ENVIRONMENTAL ACTIONS AND RESPONSE – REINFORCED CONCRETE STRUCTURES EXPOSED IN ROAD AND MARINE ENVIRONMENT

Anders Lindvall
Ph.D.-student
Department of Building Materials
Chalmers University of Technology
SE-412 96 Göteborg
E-mail: lindvall@bm.chalmers.se

ABSTRACT

In this paper a recently published licentiate-report is presented and summarised. The report deals with environmental actions on and response from reinforced concrete structures and how they influence and limits the service life. It is described how the degradation of reinforced concrete structures takes place and how it can be predicted with mathematical models. A methodology to assess the environmental actions is presented, where they are divided into four different levels depending on the dimensional scale. Finally a survey of environmental actions and response on seven road bridges around Göteborg is presented.

Key words: Environmental actions, Service life design, Chloride penetration, Moisture conditions, Road exposure, Reinforcement corrosion

1. INTRODUCTION

1.1 General

In this paper a recently published licentiate-report [1], written by the author, is presented and the content is summarised. The emphasis of the paper is put on environmental actions and response from reinforced concrete structures. To describe the environmental actions on a concrete structure a division is made into four levels depending on dimensional scale. The most accurate way to describe the environmental actions is to describe them as surface temperature, humidity, wetness and chloride conditions. The response from the concrete can be expressed as temperature and moisture conditions, carbonation depths and chloride penetration. The response from concrete structures is exemplified in a field survey of moisture and chloride conditions and frost action in seven concrete bridges around Göteborg have been performed.

1.2 Background

The expenses for repair, maintenance and remediation of existing reinforced concrete structures have significantly increased during the last decade. A large part of these expenses can be related to problems with lacking durability of the structure. Thus, to reduce the expenses there is a need to design for service life, where the total lifetime for the structure is designed. In the design for service life it is also included how the properties of the reinforced concrete change over time due to degradation. Examples of degradation processes, which change the properties of reinforced concrete, are reinforcement corrosion, initiated by chloride ingress or carbonation, frost attack and alkali-aggregate reactions (AAR).

The degradation of reinforced concrete is influenced by a number of parameters. It is possible to identify three principal parameters: (1) Material properties, (2) Execution during construction and (3) Environmental actions. The designer can choose the material properties and how the execution during construction should be made. However, the environmental actions mainly follow from the location of the (future) structure and are only possible to influence in a limited way. Additionally the material properties and environmental actions change over time, due to continuous cement hydration and seasonal variations respectively. Thus, to design for service life it is required to have sufficiently realistic mathematical models that describe how the material properties and environmental actions vary over time.

The service life can be designed with two principal methodologies: deem-to-satisfy rules, and performance-based design. The deem-to-satisfy rules are usually based on rules-of-thumb, e.g. by specifying a certain concrete composition and/or concrete cover, and the result will be a long but not specified service life. The performance-based design is based on requirements of performance from the structure, e.g. load-bearing capacity or aesthetic appearance, and the result will be a long and specified service life. The performance requirements are specified with so-called limit-states.

Until now large research-efforts have been made to clarify which influence the material properties, and to some extent the execution during construction, have on the degradation of concrete. However, good data about the influences from the environmental actions and the response from the concrete are lacking. Since data on the environmental influence are lacking the result may be that the service life designs have large statistical uncertainties. Thus there is a need to further investigate and quantify the environmental actions and response from concrete structures.

My work has been concentrated on to make an investigation of available models to determine the environmental actions on concrete structures and the response from the concrete. The investigation has been made both as a literature review and field studies. The literature review has been focused on environmental actions and response and degradation of concrete. The data from the field studies have been used to develop and quantify models.

1.3 DuraCrete

The PhD-project described in this paper was initiated during the DuraCrete-project, summarised in [2]. In the DuraCrete-project a new performance based service life design methodology for reinforced concrete structures has been developed. With this design methodology it is possible to model the complete service life for a reinforced concrete structure, i.e. from casting, until degradation has put the structure into an adverse state, e.g. when the bearing-capacity is insufficient. The project has been partly financed by the European community and 12 partners around Europe have been involved.

In the DuraCrete-project the service life has been modelled with a performance based methodology and determined with probabilistic methods. The service life is modelled as initiation and propagation of reinforcement corrosion, consequences of reinforcement corrosion and finally structural consequences. The different models consist of three principal parameters describing the influence from material properties, execution during construction and environmental actions. The probabilistic methods make it possible to also consider statistical uncertainties related to the parameters used to describe the influence from material properties, execution during construction and environmental actions.

2. SERVICE LIFE FOR REINFORCED CONCRETE STRUCTURES

In this section a short introduction of how the service life of reinforced concrete structures can be made is given. For a more detailed description see [1].

2.1 General

The degradation of reinforced concrete structures takes in a number of chemical and physical processes. The most common are: (1) Reinforcement corrosion, (2) Frost attack, (3) Alkali-aggregate reactions (AAR), (4) Sulphate attack, (5) Leaching and (6) Seawater attack.

To be able to explicitly predict the degradation of concrete in a quantitative way there is a need for mathematical models. Usually a division is made between physical and empirical models:

- **Physical models.** Physical models are based on theories on how reactions and transport of different substances takes place in a material. Together with knowledge about initial and boundary conditions, it is possible to make careful predictions of how different substances are transported into a material. The models are often quite complicated and they require an extensive validation before they can be used to make practical predictions. The predictions with physical models usually require numerical methods, e.g. finite difference or element methods to be made, which means that computers have to be used.
- **Empirical models.** Empirical models are based on observations of response from structures, exposed either in field or in laboratory. The observations are used to derive and quantify the parameters in the models. The models are often quite simple and observations are used to derive and quantify the parameters. This means that the models do not need that much validation before they can be used for practical predictions. Since the models often are quite simple they usually can be solved without computers.

