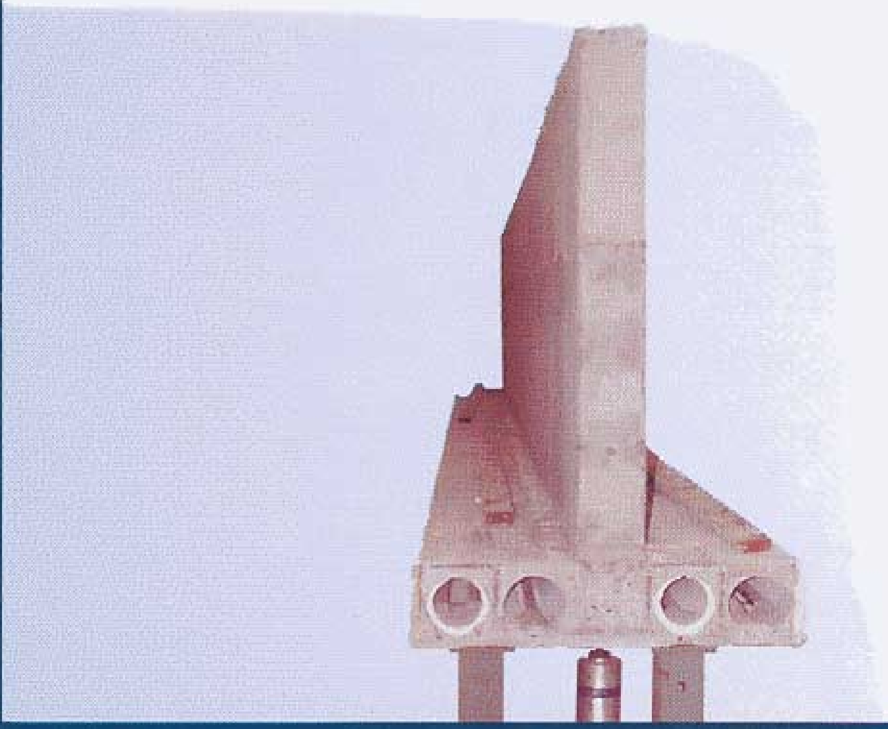
HETEK

Chloride Penetration into Concrete
Manual



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Uncontrolled terms: Threshold value

Abstract:

This report is part of a series of reports generated in the research project HETEK headed by the Danish Road Directorate. The present sub task is concerning chloride transport into concrete and this report should be regarded as the main report of this sub-task and a guide for design, execution and maintenance concrete structures exposed to chloride.

The aim of the guide is to give the reader a systematically basis for the design, execution, survey and maintenance of concrete bridge structures exposed to de-icing salts and/or marine environment in the climatic zone around Denmark and the South of Sweden.

The guide presents a complete system comprising mathematical models, expectation values, acceptance criteria and rules of thumb to ease the design and construction of durable concrete in saline environments. The guide does not give the full design or construction basis, only those parts that are directly connected to the durability of concrete towards chloride ingress.

In the end the guide presents an overview of the results of this entire HETEK sub task.

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1 Preface

HETEK is covering 8 topics. The present project is dealing with chloride penetration into concrete. The sub task is performed by the consortium ACCE consisting of AEC, Chalmers and Cementa.

1.1 Background

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

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

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

From this sub task a number of reports were published. The state-of-the-art report on Chloride penetration was first completed. The first research report describes the experimental study on the effect of *w/c* ratio on chloride penetration, cf. Frederiksen et al. [1996]. The second report describes the road environment from field investigations of chloride and moisture conditions in a number of road bridges, cf. Andersen [1996]. The third report summarises the theoretical background to the final result of the project: A system for estimation of the service-life of concrete structures exposed to chloride from sea water or de-icing salt.

1.1.1 About HETEK-1

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

1.1.2 About the research consortium

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

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

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

Cementa AB is a cement producer in Sweden. The activities of Cementa regarding concrete research are as follows: High Performance Concrete, i.e. high strength, low water content and low permeability. Concrete and environment, i.e. problems regarding moisture in concrete and emissions from concrete. Durable Concrete, i.e. long time experiments regarding chloride ingress, permeability, strength evolution and carbonation. No Slump Concrete, i.e. rheological aspects of making pre-cast concrete products.

1.2 Scope

The scope of this guide is to summarise the knowledge presented in the previous reports from this sub task of the HETEK project and make this knowledge applicable for practical purposes. The aim is to describe the most precise basis for design, construction og maintenance of concrete infra structures exposed to chloride laden environments, i.e. marine environments and road environments.

1.3 Structure

The guide is structured into ten chapters with the most design related information gathered in Chapter 4 and 5. De other chapters have a more informative profile in order to form a complete guide.

The main authors of the various sections were:

J M Frederiksen: 1-3,4.1-4.9,4.11-4.16, 5-9
E Poulsen: 4.4, 4.7, 4.10, 4.11

J M Frederiksen edited and H. Sørensen and J M Frederiksen performed the quality assurance, L-O Nilsson and P Sandberg reviewed.

1.4 Detailed information

This guide contains a lot of statements. The most of these are based on investigations described in the previously published reports of this HETEK sub task, cf. Chapter 9 of the present guide. The reader is referred to these reports for studying the theoretical background of the models and many of the statements, cf. the list of references in the back.

1.5 Limitations

The models used in this guide to calculate (estimate) the chloride ingress and prediction of the time for corrosion initiation in reinforced concrete are empirical, i.e. based on *experience*.

In spite of many years of research world wide the experience is limited to 2½ years of natural exposure and analyses in the marine exposure station in Träslövsläge on the Swedish West coast about 10 km south of Varberg. Thus the uncertainty of the models is unknown. The uncertainty is expected to be relatively large, but no one can estimate the magnitude of the uncertainty. Short of the publishing of this guide in 1997 new data from Träslövsläge will appear. Those data will help to assess the models used here and to improve the precision of the models.

The precision of the model can be judged by constructing a reinforced concrete structure with today's knowledge, places it in environments covered by this guide and wait 100 years to observe whether the durability is as predicted. This problem was known before the start of this HETEK sub task but it was the aim of this task to use the existing knowledge and experience in order to provide the best possible basis for design, construction and maintenance of reinforced concrete infrastructures.

2 Introduction

This guide is addressed to engineers working with planning, construction, operation and maintenance of reinforced concrete infrastructures exposed to chloride from the environment. The reader is first introduced to the subject and then some definitions are given.

This guide is written for engineers, who are administrating, planning, operating and maintaining reinforced concrete infrastructures, which can be exposed to chloride from the surroundings, e.g. from sea water, from spray containing de-icing salt or from other types of chloride laden water.

The guide is first and foremost written with reference to use for new structures, but is also to some extent applicable regarding existing structures built before the printing of this guide.

2.1 The damaging effect of chloride in reinforced concrete

If concrete is exposed to water containing soluble salt (e.g. NaCl), the ions in solution (here: chloride (Cl^-) and sodium (Na^+)) will penetrate into the concrete. The cover to reinforcement is normally 30-50 mm thick in reinforced concrete. If the chloride concentration at the surface of the reinforcement increases to a certain level, normally the reinforcement will begin to corrode, but at this time the concrete still can be totally intact.

The degradation will take place as pitting corrosion, for which reason the degradation will progress with a notch-like shape. When the notch grows to a sufficient size, the stress-strain relation in tension of the reinforcement will change on the corroding site and the near vicinity. Theoretically, when only approx. 8% of the area has corroded, the reinforcement no longer can be regarded as a linear-elastic, ideal-plastic material.

The notch will take up all the deformation as tensile stress in the reinforcement bar, thereby restricting the yield capacity of the bar to yielding in the notch. The result of this is that the corroding reinforcing steel will then act as a brittle material, because the deformation is now distributed in a much smaller area than before.

In the Danish codes of practice, where the ability of reinforced concrete to act as a plastic material at failure is assumed, the loading capacity at failure will be dramatically affected, when pitting corrosion occurs in critical sections. Therefore a situation like this must be prevented. One way to do this, is to take care that the time span before the critical chloride concentration reaches the surface of the reinforcement, becomes adequate.

2.2 Some important concepts

The central part of the damaging effect of chloride were described in the previous Section. Later on the *measures* against this damaging effect: *Adequate time span* *before chloride reaches the reinforcement* will be handled. But first some central concepts have to be explained/defined.

The *critical chloride concentration* (*threshold value*), C_{cr}, is the concentration, which initiates corrosion on steel embedded in concrete. It has been known for a long time that not only one critical chloride concentration exists. A threshold value exists for each concrete type and each environment. Qualified guesses on threshold values are given in Chapter 4 for different concrete types with different *w/b* ratios (The mass to mass relation between the effective water content and the added amount of binder (i.e. cement and any pozzolans)) and in different environments.

The *initiation period* is the duration from the time of manufacture of the concrete to the time when an amount of chloride corresponding to the threshold value for corrosion initiation has reached the reinforcement. The *propagation period* is the time period where the corrosive attack on the reinforcement develops. Normally the *lifetime* is regarded as the initiation period and part of the propagation period, but due to the possible fatal consequences of reinforcement corrosion to the safety and repair of the structure, the lifetime here is defined as the initiation period.

The *chloride penetration rate* is described by a transport parameter, which is called the *chloride diffusion coefficient*, D. If D is small then the chloride penetration rate is small and vice versa.

Furthermore a knowledge of the *chloride exposure* is required to be able to evaluate the time to *corrosion initiation* (i.e. the initiation period). The experience shows, that so far there is *no* existing simple and immediate understandable relation between the chloride concentration in the liquid, which exposes the concrete, and the chloride concentration in the concrete surface (the surface chloride concentration). The *surface chloride concentration*, C_s is an important parameter, because it determines how large the chloride concentration will be at a given time at any depth in the concrete. If the surface chloride concentration is small then the chloride concentration deeper in the concrete will be correspondingly small (all other parameters being equal) and vice versa. The threshold value, the chloride diffusion coefficient and the surface chloride concentration is the three most important parameters by calculations of the initiation period.

Finally is the chloride content of the concrete at the time of manufacture quite decisive. The *initial chloride content*, C_i is determined by the chloride contents in the constituent materials, the higher initial chloride content, the smaller is the margin to the critical chloride content.

2.3 Time-dependence of the chloride penetration

During the last approx. 5-10 years intensively work all over the world has been performed to gain an understanding of which processes govern the chloride penetration into concrete, and how it can be predicted.

It appeared from the beginning that it was complicated to describe and predict even the simplest possible situation: *Concrete immersed in chloride solutions at constant laboratory conditions*. The progress in the recent years, however, has enabled such predictions. But so far still only at laboratory conditions.

Based on chloride profile measurements in concrete exposed under natural conditions, it has been tried in several cases to predict the development until next inspection time and the residual lifetime. At the next inspection time, typically it appears that the predictions were wrong. Due to that reasonable doubt has been raised towards the calculative basis for the predictions.

Experience and careful studies have shown, that neither the chloride diffusion coefficient nor the surface chloride concentration are time-independent, which was believed until 1990. At that time it was eventually realised due to comprehensive research all over the world that both the chloride diffusion coefficient and the surface chloride concentration are strongly time-dependent.

Mathematical models exists, which are able to describe transport processes in porous materials. The simplest possible model is Fick's second law, which is a partial differential equation. Solutions to Fick's second law having different initial and boundary conditions are presented in mathematical handbooks. In such handbooks, however, no solutions to Fick's second law can be found, when both the chloride diffusion coefficient and the surface chloride concentration simultaneously can vary with time.

The *Mejlbro-Poulsen model* is an analytical solution to Fick's second law, where both the chloride diffusion coefficient and the surface chloride concentration can vary with time. The model is based on advanced analytical mathematics not immediate accessible to non-mathematicians. The solution, however, is expressed in a conventional form and tabulated, which enables comparison to other solutions to Fick's second law. It is described in Chapter 4 how the model can be applied by the use of charts and a minimum use of calculations.

3 The durability of concrete

This chapter gives an introduction to some basic considerations in connection to planning, design and construction of reinforced concrete structures that are to be durable toward chloride exposure in Denmark.

3.1 Expression of the needs

A load carrying RC structure (reinforced concrete structure) serves a primary purpose. This purpose shall be stated so that the functional requirements can be formulated and met in the best way possible. The stipulated service life for the structure, i.e. the time span for which the primary purpose shall be met, should also be specified. Finally the economical limits for the design, construction and maintenance shall be stated.

