations in chloride content discussed above. Independent of the width of the strip used in the simulations the results show a ”knee” at the coordinates X = 55 to X = 61 and Y = 25, when the chloride content is presented as chloride in % by weight of CaO.

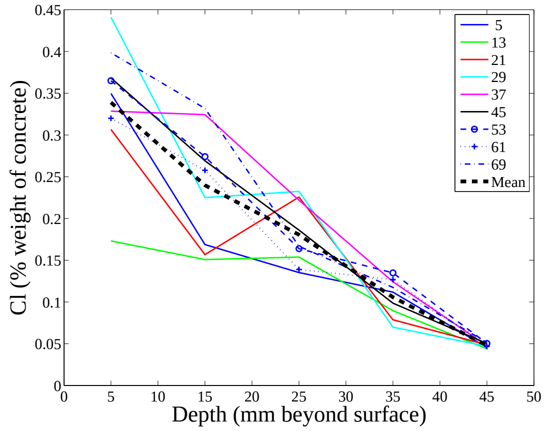

Figure 4a: Chloride profiles from simulations with 8 mm strips, chloride in % by weight of concrete

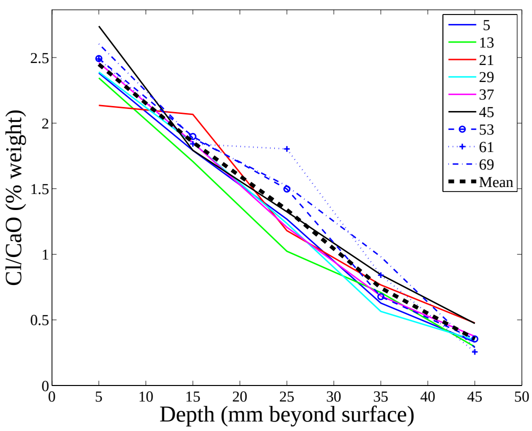

Figure 4b: Chloride profiles from simulations with 8 mm strips, chloride in % by weight of calcium oxide

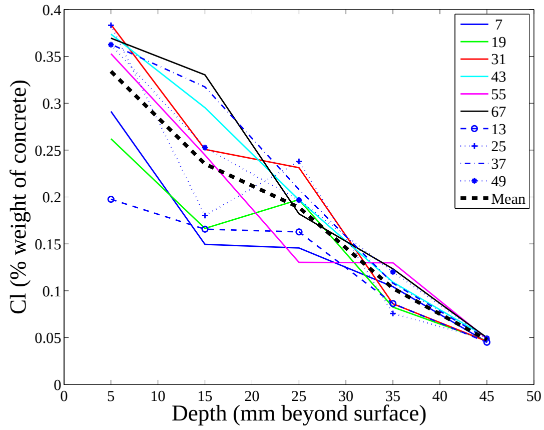

Figure 5a: Chloride profiles from simulations with 12 mm strips, chloride in % by weight of concrete

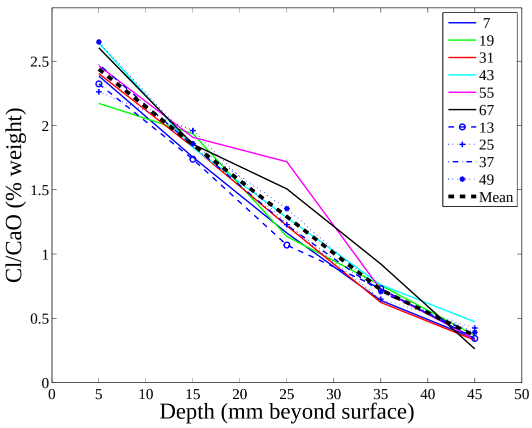

Figure 5b: Chloride profiles from simulations with 12 mm strips, chloride in % by weight of calcium oxide

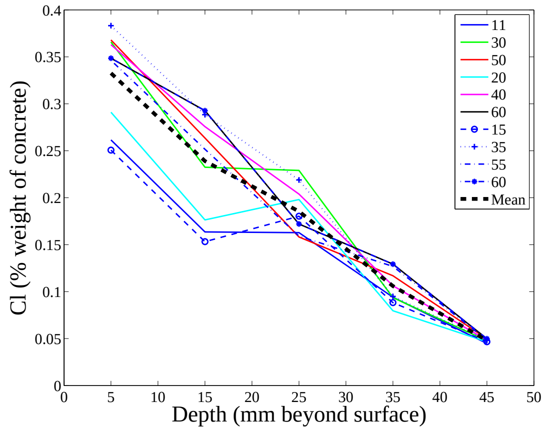

Figure 6a: Chloride profiles from simulations with 20 mm strips, chloride in % by weight of concrete