However, there is a danger to use observations from already built structures, which is the case with empirical models, since they are influenced both by the materials, environments and the workmanship during construction. All these factors may change, e.g. if a new concrete composition is introduced, which means that the old observations cannot be applied on a structure where a new material will be used. Additionally data from long-term exposure are missing.

Example of a physical model to predict chloride penetration is ClinConc (Chlorides in Concrete) [3], where the predictions are based on mass balance relations that can be defined for concrete. Examples of empirical models to predict chloride penetration are Fick's 2^{nd} law of diffusion (when applied on concrete), DuraCrete-model [4] and Mejlbro-Poulsen-model [5].

2.2 Service life design

There are two principal methods to determine the service life of reinforced concrete structures, namely deem-to-satisfy rules and performance based design.

Deem-to-satisfy rules are usually based on experiences from previously built structures, expressed as rules-of-thumb. The rules-of-thumb usually specify that a required service life can be reached by using a certain concrete mix and concrete cover. The result will be a structure with sufficiently long but not specified service life. Furthermore the rules-of-thumb only work with known materials, since they are based on experiences from previously built structures, which makes it hard to make service-life designs for structures built with new materials.

In a performance based design, the performance of the structure is specified with so-called limit-states. The limit states can be defined by for example authorities and/or the owner of the structure. To determine the probability that the structure is able to meet the performance requirements, with a specified level of reliability, a probabilistic model is formulated. The probabilistic model is based on (sufficiently) realistic mathematical models, where the different behaviour of the concrete structure is modelled, e.g. chloride penetration, consequences of reinforcement corrosion and load-bearing capacity. The results from the probabilistic calculations are given as probabilities that the structure is in an adverse state (according to what is defined from the limit states), i.e. the required performances are not fulfilled, during the desired service life. The result will be a structure with sufficiently long and specified service life.

3. ENVIRONMENTAL ACTIONS AND RESPONSE

In the following section a brief description of the environmental actions and response on concrete structures is given. A more extensive description is given in [1].

3.1 General

The general approach when the environmental actions on a concrete structure are described and modelled is to separate the actions from the response of the structure. With this approach the environmental actions can be described without knowledge about the nature of the surface and the properties of the bulk concrete. The most correct way to describe the environmental actions on a concrete structure is to express them as surface conditions.

The environmental actions can mostly be described from processes in the atmosphere. When the processes in the atmosphere are studied a division is made into two sciences, [6]:

- **Meteorology**. Meteorology is the science of atmospheric physics where atmospheric processes are analysed, explained and predicted. The weather is the current state of temperature, precipitation and wind in the nearest atmosphere.
- **Climatology**. Climatology is the science of how the climate varies between different areas and on different time-scales. The climate is the history of the weather and it gives a picture of what is normal and the probability of a certain type of weather.

It is convenient to divide the environmental actions into different dimensional scales. These scales have both different horizontal dimensions and time-scales. The following four scales can be defined: (1) **Global climate** – Macro scale, (2) **Regional climate** – Meso scale, (3) **Local climate** and (4) **Surface climate** – Micro scale. These four dimensions are explained further later.

However, it is not enough to know the environmental actions outside a concrete structure to predict the surface climate, since the surface climate is also influenced by the surface conditions. Thus, it is desirable to have knowledge about the response from the structure. The response from a concrete structure can be determined in terms of, with variations in three dimensions and time:

- **Temperature conditions**. T(x,y,z,t).
- **Moisture conditions**. RH(x,y,z,t), TOW (Time of wetness).
- **Chloride conditions**. Cl(x,y,z,t).
- **Carbonation.** CO_2(x,y,z,t).

The environmental actions can be quantified with data measured at a meteorological station. Since a meteorological station usually has somewhat different surrounding conditions compared to the location of a (future) structure the data have to be transformed to this location before they can be used. In [6] a procedure to select climate data for a determination of the surface climate is given. The procedure is divided into four steps: (1) Collection and preparation of weather data, (2) Choice of representative weather data, (3) Choice of specific format for the simulation and (4) Transformation of climate data from a weather station to the surface of the construction. The collection of weather data is standardised and the procedure is described in [7]. How weather data can be collected, prepared and characterised is described in [8].

3.2 Global climate – Macro scale

The global climate can be described with energy and mass balances in the Earth-Atmosphere system. The main parts of the energy balance is incoming solar radiation and outgoing long wave radiation. Energy of importance for the earth-atmosphere system exists in four different forms: radiant, thermal, kinetic and potential energy. The energy is all the time transformed from one form to another within the system.

In a similar way to the energy balance it is possible to establish a water-balance for the Earth-Atmosphere system. There is an exchange of water, in different phases, between the surface of the earth and the atmosphere. This is possible due to the fact that water can exist in three different states of aggregation (phases): vapour (gaseous phase), water (liquid phase) and ice (solid state).

3.3 Regional climate – Meso scale

GENERAL
The regional climate is the climate for a relatively small area, e.g. a town or a valley. It is influenced by the properties of the ground, e.g. type of terrain and vegetation, the topography, by large water bodies the location in relation to urban areas and by the exposure to marine environments. Individual buildings or structures do not influence the regional climate. Special conditions occur in urban areas and areas close roads, where de-icing salts are spread (road environments), and oceans (marine environments). The marine and road environments have influences both on the regional and local climate.