If all these facts are defined before the design stage the design shall take them into account because the goal must be to design the building to meet the functional requirements at the lowest price possible (e.g. the lowest present value of all expenses during the stipulated service lifetime).

3.2 Causes of deterioration

The general requirements can only be met if the durability of the structure is satisfactory. Insufficient durability leads to increased expenses for maintenance or a service life that is shorter than stipulated. Therefore it is necessary to know which causes of deterioration that will be governing for the durability of the structure.

Chloride penetration and subsequent reinforcement corrosion will often be dominating in Danish environmental conditions, but also deleterious alkali aggregate reactions and freeze thaw actions are risks to evaluate.

3.3 Precautions against common causes of deterioration

The precautions to counter act deleterious alkali aggregate reactions in Denmark were know since the beginning of the sixties and since the mid eighties they were covered by the national building owners specifications for concrete. The precautions are to limit the alkali content of the cement and the content of alkali reactive rock types, e.g. opaline flint. Lack of durability due to alkali aggregate reaction is therefore very seldom in Danish concrete structures erected after the mid eighties.

The precautions to counter act deterioration due to freeze/thaw action was known since the beginning of the fifties and since the beginning of the seventies it was covered by the Danish code of practice for concrete structures. The precautions are to entrain small and evenly distributed air bubbles in the concrete. Lack of durability towards freeze/thaw action is therefore very seldom in Danish concrete structures erected after the mid seventies.

The sufficient precautions to counter act deterioration due chloride penetration have not been known in the same way as for alkali aggregate reactions and freeze/thaw action. That is why precise requirements to give a sufficient safety are missing in the codes of practice and concrete guides. During the last decade in Denmark the precautions have developed toward increased concrete covers to reinforcement, dense concretes having a low w/c ratio and addition of silica fume and/or fly ash together with a number of special measures. It is still too early to state anything about the frequency of damages due to the action of chloride in Danish concrete structures erected after the late eighties.

3.4 Conditions for resistance against chloride ingress

As described in the previous section the resistance against alkali reactions and freeze/thaw actions by other parameters than those being used to obtain a better resistance against chloride penetration. Therefore it is theoretically possible to have a concrete that has sufficient resistance towards chloride ingress but that is not resistant towards freeze/thaw and/or deleterious alkali reactions.

Consequently the resistance against chloride ingress depends on the durability to freeze/thaw action and (and through carefully chosen concrete constituents) deleterious alkali aggregate reactions.

It may be difficult or impossible to produce a concrete structure without unintended cracking and defects not being a natural part of the concrete. The ability of a concrete to resist chloride penetration is as so also strongly dependent of the (unintended) intensity of cracking and defects. (Cracking due to static load is not included in the "unintended" cracks.)

3.5 Calculations of service life

It is the wish to know the total economy of the building that makes calculations of service life a necessity. In order to do the calculation of service life a detailed knowledge about the deleterious factors.

While the durability and so the service life towards alkali aggregate reactions and freeze/thaw action roughly spoken is laid down from the beginning (from the choice of constituents and mix design), the durability towards chloride penetration dependent on a number of factors during the manufacture, casting and curing of the concrete plus the action of the environment and the concrete's response to it.

Calculations of service life should therefore not be regarded as a precise measure, but as a an informed guess! The precision ought to be good due the large economical consequences, but it is not. The magnitude of the uncertain can not be quantified but a common model basis should be the base of all service life calculations. This will make such calculations more uniform and objective which must be preferred rather than "fortune tellership". Check of a service life calculation will take just as long time as the duration of the lifetime!

The most important aim of this project was exactly to lay down such a model basis as a precondition for the choice of test methods. The model is presented in Chapter 4.

4 Design

The designer carries the responsibility for the structural design in details, and he has to plan the structure so it will meet the demands from the building owner and the society. Furthermore, the design must be possible to carry out within a reasonable economy.

4.1 General points of view

Moisture takes part in all destructive processes in concrete (except vandalism). In a dry environment concrete will normally not deteriorate except by wear and collision. When a concrete structure is built outdoor or in wet indoor environments one should always make sure, that water cannot gather on surfaces, neither locally nor on larger areas unless this is the specific intention (e.g. reservoirs). Horizontal upward faces should be avoided.

Coarse cracks are not permitted acc. to the Danish code of practice for concrete structures (except for indoor dry climate), but casting joints are normally unavoidable and can unintended form such cracks. For this reason casting joints must be appropriate placed and if avoidable, not close to environmental or structural severely affected sections. On the design of casting joints, ref. Section 5.2.

The reinforcement arrangement must permit every section to be cast correctly. The concrete cover to the reinforcement shall protect the structure against future deterioration, for which reason especially here a perfect casting should be given a high priority.

Finally, it has appeared that certain details on the structure can be difficult or impossible to inspect and maintain. As an example details related to supports can be very expensive to maintain. For this reason an "inspectable" design should be made, if possible.

4.2 Requirements for constituent materials, concrete composition and production

The cost of concrete can be decisive for the choice of concrete supplier. Due to this the most inexpensive concrete, which fulfils all requirements, normally will be chosen. A close relationship is often existing between cost and properties. Therefore it is important to specify what is acceptable and what is not acceptable.

The constituents to a concrete in a structure placed in an environment containing chloride should normally and if possible be of a better quality than concrete for other types of structures. In Chapter 3 is given a brief description of some destructive processes closely related to the constituents, which can be fatal for the concrete durability.

The permeability of concrete is primarily governed by the permeability of the paste (or rather the matrix). It is though of significant importance that the aggregate permeability is low. When rock is impermeable as the material itself, but have uniformly oriented cleavage planes (normally inherent) and cracks (e.g. from crushing), this could be a reason not to choose that particular commercial product.

The concrete must be well-composed, robust and have a good workability, so that transportation and casting becomes simple and safe. It sounds banal, but as air-entrained concrete with a binder of both cement, fly ash and micro silica and a low *w/b* ratio can be required at the same time, the task is often not so simple after all.

4.3 Local environmental classes

The environmental exposure to concrete structures in different exposure situations can be divided into different classes depending on the aggressiveness of the environment. This has been done in the Danish concrete standard, where four environmental classes is used: Passive, Moderate, Aggressive and Particular aggressive environmental class. If moisture and chloride is present the environmental class is defined as aggressive or particular aggressive.

In Danish outdoor climate frost action also happens, which means that concrete in structures must be frost-resistant, if exposed to frost in a water-saturated condition during construction or in function.

The chloride-containing marine environment and the road environment can be sub-divided into a number of local classes, while the chloride exposure is depending on the part of the structure. The distance to the waterline or the lane is one of the most important parameters. When striving towards an economical design of a structure one can group the individual structural parts/sections in different local environmental classes.

An appropriate division into local environmental classes, which is relevant in both marine environment and road environment, is given below. Besides some examples on structural parts belonging to each local environmental class are stated. The purpose with this grouping is to exemplify the number of different chloride exposures, which can be seen on one structure. Among other things the division is appropriate when planning inspection on a structure, while it for many (especially smaller) constructions will be too detailed as a paradigm for division into different environmental classes with varying covers and/or concrete qualities.

1 Road environment

a) The "wet" road environment, i.e. structural parts, which are able to "see" the sky and is subjected to direct rain, e.g. edge beams and wing walls. If convenient, this local environment can be sub-divided into two additional local environments:
    - From 0 to 2 m above the road level and in the distance from 0 to 5 m from the edge of the road.
    - The region outside the borders mentioned above.

b) The "dry" road environment, i.e. structural parts, which are placed below a bridge deck and due to this not able to "see" the sky and not subjected to direct rain, but only to traffic splash, e.g. columns and abutment.

2 Marine environment

a) Immersed structures placed below level -3 m with respect to the lowest minimum water level, e.g. caissons.

b) Structures placed in the splash zone, here defined as being above level -3 m with respect to the lowest minimum water level and below level +3 m with respect to the highest maximum water level, e.g. bridge pier shafts.
c) Structures placed above level +3 m with respect to the highest maximum water level, e.g. bridge piers and the underneath of decks on marine bridges.

3 Combinations of 1a and 2c, e.g. the superstructure of marine bridges.

The resistance of concrete structures to chloride exposure is determined by:

- The thickness of concrete cover to reinforcement
- The binder type (including binder composition)
- The permeability of concrete cover (e.g. the *w/b* ratio)
- The reinforcement type (e.g. black versus stainless steel)

The purpose of the division given above is to obtain a distinct difference between each single local environment, thus an appropriate step is obtained between the precautions taken from local environment to the next in line. In this way increments in concrete cover should be at least 10 mm and increments in *w/b* ratio should be 0.1 or more.

For every type (size) of structure there will be an economical balance between the number of local environments and the number of cover increments and/or increments in concrete cover together with possible use of stainless types of reinforcement.

4.4 The response of concrete to chloride exposure

The response of concrete to chloride exposure is determined by measurement of chloride profiles, which are formed in the exposed surface layers. The chloride profile can by example be compared to the stress distribution (response), which is formed in a beam as a result of a mechanical loading (load).

A chloride profile in a concrete surface, which for years has been exposed to chloride, is described at the time t by the following parameters:

- The achieved chloride concentration at the concrete surface C_{sa}.
- The achieved chloride diffusion coefficient D_a.
- The exposure time period $\Delta t = t - t_{ex}$, where the time is counted from casting and t_{ex}. designates the time when the concrete is exposed to chloride for the first time.

Time has shown that both C_{sa} and D_a are time-dependent and depends on the local environment. Furthermore both parameters depends on the concrete composition. A physical-chemical explanation to these phenomena has not been established, and so far they cannot be modelled.

The response of concrete to chloride load have to (if possible) be described both by the local environment and the concrete parameters. Since a physical-chemical modelling cannot be used, one has to use experience from field investigations as a basis, where possible.

4.5 Threshold values for corrosion initiation

An approximate equation to estimate threshold values for corrosion initiation in different environments is presented by Frederiksen et al. [1997a]. The equation is based on a table (also in Frederiksen et al. [1997a]), which is based on engineering estimates and extrapolation of measured data. This equation is expressed in a graphical form on Figure 8, which enables the threshold value to be read for different environments. It is a precondition to the graphs on Figure 8, that the concrete cover is at least 25 mm and without cracks with crack widths larger than 0,1 mm.

4.6 Marine concrete structures

The response of a number of different concrete types to the marine environment are investigated in the Swedish marine field exposure station at Träslövsläge harbour approx. 10 km South of Varberg.

On the basis of a detailed analysis of the data obtained after 2½ years of exposure, it has been attempted to extrapolate the chloride profiles using the *Mejlbro-Poulsen model*, knowing well that it probably will be combined with very large uncertainties. In spite of that it must be considered to be the best estimate, which can be done on basis of the available knowledge and experience.

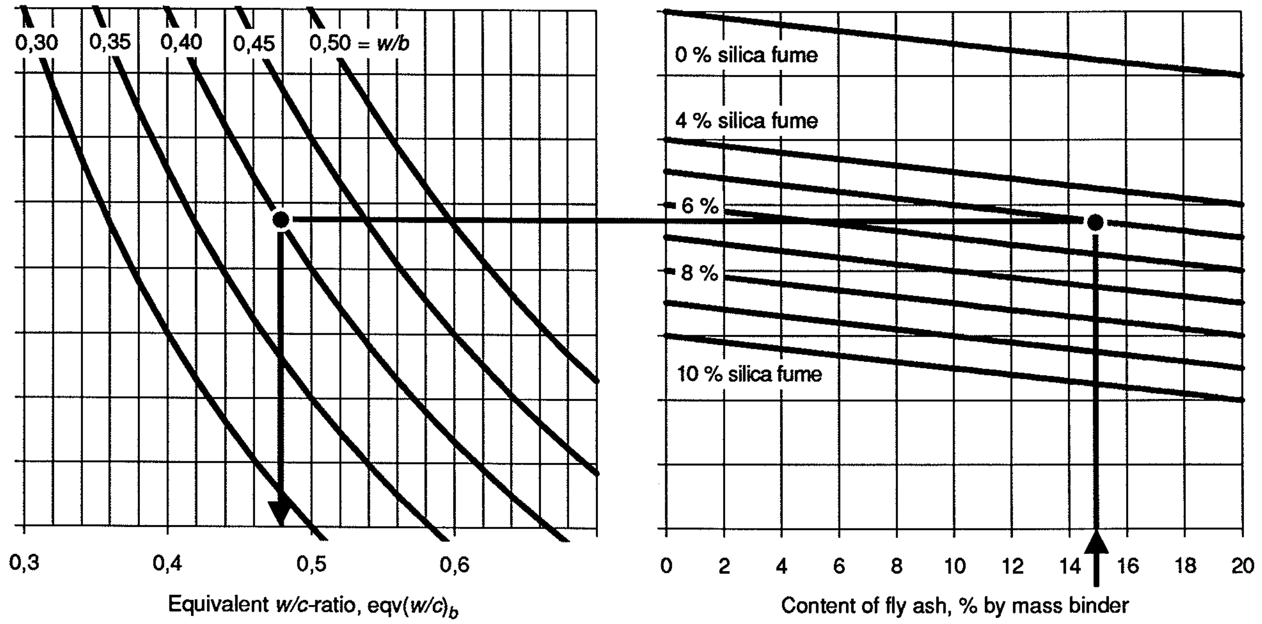
It is found convenient to describe the time-dependent boundary condition C_{sa} and the time-dependent transport coefficient D_a by means of first year values and 100 years values.