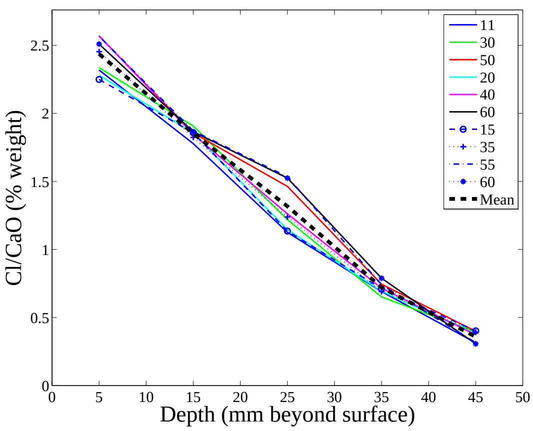

Figure 6b: Chloride profiles from simulations with 20 mm strips, chloride in % by weight of calcium oxide

The reason for this is the aggregate that is located with its centre in (X,Y) = (58,25), cf. figure 2. The sampling depth interval is 10 mm which means that the sample in the interval 20 to 30 mm contains almost no calcium oxide, only silica. Dividing a small amount of chlorides with an infinite amount of calcium oxide gives very high value on the quotient Cl/CaO. This effect could possibly explain the results by de Rooij & Polder [3]. They found large variations even though they measured the results as Cl/C. The cores that where collected in their study had almost the same size as the largest aggregate, about 50 mm in diameter.

Another advantage using the EPMA is the elimination of systematic errors compared to the dry drilling. In this study, the mean value curves for the chlorides in the simulated dust samples coincide with the simulated core which is seen in figure 7. Looking at the results from the dry drilling in the laboratory [1] shown in figure 8, it is seen that the mean value curves for the analyzed dust samples lies above the mean value curve for the analyzed cores. This is a sign of a typical systematic error of transporting chloride contaminated dust into the bore hole when drilling in intervals giving higher chloride values.

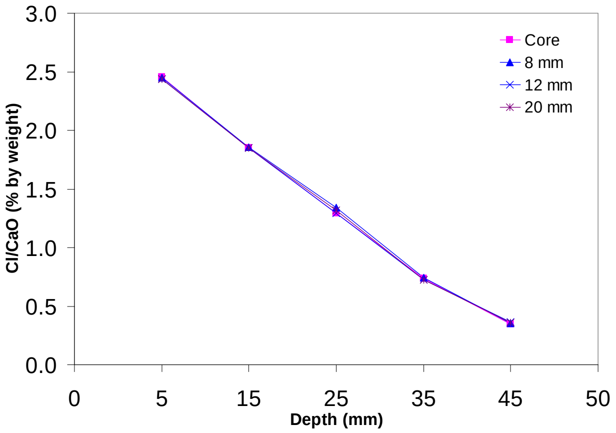

Figure 7: Chloride profiles from simulations with EPMA, chloride in % by weight of calcium oxide.

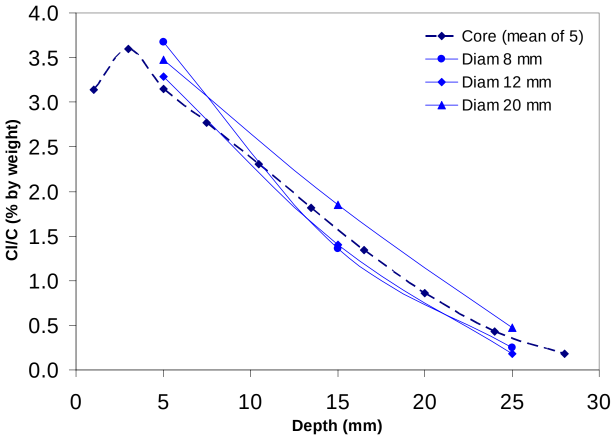

Figure 8: Chloride profiles from sampling in laboratory, chloride in % by weight of cement.

Even though the results in this study confirm earlier observations, it should be pointed out that the “sample volume” in the two-dimensional EPMA analysis, is very small or almost infinite compared to if cores are taken.

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