URBAN CLIMATE
In urban areas the climate is influenced from changes in the surface properties and the atmosphere caused by urban activities, e.g. air pollution and release of heat and water to the atmosphere. If the conditions in an urban area are compared with the conditions in a surrounding rural area, the urban climate is usually rougher, warmer and drier. Compared with a surrounding rural area the solar radiation in an urban area may be reduced with up to 20% depending on the topography and the amount of pollutions in the air. The differences in air temperature between urban and surrounding rural areas can be up to 5-6°C, with a maximum difference of up to 12°C [9]. The magnitude of the urban influence on the climate is hard to estimate, since observations of the climate in a region before and after urbanization are very rare.

MARINE ENVIRONMENT
A marine environment is the prevailing environment in and in the vicinity of an ocean or sea. Coastal areas, which can be characterized to have a marine climate, normally reach some 10 km from the coastline, due to wind-blown salt mist. However, at special occasions, e.g. during severe storms, the area influenced by the marine climate can be over 100 km from the coastline. The marine environment is characterized by, [10]: (1) Chemical composition of the seawater, (2) Temperature in the seawater, (3) Wave heights, (4) Hydrostatic pressure, (5) Tidal actions, (6) Water levels, (7) Fog and spray and (8) Currents.

In [11] it is proposed to divide the marine environment into four different zones depending on the position to the water level:

- **Submerged zone**. The zone below the water level, which means that the concrete is subjected a constant moist environment.
- **Tidal zone**. The zone between low and high tide, which means that the concrete is subjected to periodical moistening and drying (with an approximately twelve hour cycle).
- **Splash zone**. The zone over the tide level influenced by the waves, which means that the concrete is subjected to randomly moistening and drying, due to wave-actions.
- **Atmosphere zone**. The zone over the splash zone where the concrete is subjected to humid and saline marine air.

ROAD ENVIRONMENT
The road environment is to large extent influenced by if the road is thaw-salted or not. The road environment is influenced by: (1) The amount and types of de-icing salts spread on the road (2) The amount and types of traffic on the road (frequency of heavy traffic), (3) The geometry of

the road and the surroundings, and (4) The distance to the road. De-icing salt can be spread in five different forms on a road depending on the temperature of the road surface: dry salt, wetted dry salt, salt solution, sand mixed with salt and crushed aggregate and sand mixed with salt. The amount of chlorides spread on the road varies depending on the form the de-icing salt is spread, where dry salt gives the highest amount of chlorides.

The de-icing salt spread on the road can be transported into four principal processes, [12] and [13]:

- **Drainage**. De-icing salts are soluble with water and the brine, formed on the road, is forced to the side by gravitation and/or traffic movements. The drainage increases with rainfall
- **Ploughing**. When the road is ploughed, salt-laden snow is pushed to the roadside.
- **Splash**. Splash is produced by the drainage system of vehicle tyres. It consists both of water and snow-slush. The splash is directed from the car towards the side of the road. It is characterized of relatively large droplets that are not easily caught by wind-streams around vehicles.
- **Aerosols (Spray)**. Aerosols, like splash, originate from the drainage system of vehicle tyres. The aerosols are formed when water is thrown outwards by centrifugal action tangential from the tire tread and it breaks down into small droplets when it hits other parts of the vehicle. It is transported by air streams and may persist in the air behind a vehicle for a long time. The amount of aerosols formed is dependent on the speed of the vehicles.

The transport of de-icing salts from the road can be divided into initial loss and loss with time, [13]. The initial loss depends on the state of the road (mainly wetness condition), the application method and the traffic intensity. Several investigations have been made on how de-icing salt spread on a road is transported into the surroundings. The influence from the de-icing salt spread on a road can be detected up to 100 meters from the road, [14]. The transport of salt from a road is in large extent a function of the car-speed on the road. Another important factor is the duration of the slush on the road surface, where a long time of duration results in larger transport of chlorides and thus larger chloride load. The transport of chlorides is also dependant of the orientation of the road in relation to prevailing winds etc.

In [15], where a survey of 200 motorway bridges in Great Britain is presented, three main sources for exposure of chlorides on concrete road bridge are given:

- **Leakage of chlorides through joints**. The chloride-contaminated slush on the surface on the road may leak through joints and reach for example the underside of the bridge slab.
- **Splash from passing traffic**. The traffic on the road produces splash that hits the parts of the structure that are facing towards the traffic.
- **Spray from passing traffic.** The traffic on the road produces spray (aerosols) that is transported with air-streams towards the structure. This means that the chloride-contaminated spray may reach parts of the structure that are not directly facing towards the traffic.

3.4 Local climate

The local climate is the climate for a structure or a certain part of a structure. It follows from the large-scale geometry and the orientation of the (future) structure. The local climate is influenced by for example the radiation exchange between the ground and/or structure and the sky and air streams, with or without precipitation, around structures. Influencing factors are the surface properties of the ground and/or structures, the large-scale geometry of the structure, providing possible shelter against radiation and wind, the distance to larger urban areas and exposure of seawater and spread de-icing salt.

3.5 Near-surface climate – Micro scale

The microclimate, or near-surface climate, for a structure is influenced by the geometry and surface properties of the structure in question. The microclimate can be expressed in terms of:

- **Temperature conditions.** Expressed as equivalent surface temperatures, $T_{s,eq}$, where effects due to radiation (solar and long-wave radiation), evaporation/condensation, heat transfer (convection and conduction) and material and surface properties are considered. The equivalent surface temperatures are calculated by establishing an energy budget for a surface.
- **Moisture conditions.** Expressed as equivalent surface humidities, $RH_{s,eq}$, and TOW (Time Of Wetness). The equivalent surface humidity follows from the equivalent surface temperature conditions and the TOW is achieved by combining wetness due condensation, precipitation and running water. Both the equivalent surface humidity and the TOW depend on the material and surface properties for the structure in question.
- **Chloride conditions**. Expressed as an equivalent surface chloride concentration, $C_{s,eq}$, which is a combination of the exposure environment, the geometry of the structure and the material and surface properties.