Expectation values for the parameters surface concentration and chloride diffusion coefficient at 1 year and at 100 years is estimated by equations presented in Frederiksen et al. [1997a]. To do this efficiency factors for micro silica and fly ash have been determined together with environmental and time factors for the four parameters.

These equations are not presented here, but it is shown on the 5 following pages on diagrams, how an estimate of the initiation period can be determined according to the *Mejlbro-Poulsen model*, when the concrete composition is known.

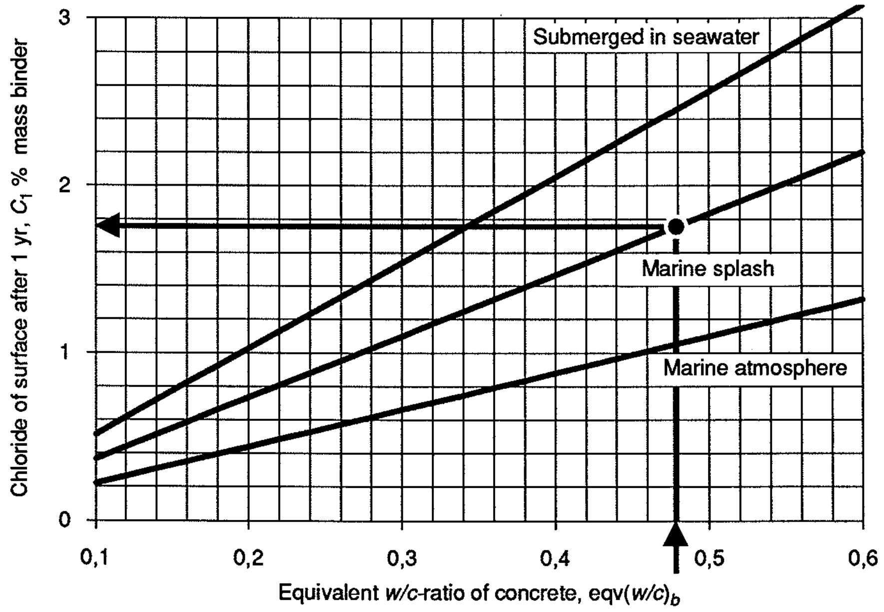
The diagrams can be used to estimate the response of the concrete in three different marine environments, to do a preliminary design of concrete cover, to do a preliminary mix design of the concrete and to establish acceptance criteria, cf. Section 4.14.

C_1 and C_{100} are first determined by use of Figure 1, 2 and 3. Then Figure 4, 5 and 6 is used to determine D_1 and D_{100}. These four parameters are transformed in Figure 7 to the fundamental parameters in the *Mejlbro-Poulsen model*, i.e. the four parameters α, D_{aex}, S_p and p. The threshold value is read in Figure 8, while the non-dimensional concrete cover is found in Figure 9. Finally is the duration of the initiation period estimated in Figure 10. The entire procedure is illustrated in section 4.9 together with a diagram, which should make the job by reading the Figures easier.

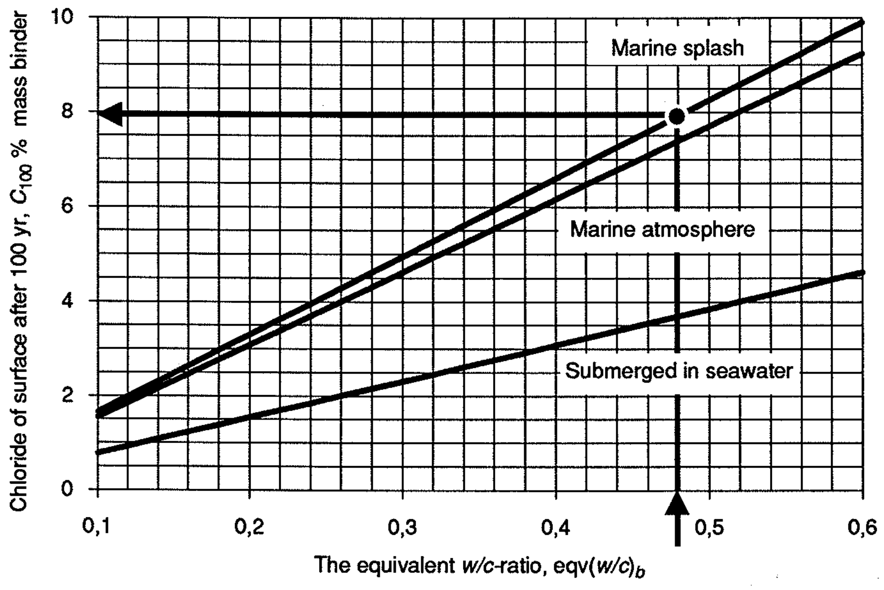


▲ *Figure 1. Diagram relating eqv(w/c)$_b$, environment and w/b-ratio of the concrete.*
For concrete exposed to the marine splash zone and having a content of fly ash of 15 % by mass binder and a content of silica fume of 5 % by mass binder and w/b = 0.40 by mass it is found that eqv(w/c)$_b$ = 0.48.

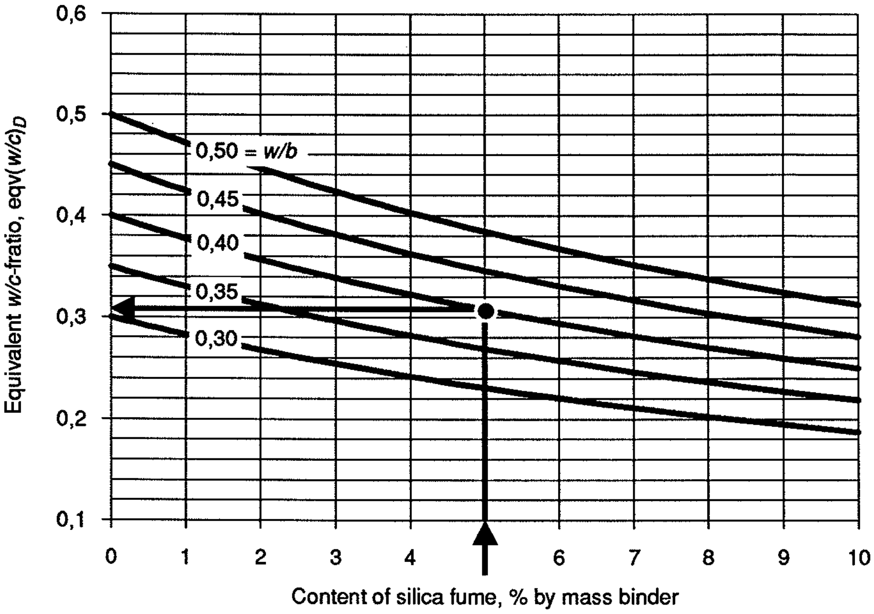
▶ *Figure 2. Diagram relating C_1, environment and eqv(w/c)$_b$. For concrete having eqv(v/c)$_b$ = 0.48 and exposed to marine splash C_1 = 1.75 % by mass binder is found.*



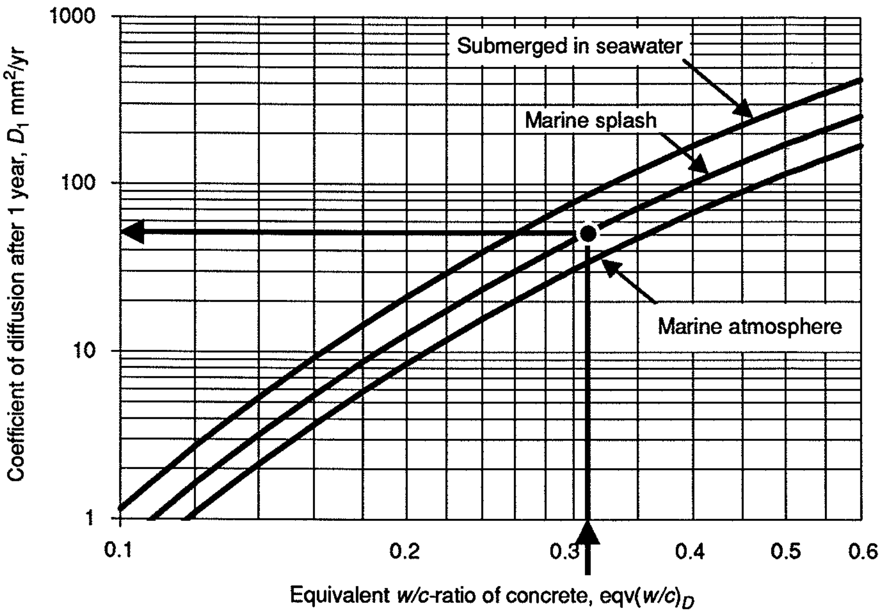
▶ *Figure 3. Diagram relating C_{100}, environment and eqv(w/c)$_b$. For concrete exposed to marine splash and having an eqv(w/c)$_b$ = 0.48 it is found that C_{100} = 7.9 % by mass binder.*



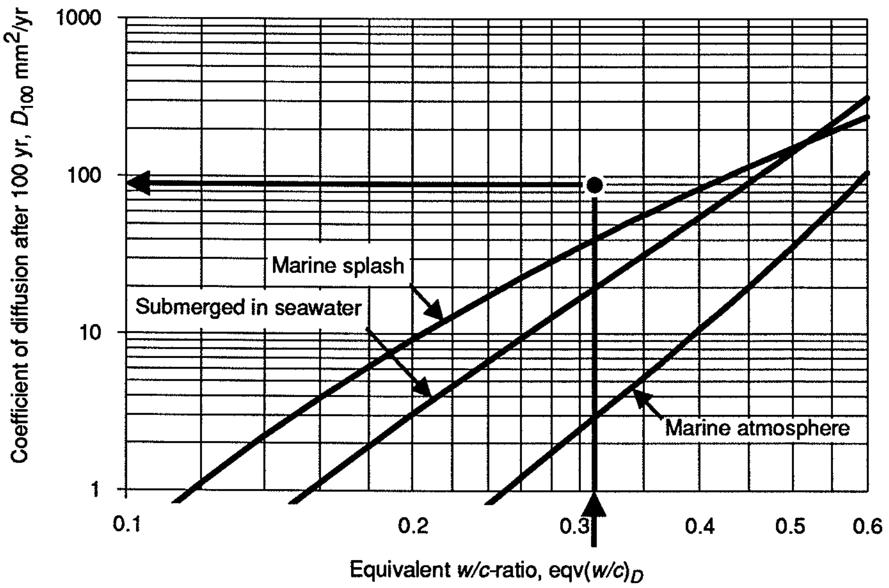
▶ *Figure 4. Diagram relating eqv(v/c)$_D$, environment and w/b-ratio of concrete. For concrete having a content of silica fume of 5 % by mass binder and a content of fly ash of 15 % by mass binder and w/b = 0.40 it is found that eqv(v/c)$_D$ = 0.31.*