3.6 Response from concrete

The environmental actions on a concrete structure result in a response from the concrete, described in terms of:

- **Temperature conditions**. The temperature conditions in a concrete structure can be predicted with the law of energy conservation. However, since concrete is an excellent heat conductor, which means that temperature gradients are usually small and will disappear rapidly. The temperature conditions are decisive for many deterioration processes.
- **Moisture conditions**. The moisture conditions in a concrete can be determined by solving the law of mass conservation, where the moisture content is expressed as evaporable and non-evaporable water. For porous materials there is a relationship between the evaporable moisture and the RH in the pores called sorption-isotherms. Moisture plays a significant role in chemical reactions in concrete and in parts of physical and chemical processes in concrete.
- **Chloride conditions**. The chloride conditions in a concrete can be determined as chloride penetration profiles. The chloride penetration into concrete is a complicated process, influenced by number parameters, e.g. the chloride concentration in the surrounding environment, the temperature and moisture conditions, wind-streams around the structure etc.
- **Carbonation**. Carbonation in concrete can be determined in terms of carbonation depths.

3.7 Quantification of environmental actions

To be able to make service life designs with the different mathematical prediction models it is necessary to quantify the parameters in the models. The quantification of environmental influence on the deterioration of a concrete structure can be made in the following ways:

- **Environmental actions.** The quantification is based on information about the environmental actions on the structure, i.e. the surface conditions expressed as temperature, moisture, chloride and carbon dioxide conditions.
- **Response from concrete.** The quantification is based on information about the response from the concrete on the environmental actions, i.e. chloride penetration profiles, carbonation depths and moisture and temperature distributions in the concrete. However, the response from the concrete does not only includes effects from the environmental actions but also effects from the material properties, e.g. concrete composition, and the execution during construction.

The presently used prediction models do not include the environmental actions in an explicit way, which means that the environmental influence must be quantified with the response from the concrete. This requires knowledge about how the environmental actions vary over a structure over time and how this influences the response. Information about these variations is still scarce and it has been shown that there can be significant variations, in environmental actions and response, even on one single structure. Additionally data from long-term exposure are missing, which makes it hard to assess to long-term properties of the concrete.

In [4], a procedure to quantify the parameters in degradation is proposed. The parameters in the mathematical prediction models are divided into the following three classes:

- **Construction influences.** Follow from the execution during the construction phase, e.g. the placement of the reinforcement, concrete composition, curing conditions etc.
- **Environmental influences.** Follow from the conditions at the location of the structure, e.g. temperature and humidity conditions.
- **Material influences.** By choosing different binder types, binder content, w/b, type of aggregate etc, it is possible to control the material influences. The material influence can be determined in the laboratory, as for example chloride diffusivities.

The designer can choose how the material and partly the construction influences the performance of the structure, but the environmental influences follows from the conditions at the location of the structure.

4. FIELD SURVEY – RESPONSE FROM CONCRETE

In the following section a field survey of seven concrete bridges around Göteborg is presented. The survey was made in November and December of 1998 and 1999. In this section a short description of the survey and results is given. More extensive descriptions are given in [1] and [16].

4.1 Determination of response

Cores have been taken from the examined bridges by drilling with water-cooling for further analysis in the laboratory to determine the response from the concrete. The response from the examined bridges have been determined in terms of:

- **Chloride penetration**. Presented as chloride penetration profiles, where the quotient between the chloride and calcium content at different depths is shown. The chloride penetration profiles have been determined with powder samples achieved from profile grinding in depth intervals, with increasing intervals with increasing depths. The powder has been dissolved in acid and soda and analysed for chloride and calcium with potentiometric titration.
- **Concrete cover**. The concrete cover has been determined with an electrical cover meter. It should be noticed that the measured cover-depth with an electrical cover-meter is only an approximate value of the cover-depth. To get accurate figures of the concrete cover, cores should be drilled into the reinforcement and the concrete cover measured directly.
- **Visible signs of reinforcement corrosion**. The examined bridges have been examined for visible signs of reinforcement corrosion, e.g. cracks with precipitation of rust or rust stains on the surface of the concrete. With information about the chloride penetration profiles it is possible to determine the chloride threshold value for reinforcement corrosion.

Apart from the investigations mentioned above the bridges have also been investigated for chloride diffusivity with the CTH-method, described in [3] and NT BUILD 492 [17], moisture conditions, profiles with RH and S_{cap}, and frost resistance determined with NT BUILD 376 [18]. However, the results from these investigations are not presented in this paper. Complete listings of all results are given in [1] and [16].

The cores used to determine the chloride penetration had a diameter of 50 mm and the cores used to determine the chloride diffusivity, the moisture conditions and frost resistance had a diameter of 100 mm. More extensive descriptions of the different methods to determine the response from the concrete are given in [1] and [19].

4.2 Examined bridges

Seven bridges around Göteborg have been included in the study. The bridges have been selected in such way that each of them represents typical Swedish concrete road bridges, with an age between 25 and 35 years. With a typical Swedish bridge means that the bridge was designed and constructed according to valid Swedish concrete standards. This means that the bridges have been built with a K 400 concrete, with a cement content varying between 300-360 kg/m^3 and a w/c of 0.45-0.50. All the examined bridges are motorway-bridges, where the motorway crosses, either above or below, another way.

The following bridges have been included:

- **Bridge N 434**. Bridge, built 1972, over the motorway E6, where E6 crosses the road between Kungsbacka and Onsala, approximately 30 km south of Göteborg. The southern side-beam on the bridge slab and the two southern columns (middle and side) at the eastern roadway (direction Göteborg) have been examined.
- **Bridge O 670**. Bridge, built 1968, where the motorway E6 crosses Nordre Älv in Kungälv approximately 20 km north of Göteborg. The western side-beam and the underside of the bridge slab have been examined.

- **Bridge O 707**. Bridge, built 1968, with a combined exit- and entry-road to the motorway E6. The eastern side-beam at the abutment and a column at a local road have been examined.
- **Bridge O 762**. Bridge, built 1974, where the high Rv40 crosses Landvettervägen at Slamby, approximately 13 km east of Göteborg. The northern side-beam and the southern of the eastern columns have been investigated. Bridge O 762 is situated approximately 2 km west of bridge O 978.
- **Bridge O 832**. Bridge, built 1972, with exit and entry to the motorway E20, approximately 7 km east of Göteborg. The bridge is a part of a roundabout over E20. The northern side-beam and the eastern of the northern columns have been examined.
- **Bridge O 951**. Bridge, built 1972, over the motorway E6, where a local road crosses E6 in Lindome, approximately 20 km south of Göteborg. The southern of the middle columns have been examined.
- **Bridge O 978**. Bridge, built 1974, over the motorway Rv40, where a local road crosses Rv40 at Landvetter centre, approximately 15 km east of Göteborg. The western side-beam and the westerly of the middle-columns have been examined. Bridge O 978 is situated approximately 2 km east of bridge O 762.

The concrete covers of the examined bridges were found to vary between approximately 22 mm (underside of bridge slab) and 45-55 mm (side-beams). The low concrete cover on the underside of the bridge slab has probably occurred probably due to insufficient execution during construction and lack of quality control.

4.3 Environmental conditions

The environmental conditions for the different bridges have been determined as the regional climate for the Göteborg-region and the road climate for each bridge. Examples of the regional climate for the Göteborg-region are given in figure 1, where the monthly mean values and 5%- and 95%-fractiles for the air temperature and air humidity over the year are presented. The road climate for the examined bridges is given in table 1.

Table 1 – The road climate for the examined bridges

Bridge	Built	Traffic		De-icing	Lanes	
		Amount [ÅDT]	Speed limit [km/h]	kg/m^2 year	Number	Safety lane
O 978*	1974	26000	110	3.0	2+2	Yes
O 978+	1974	♦	50	♦	1	Yes
N 434*	1972	27000	110	2.8	3+3	Yes
N 434+	1972	♦	70	♦	1+1	No
O 951*	1972	34000	110	2.8	2+2	Yes
O 670*	1968	40000	110	3.1	2+2	Yes
O 670†	1968	♦	♦	♦	2+2	Yes
O 707-	1968	♦	50	2.3	1+1	No
O 707+	1968	2400	50	♦	1+1	No
O 762*	1974	32000	110	3.0	3+2	Yes
O 762+	1974	♦	70	♦	1+1	No
O 832*	1972	50000	90	2.7	3+3	Yes
O 832+/-	1972	13200	50	♦	2	No

* : Motorway.
+ : Local roadway.
- : Exit/entry on motorway.
† : Underside bridge slab.
ÅDT : Mean-traffic during a day.
♦ : not known

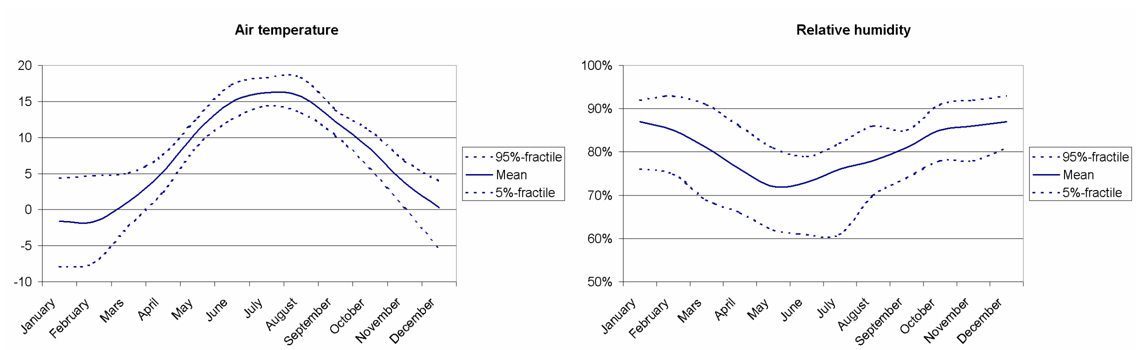

Figure 1 – Variations in monthly air temperatures and humidities in Göteborg. Based on data from [8].

4.4 Results – response from concrete

All chloride penetration profiles are analysed from cores taken during November or December in 1998 or 1999, i.e. before or in the beginning of the season when de-icing salts are applied. When de-icing salts are applied chlorides penetrate into the concrete while during the summer the chlorides in the surface layers of the concrete are washed out. The chloride penetration rate is highest for vertical surface, but the amount total amount of chlorides that penetrate during a winter is higher for horizontal surfaces. This effect is described in [20].

A selection of the chloride penetration profiles from the examined bridges is shown in figure 2. A complete listing of all the chloride penetration profiles is given in [1]. The first index show if the profile comes from a column (C), side-beam (SB) or other part of the structure (Ö), the second index shows which bridge the profile comes from and the third index indicates the name of the profile. The profiles have been analysed after exposure times between 25 and 30 years.