▶ *Figure 5. Diagram relating D_1, environment and eqv(w/c)$_D$. For concrete exposed to marine splash and having an eqv(w/c)$_D$ = 0.31 it is found that D_1 = 50 mm^2/yr.*



▶ *Figure 6. Diagram relating D_{100}, environment and eqv(w/c)$_D$. For concrete exposed to marine splash and having an eqv(v/c)$_D$ = 0.31 it is found that D_{100} = 40 mm^2/yr.*



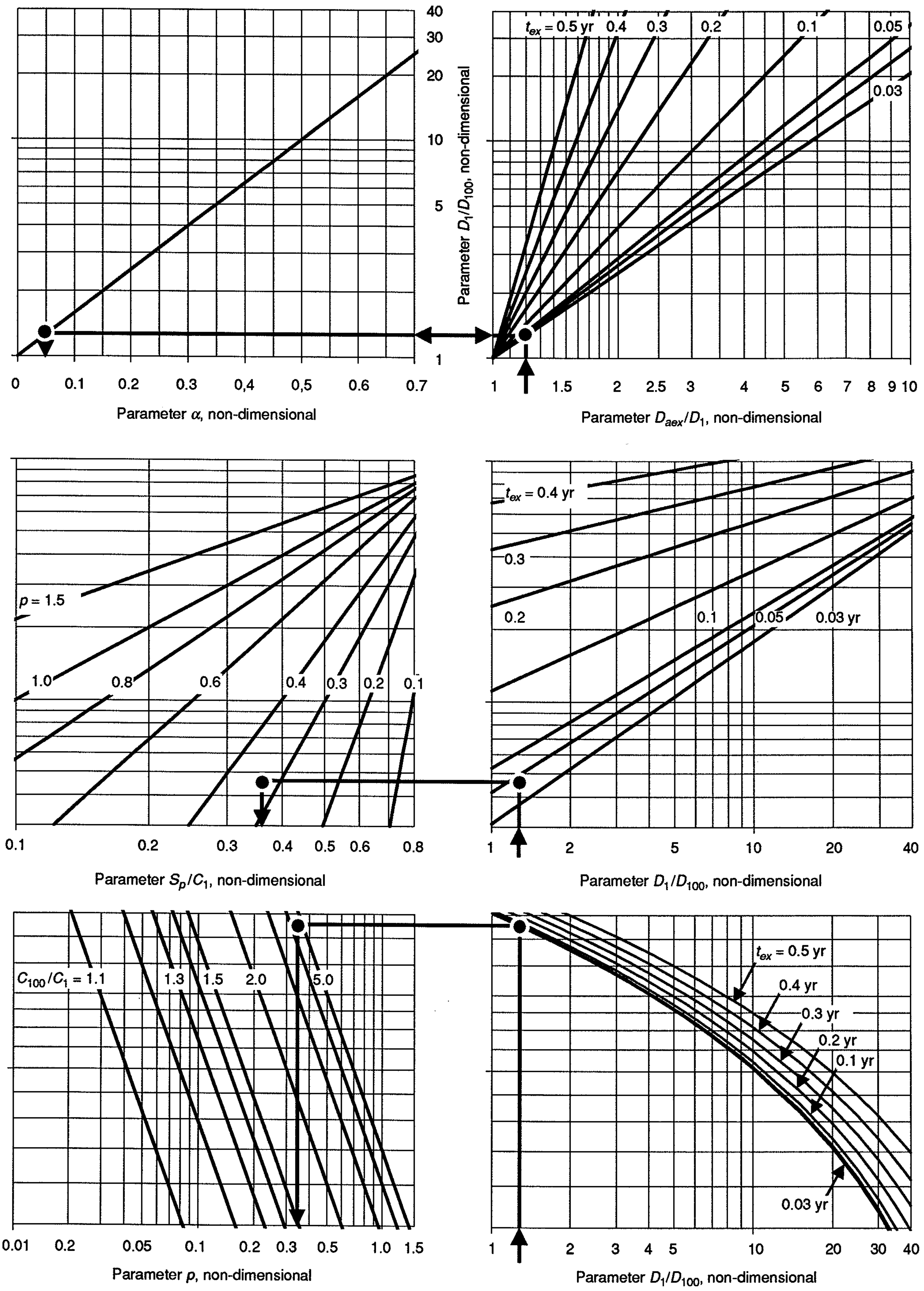
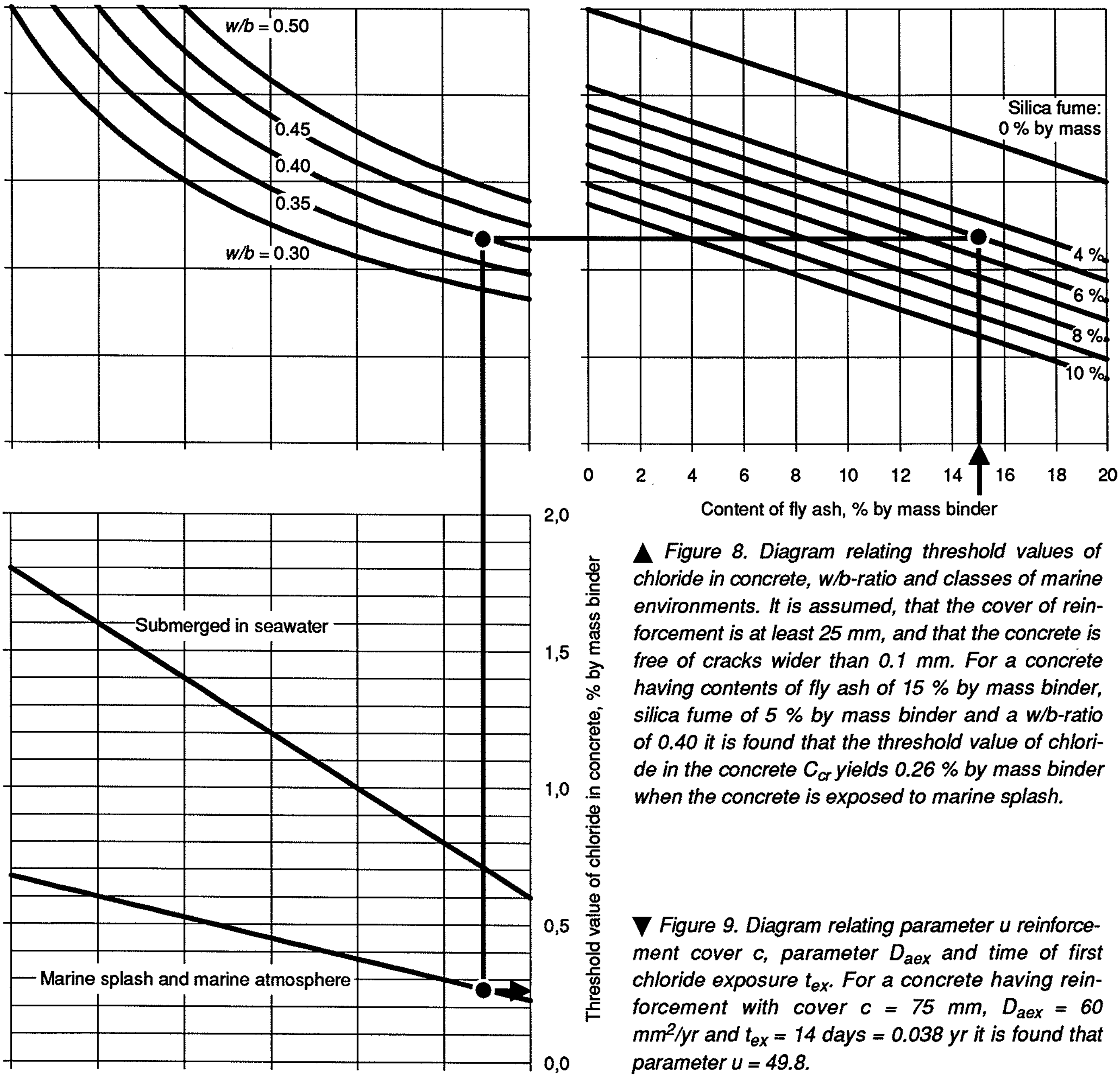
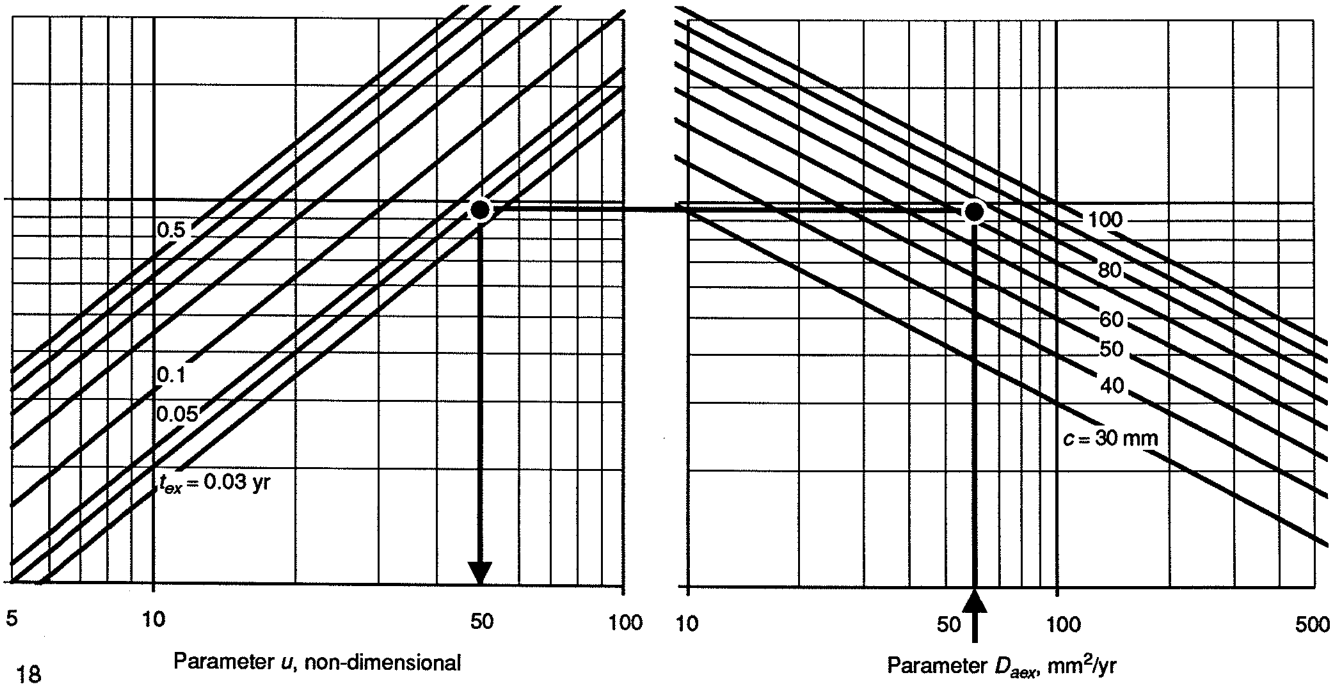


Figure 7. Diagram relating the basic parameters α, D_{aex}, S_p and p with the derived parameters D_1, D_{100}, C_1, C_{100} and t_{ex}. If $D_1 = 50$ mm^2/yr, $C_1 = 1.7$ % by mass binder and $t_{ex} = 0.038$ yr and $D_1/D_{100} = 1.3$ and $C_{100}/C_1 = 4.8$ it is found from the diagram, that $\alpha = 0.05$, $D_{aex} = 1.2 \cdot 50 = 60$ mm^2/yr, $p = 0.34$ og $S_p = 0.36 \cdot 1.7 = 0.61$ % by mass binder.