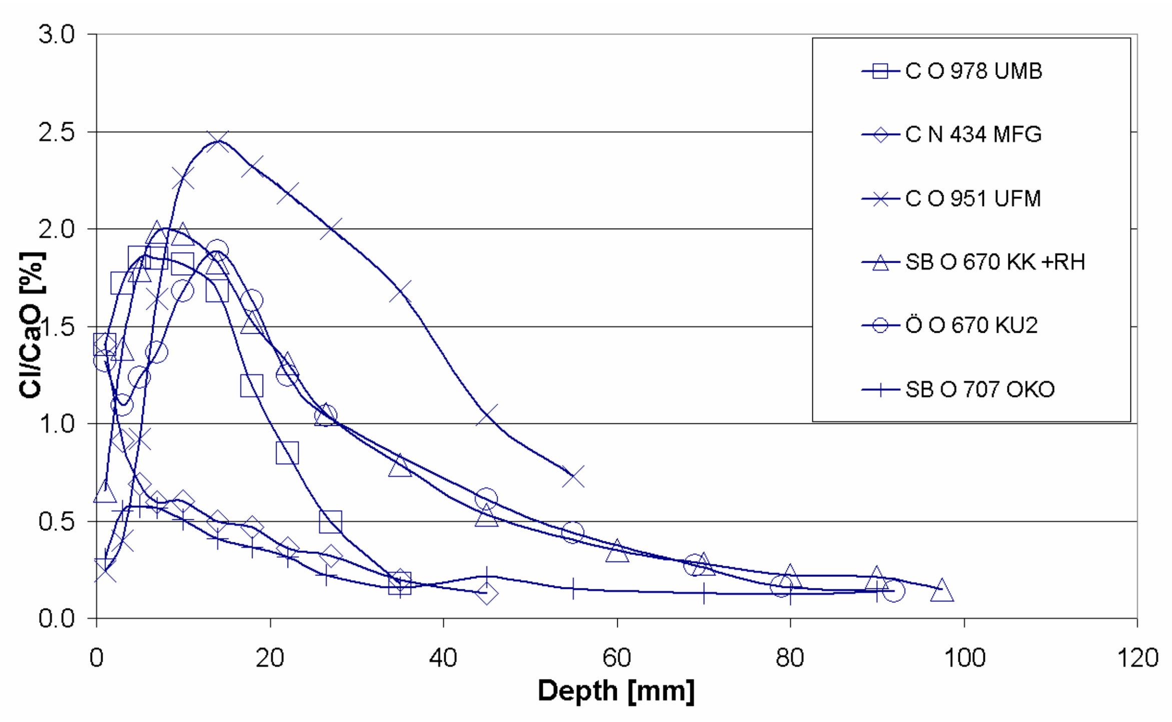

Figure 2 – A selection of typical chloride penetration profiles from the examined bridges.

The chloride ingress in the columns on the bridges O 978, O 951 and N 434 have been investigated on three different heights over the roadway and four different directions towards the traffic. In figure 3a the different sampling spots are presented and in figure 3b the chloride penetration profiles from the column on bridge O 978 are presented. The indexes U, M and Ö show the height over the roadway and the indexes F and M show the orientation towards the traffic. In figure 3b the first letter in the index of each profile shows the height over the roadway and the second and third letters which direction towards the traffic the cores have been taken.

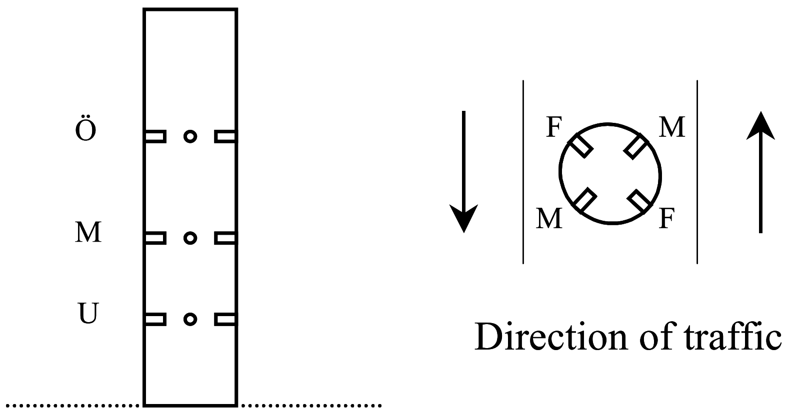

Figure 3a – The different sampling spots in columns on bridge N 434, O 951 and O 978.

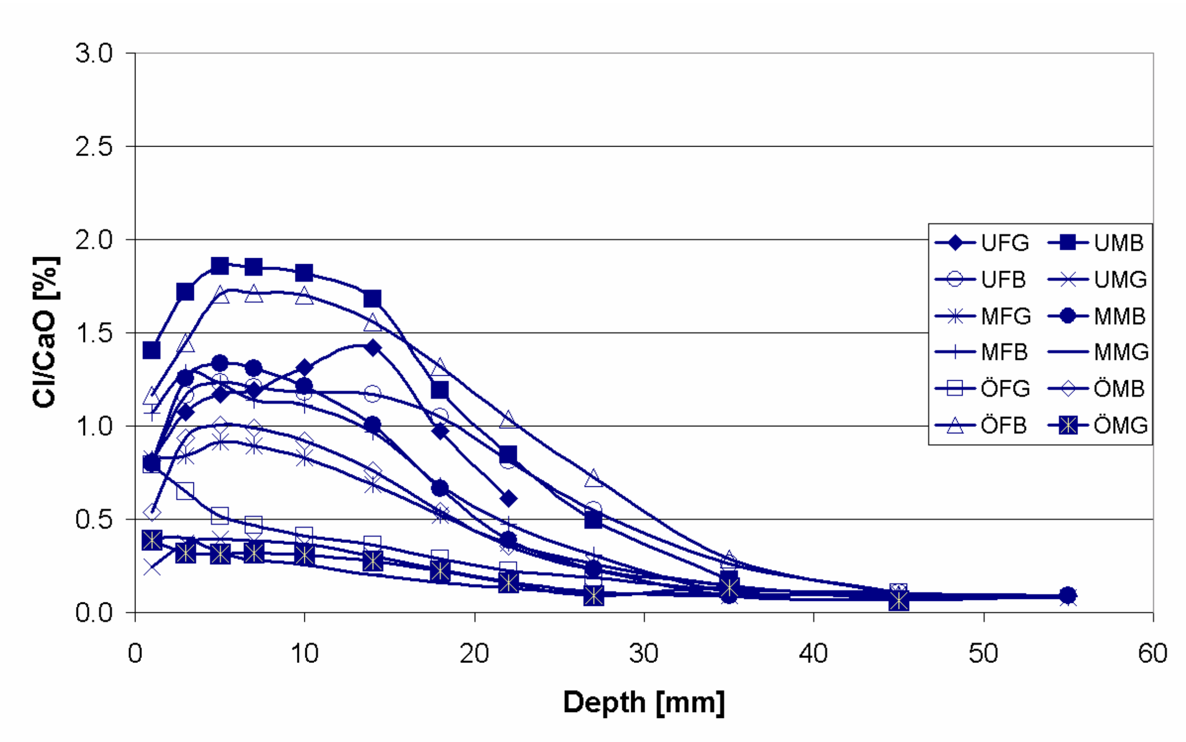

Figure 3b - The chloride penetration profiles from the column on bridge O 978.

5. DISCUSSION AND ANALYSIS

The effect from height over the roadway and orientation towards the traffic has been investigated. Cores have been taken from three different heights in the same orientation direction to determine which effect the height over the roadway has on the chloride penetration on bridge N 434, O 951 and O 978. It is commonly believed that the surface most exposed for chloride penetration is the surface with an orientation of 45º towards the traffic. This is due to the fact that the splash from the traffic on the road usually is orientated with an angle of 45º from the direction of the traffic.

The chloride penetration in bridge N 434 and O 951 was found to agree with the "normal" pattern, with large chloride penetration at the lowest level and little chloride penetration at the highest level. However, on bridge O 978, large chloride penetration was found on the high level, Ö, on a surface orientated towards the traffic. Along the same roadway, on a surface facing from the traffic the chloride penetration is significantly lower on all levels. The chloride penetration profiles are presented in figure 4a, where the profiles from the surface facing towards the traffic from Borås (direction FB) are shown, and figure 4b, where the profiles from the surface facing from the traffic from Borås (direction MG) are shown. The first index indicates the level over the roadway, described in figure 3a.

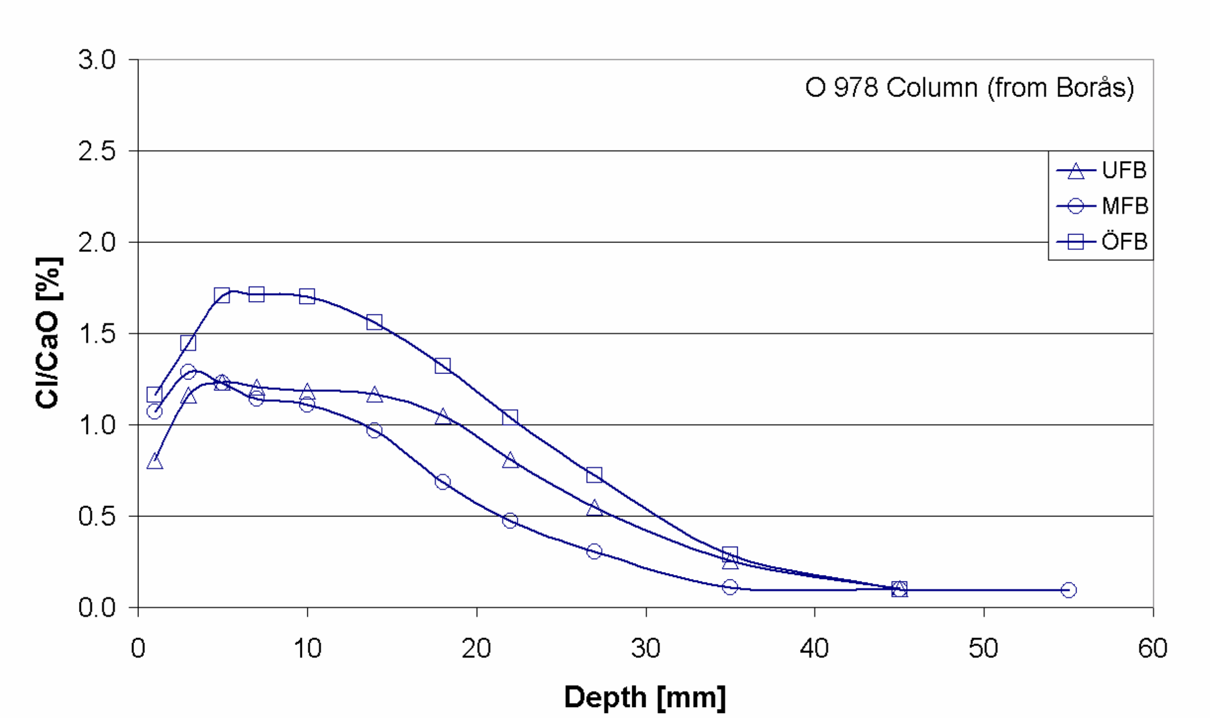

Figure 4a – Chloride penetration profiles from bridge O 978 from the surface facing towards the traffic from Borås (direction FB).