▲ *Figure 8. Diagram relating threshold values of chloride in concrete, w/b-ratio and classes of marine environments. It is assumed, that the cover of reinforcement is at least 25 mm, and that the concrete is free of cracks wider than 0.1 mm. For a concrete having contents of fly ash of 15 % by mass binder, silica fume of 5 % by mass binder and a w/b-ratio of 0.40 it is found that the threshold value of chloride in the concrete C_{cr} yields 0.26 % by mass binder when the concrete is exposed to marine splash.*

▼ *Figure 9. Diagram relating parameter u reinforcement cover c, parameter D_{aex} and time of first chloride exposure t_{ex}. For a concrete having reinforcement with cover c = 75 mm, D_{aex} = 60 mm^2/yr and t_{ex} = 14 days = 0.038 yr it is found that parameter u = 49.8.*



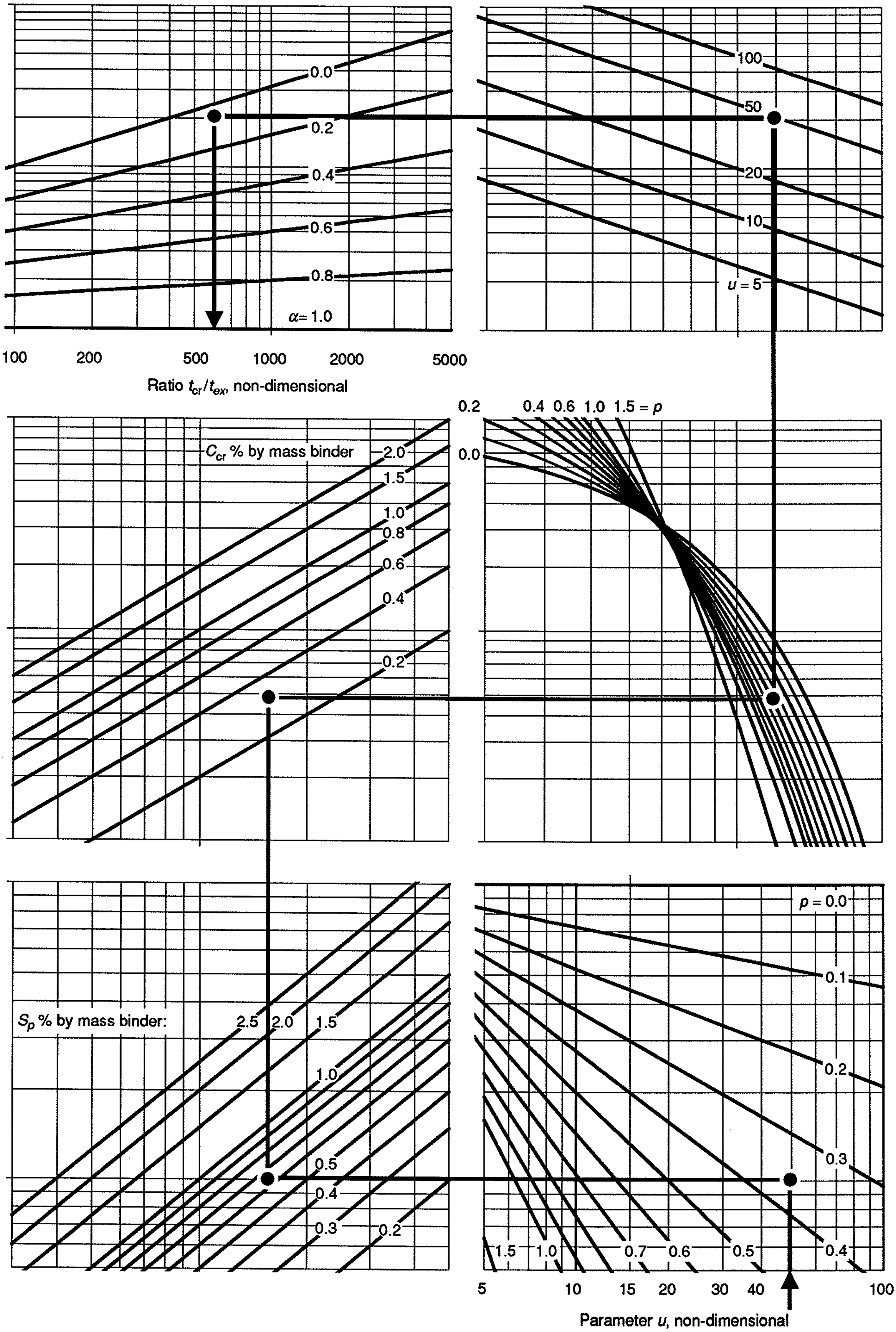


Figure 10. Diagram relating initiation period t_{cr} and the six decisive parameters α, D_{aex}, S_p, p, t_{ex} and C_{cr}. If $u = 49.8$ (cf. figure 9), $S_p = 0.61$ % by mass binder (cf. figure 7), $C_{cr} = 0.26$ % by mass binder (cf. figure 8), $\alpha = 0.05$ (cf. figure 7) and $p = 0.34$ (cf. figure 7) the initiation period yields: $t_{cr} = 600 \cdot 0.038 = 23$ yr.

4.7 Structures in the road environment

The data from the road environment are scarce and insufficient for a detailed description of the road environment. So far we have to be satisfied with learning from the marine environment by analogy. The analogy has to be based upon engineering intuition. To this qualitative experience can be added from investigations abroad and from investigations of structural parts in the dry road environment on a few existing Danish bridges plus preliminary results of experimental work in the Swedish field exposure station situated on the highway Rv 40 between Borås and Gothenburg.

The local environment around a road bridge can based on the present observations be divided into a "wet" and a "dry" environment, cf. Frederiksen et al. [1997a]. The observations include very limited observations from highway bridges in Denmark and from the approx. 2 years old field exposure station in Sweden.

The observations are limited because only few measurements describe the development in time of chloride profiles when structures are exposed in the "wet" and the "dry" road environment in Denmark. Therefore these observations have been complemented with information from foreign inspections of chloride diffusivity of concrete structures in road environments.

All over Europe and North America the interest for the problems that the road environment is increasing. It is therefore expected that an increased number of observations from such structures resulting in more knowledge.

Below the response of concrete to the road environment is described in terms of the Mejlbro-Poulsen model, i.e. the four parameters: α, D_{aex}, S_p and p. From these guidelines one can seek to estimate the values of D_1, D_{100}, C_1 and C_{100}. Subsequently the governing parameters can be determined as shown for the marine environment in Section 4.9.

4.7.1 "Dry" road environments

From Frederiksen et al. [1997a] the following conclusion can be drawn about the diffusivity of concrete:

- C_{sa} is observed to be about 0.5 % mass concrete at an exposure time of approx. 40 years.
- C_{sa} is observed to decrease with increasing level above the traffic lane.
- C_{sa} is observed to decrease with increasing distance from the traffic lane.
- C_{sa} is observed to have a maximum on the lee side compared to the traffic.
- The product $t \times D_{aex}$ will increase in time and become a constant.

4.7.2 "Wet" road environments

Systematically measurements in "wet" road environments are scarce, cf. Frederiksen et al. [1997a]; the following conclusion can however be drawn:

- C_{sa} will increase during winter time and decrease during summer time, but will probably steady quickly.
- C_{sa} is observed to decrease with increasing level above the traffic lane.
- C_{sa} is observed to decrease with increasing distance from the traffic lane.
- The product $t \times D_{aex}$ will increase in time but will hardly become a constant.

4.8 Structures exposed to marine atmosphere and de-icing salt

Only few inspections have been reported from the combined exposure in marine environment and road environment. Now (1997) the recommendation must be to count in an increase exposure, but a superposition of the actions seem not to be observed.

4.9 Example of how to estimate the initiation period

Below an example of how the initiation period t_{cr} can be estimated by using diagrams and a pocket calculator for a chosen composition of the cementitious and a chosen cover to the reinforcement.

Imagine a concrete being manufactured with addition of binder and water as given below.

Cement	80% of binder
Fly ash	15% of binder
Silica fume	5% of binder
w/b ratio	0,40

The cover is chosen to 75 mm in the splash zone and the time of first chloride exposure is fixed to 14 days (0.038 year). From Figure 1, 2 and 3 the two parameters C_1 = 1.7 % mass binder and C_{100}= 8 % mass binder are read. From Figure 4, 5 and 6 the two parameters D_1 = 50 mm^2/yr and D_{100} = 40 mm^2/yr are read.

Thereupon are calculated the proportions C_{100}/C_1 = 4.8 and D_1/D_{100}= 1.3, whereupon the four basic parameters D_{aex}, α, p and S_p can be read in Figure 7 as shown. From Figure 8 the threshold value are read to the value C_{cr}= 0.26 %mass binder and from Figure 9 the dimensionless cover to reinforcement u are read to 50.

Finally the dimensionless initiation period are read in Figure 10 to 600. By multiplying with the chosen time of the first chloride exposure t_{ex}= 14 days = 0.038 year, the length of the initiation period yields 600 × 0.038 = 23 years.

If the found initiation period is not sufficient a larger cover is chosen followed by a new reading in Figure 10. If an acceptable cover can not be achieved another mix design is chosen (a lower *w/b* ratio and perhaps an increased content of silica fume). When the necessary and sufficient cover is determined the covers for the other marine environments are derived in the same way.

The form in Figure 11 can be a help to carry out the estimation by this diagram method.

Marine local environment:

Ref.	Description	Value	Unit
	Content of cement		%mass binder
	Content of fly ash		%mass binder
	Content of silica fume		%mass binder
	w/b ratio		mass ratio
	Time of first chloride exposure, t_{ex}		year
	Cover, c		mm
	Read in Figure 1, 2 and 3		
	eqv $(w/c)_b$		-
	C_1		%mass binder
	C_{100}		%mass binder
	Read in Figure 4, 5 and 6		
	eqv $(w/c)_D$		-
	D_1		mm^2/year
	D_{100}		mm^2/year
	Calculate		
	D_1/D_{100} =		-
	C_{100}/C_1 =		-
	Read in Figure 7		
	p		-
[1]	S_p/C_1		-
	α		-
[2]	D_{aex}/D_1		-
	Calculate		
	$S_p = C_1 \times [1] =$		%mass binder
	$D_{aex} = D_1 \times [2] =$		mm^2/year
	Read in Figure 8		
	C_{cr}		%mass binder
	Read in Figure 9		
	u		-
	Read in Figure 10		-
[3]	t_{cr}/t_{ex}		-
	Calculate		
	Initiation period, $t_{cr} = t_{ex} \times [3] =$		years

Figure 11. Form to help at the estimation of the initiation period by the diagram method.

4.10 Lifetime

The building owner and the society set up specifications for a concrete structure in order to make it meet it's functional requirement for a sufficiently long time, the "life span". The society has formulated requirements in codes of practice and in standards and the building owner complement with special specifications for the structural parts.

The Danish codes of practice provide safety for achieving reasonable initial properties and characteristics whereas keeping up these seem to be more of a problem for marine and/or de-iced reinforced concrete structures. The time is now ready for putting down specifications for the "life span" of those concrete structures.

4.10.1 Definition of life span

At first it seems reasonable to put down certain specifications for the life span or durability of a concrete structure. Before making this demand one must realise what the term "life span" means. It is natural to start with the development of the deterioration of a reinforced concrete structure being exposed to chloride. Here the stages normally are:

- Chloride penetrates the reinforcement cover. The threshold value is reached and corrosion is initiated (the initiation period).
- Rust becomes visible on the surface.
- Cracking and spalling due to the voluminous nature of the corrosion products.
- Reduction of the safety level due to loss of reinforcement.

The society naturally requires that the safety level of the codes of practice are maintained in the stipulated lifetime. Moreover the building owner may have different views of the development of the building's condition:

- *Public opinion.* Rust, cracks and spalling will reduce the commercial value of the building why they are undesirable.
- *Aesthetics.* The users do not always have the necessary knowledge about the importance of rust, cracks and spalling and will react negative toward continued use.
- *Public safety.* Pieces of concrete falling down are dangerous to people that go about the building.

Corrosion damages on reinforcement due to chloride attack can be difficult and expensive to stop when started. Economical aspects are behind the wish of not letting the corrosion start. But also technical reasons justify this wish. A reinforcement bar suffering from pitting corrosion can be brittle like cast iron. In this guide the "lifetime" (life span) in a point of a chloride exposed structure is defined as the time to corrosion initiation, i.e. the time from the mixing of the concrete until the reinforcement in the point in question starts to corrode. The model used in the guide can be used to estimated the time of initiation in any point of a structural part.

A structural part can have different local environments varying concrete properties (chloride diffusivity), varying covers etc. Corrosion will not start simultaneously anywhere in a structural part. The question is now how much ongoing corrosion to accept at the time defined as the "lifetime" or the "initiation period" of the structural member. In agreement with Danish codes of practice it would not be unreasonable to define the "lifetime" or the "initiation period" of a structural member as the time from mixing the concrete until 5 % of the reinforcement area of the structural member has begun to corrode.

4.11 Safety concept

If a deterministic calculation of lifetime based on average values is used the real lifetime will be less than estimated in approx. 50 % of the cases. Naturally this is unacceptable. The example in Section 4.9 is solely based on average values.

The problem is not essentially different from calculation of load carrying capacity and deformation as known from the codes of practice for materials and structures. In those a safety margin is introduced so that failures only occur in few case if the procedure is repeated. It should be noted that there is a different safety margin whether calculating the load carrying capacity or the deflection of a beam. For the load carrying capacity a high safety margin is required (small risk of failure) while for the deflection a smaller safety margin is required (to much deflection can be an economical problem, but there is no risk of human life).

The risk of corrosion damages due to chloride attack shall be small, but if it happens the damage will be noticed (rust, cracking and spalling). It can be an economical problem, but usually there is no risk of human life. A few cases of sudden failures of structures suffering from corrosion attack due to chloride, but in those cases other structural faults were involved.

The conclusion is that a limited safety margin is acceptable especially when the governing parameters are under control in the construction phase.

4.11.1 Deterministic approach

There are two ways to carry on:

- The calculation is based upon average values of the governing parameters (environmental parameters and the diffusivity of concrete) and use a design value for the initiation period being equal to the required lifetime plus an addition of 25 to 50 years, if the required lifetime is 100 years.
- The calculation is based upon characteristic values of the governing parameters (environmental parameters and the diffusivity of concrete) and use a lifetime that is equal to the required., e.g. 100 years.

Both methods are possible, but is beyond the object of this guide to put up such general requirements for design of concrete structures.

The first method is the simplest one today where the observations are scarce and reasonable characteristic values for the governing parameters of the environments and the concrete's response to those can not be drawn up.

4.11.2 Stochastic design

When speaking of large marine structures and infrastructures of reinforced concrete design according to the deterministic approach e.g. with characteristic values become expensive. In such cases it may sometimes be profitable to use probabilistic methods to assess the possibility of the lifetime to be less than required.

Use of probabilistic methods requires detailed knowledge about the reliability of the mathematical model and the statistical distributions of the governing parameters for chloride penetration into the concrete in question. If the information based on data about the statistical behaviour of these parameters is weak the statistical distribution should be estimated on the safe side. Two different probabilistic methods can be applied namely the method of reliability index and probabilistic method.

The method of reliability index

The chloride penetration problem and the subsequent risk of corrosion can be described in such a way that a set of parameters shall fall in a certain area (corrosion domain), to initiate corrosion. The distance between the point described by the average values of the parameters in question and the limiting curve of the corrosion domain is a measure named the reliability index. This safety approach is used e.g. to determine partial safety factors in the Danish codes of practices for structures. A large reliability index correspond to a large safety margin while a small reliability index correspond to a small safety margin. The method is independent of the statistical distributions for the governing parameters.

Probabilistic method

When applying a probabilistic method one has to know the effect of the governing parameters on the lifetime and in addition the statistical distribution of the governing parameters must be known. This knowledge can be based upon observations or be estimated from engineering experience in the topic.

The statistical distribution of the lifetime can be calculated with the above knowledge. It is however only possible to make such calculations on supercomputers.

It is difficult the determine the safety level to be used in assessment of the lifetime of concrete structures where the experience is scarce. For that reason the probabilistic methods are usually applied to new structures that are going to have the same safety level as an older concrete structure that has proved to be satisfactory. As experience grow we will gain knowledge about the needed safety level for durability of concrete structures in chloride environments.

4.12 Importance of structural cracks

The importance of structural cracks has been described in Frederiksen et al. [1997a]. A short summary is given here of the preconditions, which forms the basis for the used models.

It is a precondition for the threshold values expected to be valid, that no cracks widths are larger than 0.1 mm. Due to this cracks related to structural conditions must be restricted to crack widths below 0.1 mm. This roughly corresponds to the requirements, which normally is stated in Danish standards for aggressive environment.

4.13 Requirements for cover design

By use of the models presented in Frederiksen et al. [1997a] expectation values for the penetration depth of the critical chloride concentration can be calculated. The result from such a calculation for five different concrete types is presented in Table 1.

Table 1. Expectation values for the depth of threshold value after 100 years exposure in marine environments.

	Submerged	Splash zone	Atmosphere
100% cement			
w/b =0.3	14	75	13
w/b =0.4	62	133	34
w/b =0.5	144	186	71
95% cement + 5% silica fume			
w/b =0.3	15	51	6
w/b =0.4	49	95	16
w/b =0.5	105	136	32
90% cement + 10% silica fume			
w/b =0.3	15	37	3
w/b =0.4	45	72	9
w/b =0.5	95	105	18
80% cement + 20% fly ash			
w/b =0.3	29	76	13
w/b =0.4	96	140	36
w/b =0.5	215	196	75
80% cement + 5% silica fume + 15% fly ash			
w/b =0.3	25	52	6
w/b =0.4	75	100	17
w/b =0.5	173	144	34

Determination of cover for a given concrete composition and a given local environment on a structure can be performed by an estimation of the uncertainties, which are built-in the values presented in Table 1. The presented values are *estimated* expectation values - *not* accurate values. The necessary safety must be defined by each consultant and building owner. Inspiration can be found in Frederiksen et al. [1997a], but not a safe solution to the problem.

At present the most simple way to build-in safety is shown in section 4.11.1, where the stipulated (i.e. the wanted) lifetime is multiplied with a factor (e.g. 1.25-1.5) to get the required initiation period in the project.

Now the only thing left for the designer is to specify the *maximum allowable* concrete cover, because it must be presumed that a skin reinforcement has to be used, if the cover thickness exceeds a certain limit (normally approx. 75 mm). Subsequently, it is the contractors task to choose the most economical building technique.

4.14 Determination of acceptance criteria

The diagrams in the present report or the equations for the parameters C_{cr}, C_1, C_{100}, D_1 and D_{100} presented in Frederiksen et al. [1997a] together with the described model gives the parameters, which are to be aimed. Besides relations between marine local environments in Träslövsläge and laboratory measurements acc. to NT BUILD 443 is given in Frederiksen et al. [1997a].

Together this information enables the definition of only one acceptance criteria for a concrete, even if this concrete will be used in three different environments in a specific structure. The following is done:

1. The contractor suggests a mix design.
2. The concrete parameters are estimated.
3. The initiation periods are calculated for each of the actual local environments as shown by the example in Section 4.9.
4. It is checked, whether it is possible to estimate the specified initiation period using the chosen cover (by the contractor) and the chosen exposure time for the concrete. If this is impossible, another mix design and/or another cover is chosen, until the estimated initiation period is equal to or larger than the specified value.
5. The parameter C_1 is now read or calculated for the *marine splash zone*, while D_1 is read or calculated for the *marine immersed zone*, both corresponding to the mix design determined in clause 4. To do this either the equations in Frederiksen et al. [1997a] or the diagrams in Figures 2-4 and Figures 5-7 can be applied. *This is done no matter which marine environment the concrete has to be used in.*
6. The calculated values from clause 5 is now designated C_1' and D_1'.
7. The requirement for the resistance of the concrete to chloride penetration is calculated by existing empirical relations between these two parameters and laboratory measurements acc. to NT BUILD 443, cf. Frederiksen et al. [1997a].The relations are $3 \times C_1' = C_{sp}$, where C_{sp} is the surface chloride concentration determined in the laboratory acc. to NT BUILD 443, and $2 \times D_1' = D_{pex}$, where D_{pex} is the transport coefficient determined in the laboratory acc. to NT BUILD 443.

The requirement for the concrete discussed in Section 4.9 would be $C_{sp} < 1.7 \times 3 = 5.1$ %mass binder content or approx. 1 %mass concrete and $D_{pex} < 84 \times 2 = 168$ mm^2/year, but it is already known from Section 4.9, that this particular concrete only would have an estimated initiation period in the splash zone of 23 years.

As shown before, there is a mutual dependence between the mix design and the acceptance criteria, as the latter is a result of a lifetime estimation based on the chosen binder composition and the relation between water and binder (powder) in the concrete.

4.15 Test methods

A collection of test methods relevant to chloride penetration into concrete is presented in Frederiksen [1997c]. Some of these methods is applicable to pre-testing, while others are meant for inspection testing and if necessary, for preliminary choice of concrete mix design. Methods used for investigations of special conditions regarding chloride penetration into concrete are also presented, e.g. chloride penetration around cracks, construction joints and spacers.

4.16 Pre-testing and inspection testing

When the acceptance criteria for a concrete to a structure is described acc. to the above given guidelines, consequently the concrete must be tested according to NT BUILD 443 at an age of 28 days. This testing can be performed on cast cylinders at pre-testing until it is ensured, that a sufficiently impermeable concrete has been chosen, which meets the acceptance criteria.

At the pre-testing of the trial casting at least three cores should be taken from representative parts of the structure. This has to be done before the concrete age is approx. 7 days in order to start the immersion test in time.

During the inspection testing the attainment of a sufficient resistance to chloride penetration should be verified by drilling concrete cores from the actual structure. The measurement should of course be performed on the concrete cover acc. to NT BUILD 443.

The extent of testing including drilling of concrete cores from the actual structure should be limited, but should, however, be performed to an extent corresponding to other testing of drilled cores. The verification of uniform concrete properties regarding chloride penetration can be performed in the laboratory by measuring the electrical resistivity on standard concrete cylinders, cf. Frederiksen [1997c].

5 Execution

The contractor is responsible for the construction work and must make plans for the work in such a way that the designers requirements and specifications are met. It is presupposed that the work is done by a contractor that has the concrete delivered from a ready mixed concrete factory whether it is his own or an external one.

5.1 Concrete mix design

The supplier of concrete should give a proposal for a concrete mix design so that the requirements for the durability and the maximum reinforcement cover can be met. At the same time other durability requirements (e.g. freeze/thaw resistance) and the strength requirement should be taken into account as well as the contractors requirements to the fresh concrete.

The price of the concrete will be important, but it is a well-known fact that the "price" for the concrete is not only the price for the constituents. Expenses for development, pre-testing and current documentation of the concrete in production are considerable parts in the price for the concrete. Naturally the concrete supplier will aim at the cheapest concrete that meet all requirements.

It will require more care to be supplier of concrete in chloride exposed structures than to other structures and so the price must be expected to be higher. Everything considered it will probably be profitable to limit the number of concrete types to one or two, e.g. one specially dense concrete for the marine splash zone and one for the other two marine environments.

Inspiration for choosing the composition of the cementitious may be found in Table 1.

5.2 Methods of execution

The contractor can normally choose between different ways of executing the work. Again the economy plays an important role. Special shuttering systems exist, e.g. textile form liners that improve the outlook and the impermeability of the surface. Such systems can gain shares of the market if the positive effects can be capitalised and counterbalance savings in other parts of the execution phase. The effect of such measures can be tested in the laboratory, cf. Frederiksen et al. [1997c] and can in principle be encountered in the model presented here. It is however not within the scope of this guide to deal with this.

Clamps and spacers are examples of details that should be chosen and made carefully. The adhesion between a smooth plastic surface and concrete is not durable. Spacers should be of a non-corroding material such as concrete. If concrete spacers are used attention should be on the joint between spacer and concrete. Insufficient adhesion and leakiness at the spacers will lead to rapid corrosion of the reinforcement. The impermeability of such a casting can be tested in the laboratory, cf. Frederiksen et al. [1997c].

The cover to reinforcement situated next to holes from clamps shall meet the requirements of the local environment. If the hole from a clamp must be tight special care shall be taken to ensure this.

Experience from large construction works in the early nineties showed that construction joints can be made of high quality. The surface that are to be the construction joint must be cleaned early after the setting, i.e. the day after the casting. The coarse aggregates are laid bare by high pressure sluicing (jet sluicing) with clean water so that the depth of the roughness becomes about 5 mm. The so produced surface must be cleaned for ordinary dust before casting, but it is ready to be part of a construction joint having a tightness almost like that of the rest of the concrete. This can be verified in the laboratory, cf. Frederiksen et al. [1997c].

Repair should be all means be avoided - it is a sign of lacking care and/or bad planning (to also design belongs). Repairs often fail before the rest of the concrete and that is unsatisfactory to all parties. How to handle repairs in the construction phase was given a thorough treatment in the sub task 8 of HETEK. A number of reports and a guide on this topic are available why the readers that are interested in this are referred to those, cf. the list of references in Chapter 9.

Pre-testing shall be regarded as an offer to support the planning of the execution. Regardless of own experience it will always be useful to pay serious attention to the pre-testing because possible problems of an approaching production phase can be discovered and the necessary steps can be taken for correction. It is difficult to remove hardened reinforced concrete! Pre-testing was given a thorough treatment in the sub task 7 of HETEK. A number of reports and a guide on this topic are available why the readers that are interested in this are referred to those, cf. the list of references in Chapter 9.

The casting itself can determine the quality of the result. How to design, cast and compact were given a thorough treatment in the sub task 5 of HETEK. A number of reports and a guide on this topic are available why the readers that are interested in this are referred to those, cf. the list of references in Chapter 9.

A cost demanding activity is the curing. Since the beginning of this century it was believed that prolonged curing time gave the best result. Experience and studies have showed that what is lost in the days just after the casting will be caught up later because rain and moisture from the surroundings will help. Different curing methods were given a thorough treatment in the sub task 6 of HETEK. A number of reports and a guide on this topic are available why the readers that are interested in this are referred to those, cf. the list of references in Chapter 9.

5.3 The effect of fine cracks

In Frederiksen et al. [1997a] a theoretical study of the effect of fine cracks on chloride penetration into concrete. Fine cracks are defined as cracks having widths between 0.01 mm and 0.1 mm. Fine cracks often originate from the execution phase caused by differential elongation in the concrete, e.g. due to heterogeneous shrinkage or constraints due to the temperature development of hardening concrete.

In Frederiksen et al. [1997a] it is shown that if fine cracks perpendicular to the surface do *not* pass through the cover then the *distance* between the cracks and *length* of the cracks determine the reduction of the effective thickness of the concrete cover, cf. Figure 12.

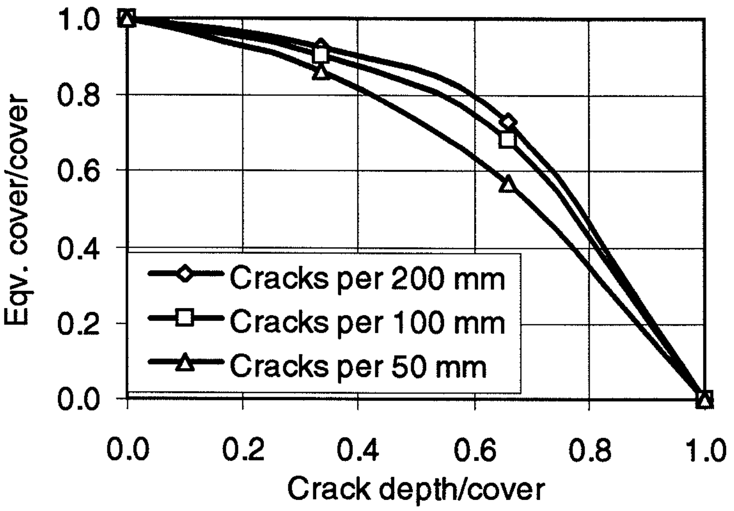


Figure 12. The effect of the depth of the crack perpendicular to the surface on the equivalent thickness of the concrete cover at different intensities of fine cracks, cf. Frederiksen et al. [1997a].

6 Service and maintenance

The building owner has also commitments. In order to prevent premature deterioration the building should be kept under qualified surveillance. It may be necessary to support the surveillance with analyses to ensure that maintenance and repair are done at the right time.

6.1 Economical aspects

Expenses for frequent inspection of a building should be kept on a reasonable level. The resources should however be sufficient to maintain a conviction the everything is as planned.

It is evident that for a building were execution phase was problematic and where maybe a number of repairs were done will need more surveillance than a building where the execution phase was successful. Most construction works do however not follow the intentions, but that does not necessarily mean heavily increased expenses for the frequent surveillance.

6.2 Inspection plan

As it appears from Chapter 4 it will be appropriate with an effort of inspection that in the beginning takes place with short time intervals but where the intervals are doubled until they have reached a duration of approx. 10 years. By way of example inspection times, counted from the time of exposure, at ½, 1, 2, 4, 8, 16, 25, 35, 45 years etc. would be appropriate.

The purpose of the intensive inspection at the beginning is to gain time for reaction if the development suggest that the chloride penetration takes place faster than expected. Moreover a better basis for verification or adjustment of the models.

6.3 Extent of inspection

For the structure in question one has to decide a reasonable number of local environments to split up the structure into. The bigger the structure the more local environments. The three local environments (cf. Section 4.3) are most likely an appropriate maximum for most marine bridges. The more complex road environment has more local environments (cf. Section 4.7). But as road bridges often are considerable smaller than marine bridges it will not be reasonable to split up the structure into more local environments. Thus a coarser grouping should be used.

If the structure has more than one class or type of concrete is exposed to chloride the number of samples should be increased correspondingly.

One local environment can have different degrees of chloride exposure. As an example the lee side compared to the dominating wind direction on a bridge pier be exposed to the worst chloride action. In Nilsson et al. [1996] and in Frederiksen et al.

[1997a] it is described in more details how the environmental actions can vary on different structures.

If the purpose of the inspection is to get or gain knowledge about the progress of the chloride penetration in general, the samples should be taken so that the following requirements are met:

- The samples should be taken in areas without local defects.
- The samples should to the extend possible be taken so that enough room for following samples.
- The samples should represent the most intense action of the local environment.

If the owner wants to monitor the structure by using analyses directly on the structure the necessary measures should be taken already at the design stage.

6.4 Inspection methods

In a definite structure it may be reasonable to survey the action of the chloride by using inexpensive methods; to those belongs:

- experience,
- visual methods and/or
- quantitative chloride analyses.

For this purpose liberty in the choice of method is acceptable because the "measurements" only have a relative meaning within the particular structure.

The greater part of an inspection takes place visually and extensively use of photos. As the chloride penetration is not visual only measurable appropriate samples for this purpose shall be taken.

The sampling must take care of the continued use of the structure. Core drilling using a water cooled diamond tool and subsequent analysis in laboratory conditions should be preferred because the measurements of chloride profiles can be adjusted so that every point of the chloride profile gives the best information possible. In Frederiksen et al. [1997c] are presented suitable test methods for this purpose.

It should more over be considered to make moisture profiles. Experience from Andersen et al. [1996] is that in covered parts of the structures of the road environment the moisture content may be so low that the chloride ingress is prevented.

It is essential to locate the reinforcement before core drilling both because damages to the reinforcement are avoided and because the cover thickness can be measured (provided that the dimension of the reinforcement is known). The drilling positions are recorded on a rough outline and/or by a photo.

In Andersen [1996] it is demonstrated how important it is to measure the depth of carbonation in connection to the measurement of chloride profiles because deviations from the normally expected curvature often can be explained by changes in the cement paste often due to carbonation.

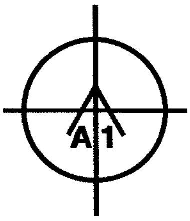


Figure 13. Indication of the end of a drilled core. The arrow marks "upwards" or "North" from a horizontal or vertical core respectively. On a horizontal core the level of the horizontal line should be noted as the level of the sample.

6.5 Maintenance and surface protection

Good concrete and a suitable design requires little maintenance while bad concrete and/or unsuitable design requires much maintenance. In case of the latter can surface protection with paint be a satisfactory solution.

Measures for maintenance should always be assessed carefully as regards the profitability because the concrete and the design were made for the environment in question. Even simple measures of maintenance that are repeated year after year can be unprofitable compared to "chance it".

Decision about maintenance measures should be taken on a safe basis and if the development have been followed carefully the right maintenance measure can be executed at an optimum time. Then the maintenance measure will be profitable.

6.6 Repairs

Prevention is usually cheaper than cure. By planned and frequent inspection one can gain an insight into the development of the chloride ingress and there should be no need for repairs. Local defects often give rise to repair measures. Such repairs should however be assessed in general because the structural importance can be small while the visual significance can be great.

7 Summary of the sub task

This chapter summarises this HETEK sub task. The intention is to give an overview of the reports and the main results from the sub task - and where to read what. All the reports were prepared in English. Only this guide exists in Danish as well.

7.1 State of the art at the beginning of the sub task.

Nilsson et al. [1996] first introduce the reader to the subject by some qualitatively descriptions of the complex coherence that govern chloride penetration into concrete. Then mathematical models are described and evaluated in connection with experimental experiences about chloride binding, diffusion and other types of chloride transport in concrete. The effect of the decisive parameters is described. Corrosion initiation and predictions models are described.

The report concludes that the "old" model basis has been misused because the difference between material properties and apparent (or achieved) properties was not recognised. The material properties may be constants while the achieved properties are time dependent.

The lack of knowledge about chloride penetration into concrete is summarised and the needs for further clarification are identified. High in the list of priorities were the following:

- Conditions for corrosion initiation.
- Test methods for convection of chloride.
- Transport processes in non-saturated concrete.
- Chloride binding, the effect of different binders and temperature variations.
- Mechanical properties of reinforcement having a chloride attack.
- Studies of the environmental conditions in-situ in wetting and drying conditions.
- True electrochemical potentials depending on the local environment in-situ.
- The influence of the micro climate in different positions of a structure on the chloride ingress.
- The relation between "achieved" and "potential" parameters for describing chloride ingress.
- The effect of the time of the year on the transport parameters.
- The possibility of calibrating the models for prediction of chloride penetration at 100 years of natural exposure.

As regards HETEK the following topics were pointed out as the most needed:

- Investigation of the effect of the w/c ratio on the diffusivity
- Comparison of theoretical modelled profiles with profiles measured after a laboratory exposure.
- A limited theoretical analysis and modelling of convection of chloride in concrete under varying environmental conditions.
- Analysis of existing and new field measurements from Danish road bridges.
- An analysis of the road environment with exposure to de-icing salt.
- An improvement and theoretical verification of the analytical prediction method(i.e. the empirical model or the *Mejlbro-Poulsen model*) for use in the road environment.

The aim of the supplementary research and unravelling was to meet the above mentioned points as well as possible within the limits of the project.

7.2 Investigation of the effect of the *w/c* ratio

The effect of the w/c ratio on the permeability in general and especially on chloride diffusivity has been known for a long time. Lately new and better test methods for determination of parameters for the description of chloride ingress was developed. The relations between the new methods were missing together with the effect of the w/c ratio on the determined transport parameters, cf. Frederiksen et al. [1996].

Seven concretes made of the Danish Low Alkali Sulphate Resisting Portland Cement having a constant volume of cement paste, but different *w/c* ratios was investigated. Three test methods were used: NT BUILD 443, Accelerated Chloride Penetration, CTH-Rapid Method, that involves an electrical field and APM 219, an electrical resistivity measurement.

A clear and unambiguous relation between the *w/c* ratio and the transport parameters was found. As expected agreement between the NT BUILD 443 and the CTH method was found for the investigated types of concretes (free of any pozzolana, i.e. fly ash, micro silica and slag). In addition it was found that the resistivity measurement are able to give reliable results that are useful for quality testing a concrete production. The resistivity measurement is inexpensive and quick to perform, but it is the least sensitive measurement of the three tested methods.

7.3 Investigation of Danish road bridges

The development of the chloride ingress into five Danish road bridges was investigated, cf. Andersen [1996]. The investigation was started from earlier investigations of which only few had an acceptable quality as basis for the further investigations. The previous investigations were all from pillars why all the new measurement in this investigation were repeated on those parts of the structures. The previous investigations were all from 1991-92.

To the extent possible the new samples were taken in the immediate vicinity of the previous samples. This enabled good comparisons to the previous chloride profiles so that the development in time of the chloride ingress could be analysed. At the same time the moisture profiles were measured.

The investigations showed no or only insignificant further chloride ingress. The moisture measurements showed a concrete humidity of about 70-80 % RH, which is a little lower than the humidity in Copenhagen that on an annual basis is approx. 79%

RH in average. The investigations confirmed earlier investigations on the point that the chloride exposure decreases with increasing height above the road level. Finally the investigations showed an increased chloride exposure on the back side compared to the front facing the traffic.

Some of the observations were surprising but they gave rise the a deeper understanding of the way of presenting the problem:

- When the concrete is sufficiently dry (humidity of 70-80% RH) the chloride ingress only proceed very slowly or do not proceed at all.
- An explanation of why the concrete in the investigated parts of the structures (pillars below bridge decks) were "dryer" than the annual average of the surroundings, could be that the radiation (cooling) to the sky during the night is restricted (which leads to a little higher temperature of the structure compared to the surrounding air so that the relatively low humidity of the concrete can be explained by this).
- Due to the previous explanation to main groups of local road environments may exist: a "dry" and a "wet" road environment.

Still enough understanding of the road environment is missing. Research is going on in the Swedish research project "Durability of Concrete Structures exposed to De-icing salt". Preliminary results from that project have been used in this project, but within a few years better understanding may be achieved to the "riddle" of the road environment.

7.4 Theoretical background for estimation of chloride ingress into concrete

The report Frederiksen et al. [1997a] is the theoretical background for the chloride penetration models and the recommendations of this guide. The report consists of three parts: Models, Data and Design.

The first part contains the complete scientific basis for the models and examples of the use and the performance of the models in relation to laboratory measurements and mutually. In addition is described the effect of cracks both from a theoretical point of view and in practice concerning reinforcement corrosion.

The second part presents the data that is the basis for the recommendations given later.

The third part presents the design related aspects. Suggestions are given for concrete and environmental dependent models for specific parameters together with examples of the use of the parameters. Further it is shown how to apply the Mejlbro-Poulsen model in design of new marine structures and when inspecting existing structures.

The report summarises the findings and gives conclusions from which it is accentuated that substantial uncertainties have been revealed.

7.5 Collection of test methods

In order to complete the project a number of relevant test methods were put together in one volume, cf. Frederiksen et al. [1997c]. The report gives full copies of the detailed test methods being a part of the basis for most of the work done in connection with the development of the described models. The test methods are all tried out in laboratory conditions and were found suitable:

- NT Build 208, Hardened Concrete, Chloride Content.
- NT Build 357, Concrete, Repairing Materials And Protective Coating: Carbonation Resistance.
- NT Build 443, Hardened Concrete, Accelerated Chloride Penetration (formerly known as APM 302).
- APM 207, Concrete Testing, Hardened Concrete: Micro Chloride Profile.
- APM 214, Concrete Testing, Hardened Concrete: Calcium Content.
- APM 219, Concrete Testing, Hardened Concrete, Electrical Resistivity.
- APM 303, Concrete Testing, Hardened Concrete, Determination of threshold value for corrosion initiation (in Danish).
- APM 321, Concrete Testing, Hardened Concrete, Qualitatively 2D chloride penetration (in Danish).
- APM 402, Concrete Testing, Hardened Concrete, The chloride barrier effect of paint on concrete.
- CTH Rapid Method: Recommended Procedure for Determination of Chloride Diffusion Coefficient by using CTH Rapid Method.

The report depict the field of application for each of the test methods.

8 Conclusion

The presented system for estimation of service lifetime can be regarded as complete with respect to the marine environment, while the road environment only was treated qualitatively due lack of access to good data from existing structures and systematically data from field exposure tests.

Even though the "service life system" can be regarded as complete with respect to the marine environment it has not been tested in practice and possible weaknesses connected to the application is not revealed. Moreover the uncertainty is unknown, but *significant deviations* between "the actual initiation periods" and "the predicted ones" using this system.

The strength of the "system" is that the *Mejlbro-Poulsen model* was build on a coherent narrative mathematical basis adapted to practical experience. To this a number of data are linked so that the effect of different environmental conditions and concrete mix designs can be estimated. Finally simple relations between field data and laboratory data were found and operational acceptance criteria were formulated. The entire system is to the extend possible based on objectivity towards experience (the field data from Träslövsläge). The weakness of the "system" is paradoxically that it is based on experience. The experience will always be claimed to be "too little" or too poor", but the only solution to this is: to collect more good data!

9 References

Below are given the references to all the reports and guides published under the entire HETEK project. Normally the reports are written in English, but main reports and guide exist both in Danish and English versions.

Sub task 1, Chloride penetration into concrete

Nilsson et al. [1996]: Report No. 53
Title: HETEK, Chloride penetration into concrete, state-of-the-art, Transport processes, corrosion initiation, test methods and prediction models
Authors: L.-O. Nilsson, E. Poulsen, P. Sandberg, H. E. Sørensen, O. Klinghoffer

Frederiksen et al. [1996]: Report No. 54
Title: HETEK, The effect of the *w/c* ratio on chloride transport into concrete - Immersion, migration and resistivity tests
Authors: J. M. Frederiksen, H. E. Sørensen, A. Andersen, O. Klinghoffer

Andersen [1996]: Report No. 82
Title: HETEK, Investigation of chloride penetration into bridge columns exposed to deicing salt
Author: A. Andersen

Frederiksen et al. [1997a]: Report No. 83
Title: HETEK, A system for estimation of chloride ingress into concrete, Theoretical background
Authors: J.M. Frederiksen, L.-O. Nilsson, E. Poulsen, P. Sandberg, Tang L. & A. Andersen

Frederiksen et al. [1997b]: Rapport nr. 87
Title: HETEK, Chloridindtrængning i beton - vejledning
Authors: J.M. Frederiksen & E. Poulsen

Frederiksen et al. [1997c]: Report No. 94
Title: HETEK, Chloride Penetration into Concrete - Relevant test methods
Editor: J. M. Frederiksen

Frederiksen et al. [1997b]: Report No. 123
Title: HETEK, Chloride penetration into concrete - guide
Authors: J.M. Frederiksen & E. Poulsen

Sub task 2, Freeze/thaw resistance

Report No. 55, 1996
Title: HETEK, Method for test of the Frost Resistance of High Performance Concrete, State of the Art
Authors: Peter Laugesen, Mette Geiker, Erik Jørgen Pedersen, Niels Thaulow, Finn Thøgersen

Report No. 86, 1996
Title: HETEK, Method for test of the Frost Resistance of High Performance Concrete, Supplementary Research.
Authors: Kirsten Eriksen, Anders Henrichsen, Jens Ole Frederiksen, Mette Geiker, Per Goltermann, Bent Grelk, Peter Laugesen, Erik Jørgen Pedersen, Niels Thaulow, Finn Thøgersen.

Report No. 93, 1997
Title: HETEK, Method for test of the Frost Resistance of High Performance Concrete, Performance Testing Versus In Situ Observations.
Authors: Kirsten Eriksen, Anders Henrichsen, Jens Ole Frederiksen, Mette Geiker, Per Goltermann, Bent Grelk, Peter Laugesen, Erik Jørgen Pedersen, Niels Thaulow, Finn Thøgersen.

Report No. 97, 1997
Title: HETEK, Method for test of the Frost Resistance of High Performance Concrete, Summary, Conclusions and Recommendations.
Authors: Anders Henrichsen, Peter Laugesen, Mette Geiker, Erik Jørgen Pedersen, Niels Thaulow.

Report No. 105, 1997
Title: HETEK, Frostprøvningsmetoder til bestemmelse af højkvalitetsbetons frostbestandighed. Opsummering, konklusion og anvisning.
Authors: Anders Henrichsen, Peter Laugesen, Mette Geiker, Erik Jørgen Pedersen, Niels Thaulow

Sub task 3+4, control of early age cracking

Report No. 52, 1996
Title: HETEK, Control of Early Age Cracking in Concrete, State of the Art
Authors: Erik Steen Pedersen, Helle Spange, Erik Jørgen Pedersen, Anders Boe Haugaard-Nielsen, Jacob Hougaard Hansen, Ole Mejlhede Jensen, Birgitte Friis Dela

Report No. 59, 1996
Title: HETEK, Control of Early Age Cracking in Concrete, Phase 1: Early Age Properties of Selected Concrete
Authors: Helle Spange, Erik Steen Pedersen

Report No. 98, 1997
Title: HETEK, Control of Early Age Cracking in Concrete, Phase 8: Modelling of Support Conditions.
Authors: Helle Spange, Erik Steen Pedersen.

Sub task 5a, Structural design and execution

Report No. 85, 1997
Title: HETEK, Structural Design and Workmanship, State of the Art
Authors: Find Meyer, Erik Skettrup

Report No. 95, 1997
Title: HETEK, Vejledning i udformning som forbedrer udførelsen af armerede betonkonstruktioner.
Author: Find Meyer

Report No. 96, 1997
Title: HETEK, Guidelines for Structural Detailing to improve Concreting
Author: Find Meyer

Sub task 5b, Poker vibration

Report No. 74, 1997
Title: HETEK, Anvisning i stavvibrering
Authors: Jens Frandsen, Karin-Inge Schultz

Report No. 81, 1997
Title: HETEK, Recommendation for Poker Vibration
Authors: Jens Frandsen, Karin-Inge Schultz

Report No. 88, 1997
Title: HETEK, Undersøgelse af stavvibrering
Authors: Jens Frandsen, Karin-Inge Schultz

Report No. 89, 1997
Title: HETEK, Investigation of Poker Vibration
Authors: Jens Frandsen, Karin-Inge Schultz

Sub task 5c, Laboratory investigation of poker vibration

Report , 1996
Title: HETEK, Laboratorieundersøgelser af vibrering, Afgangsprojekt, efterår 1996. DTU - Institut for Anvendt Bygge- og Miljøteknik
Authors: Anne Kirstine Gjaldbæk, Pernille Konner

Report No. 90, 1997
Title: HETEK, Laboratory Tests of vibration
Authors: Anne Kirstine Gjaldbæk, Pernille Konner, Jens Frandsen

Sub task 6, Curing

Report No. 37, 1996
Title: HETEK, Curing, State of the Art
Authors: Anette Berrig, Marlene Haugaard, Per Fogh Jensen

Report No. 38, 1996
Title: HETEK, Curing, Supplementary Research, Proposal
Authors: Marlene Haugaard, Anette Berrig

Report No. 73, 1996
Title: HETEK, Curing, Phase 1: Laboratory Tests
Authors: Kirsten Riis, Marlene Haugaard

Report No. , 1997
Title: HETEK, Curing, Phase 2: Evaluation of Test Results
Authors: Tommy Nielsen

Sub task 7, Guide for Trial Castings

Report No. 40, 1996
Title: HETEK, Guide for Trial Castings, State of the Art
Author: Find Meyer

Report No. 65, 1996
Title: HETEK, Pre-Testing of Concrete, Constituent Materials, Composition and Workmanship
Author: Find Meyer

Report No. 84, 1996
Title: HETEK, Test Panels and Exposure Sites
Authors: Find Meyer, Lasse Toft

Rapport Nr. 91, 1997
Title: HETEK, Forprøvning af fremstilling af betonkonstruktioner. Hovedrapport og orienterende beskrivelse
Author: Find Meyer

Report No. 92, 1997
Title: HETEK, Pre-Testing of Concrete Properties and Workmanship. Main Report and Guidelines
Author: Find Meyer

Intern rapport, 1996
Title: State of the Art, Bilagsrapport. Oplysninger fra 12 projekter

Sub task 8, Repairs during the Construction Phase
Report No. 67, 1996
Title: HETEK, Repair during the Construction Phase, State of the Art
Authors: Ole Viggo Andersen, Anders K. Christoffersen, Bodil Børgesen, Bent Foverskov

Report No. 68, 1997
Title: HETEK, Repairs during the Construction Phase, Field Studies
Authors: Ole Viggo Andersen, Anders K. Christoffersen, Bodil Børgesen

Report No. 69, 1997
Title: HETEK, Guidelines for Repairs during the Construction Phase
Authors: Ole Viggo Andersen, Anders K. Christoffersen, Bent Foverskov

Internal reports:
1996
Title: HETEK, Reparationer i udførelsesfasen. Afvigelser i udførelsesfasen

1996
Title: HETEK, Reparationer i udførelsesfasen. Arbejdsprocedurer for reparationer

1996
Title: HETEK, Reparationer i udførelsesfasen. Oversigt over reparationsmaterialer

1996
Title: HETEK, Reparationer i udførelsesfasen. Prøvningsmetoder og godkendelseskriterier

1996
Title: HETEK, Reparationer i udførelsesfasen. Billedmateriale

1997
Title: HETEK, Reparation i udførelsesfasen, Feltstudier. Bilagsrapport