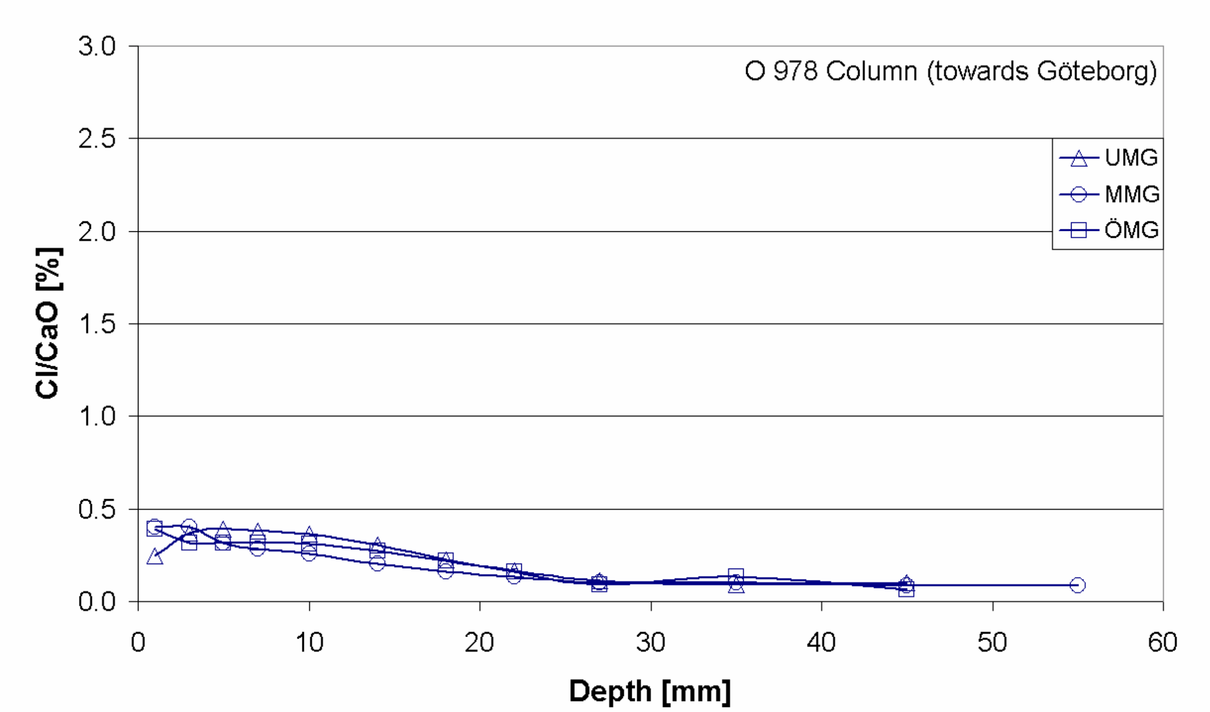

Figure 4b – Chloride penetration profiles from bridge O 978 from the surface facing from the traffic from Borås (direction MG).

A possible explanation to these results can be that the at certain wind directions airborne chlorides, e.g. chloride-contaminated aerosols from the road, will follow air-streams and be deposited on the lee-side (orientation direction FB) of the column. These chlorides will not be washed away but each time with the "right" wind-direction the concentration of chlorides will increase. In orientation direction MG deposited chlorides are constantly washed away on all heights over the roadway, which result in low penetration depths. A schematic pattern for the wind-streams around bridge O 978 is shown in figure 5. The dominating wind-direction is from the west.

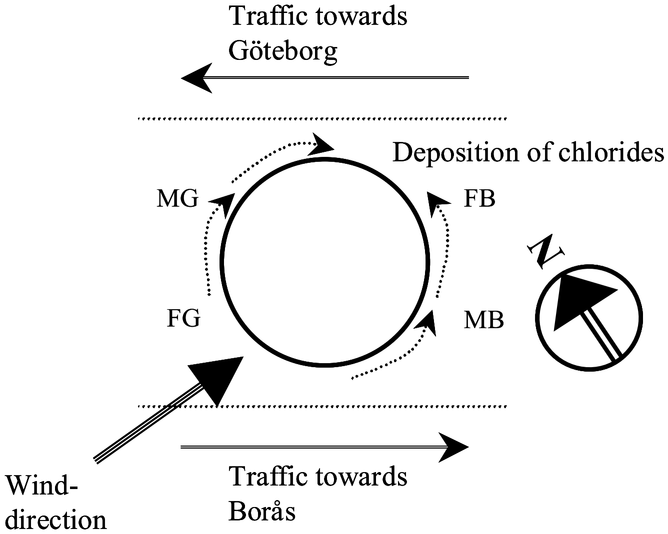

Figure 5 – Schematic picture of the wind-streams around bridge O 978. Dominating wind-direction is from the west.

The application of de-icing salts is normally during the nighttime or early in the morning. Thus, the surfaces on a road concrete structure exposed to splash from the morning traffic should also be the surfaces with the highest chloride exposure. This can be observed on bridge O 951 where the surface orientated towards the traffic towards Göteborg (orientation direction FM) has larger chloride penetration depths compared to the other surfaces. In figure 6a the chloride penetration profiles from the lowest level is shown and in figure 6b the chloride penetration profiles from the middle level are shown. The traffic intensity under bridge O 951 is high towards Göteborg in the morning and from Göteborg in the afternoon/evening.

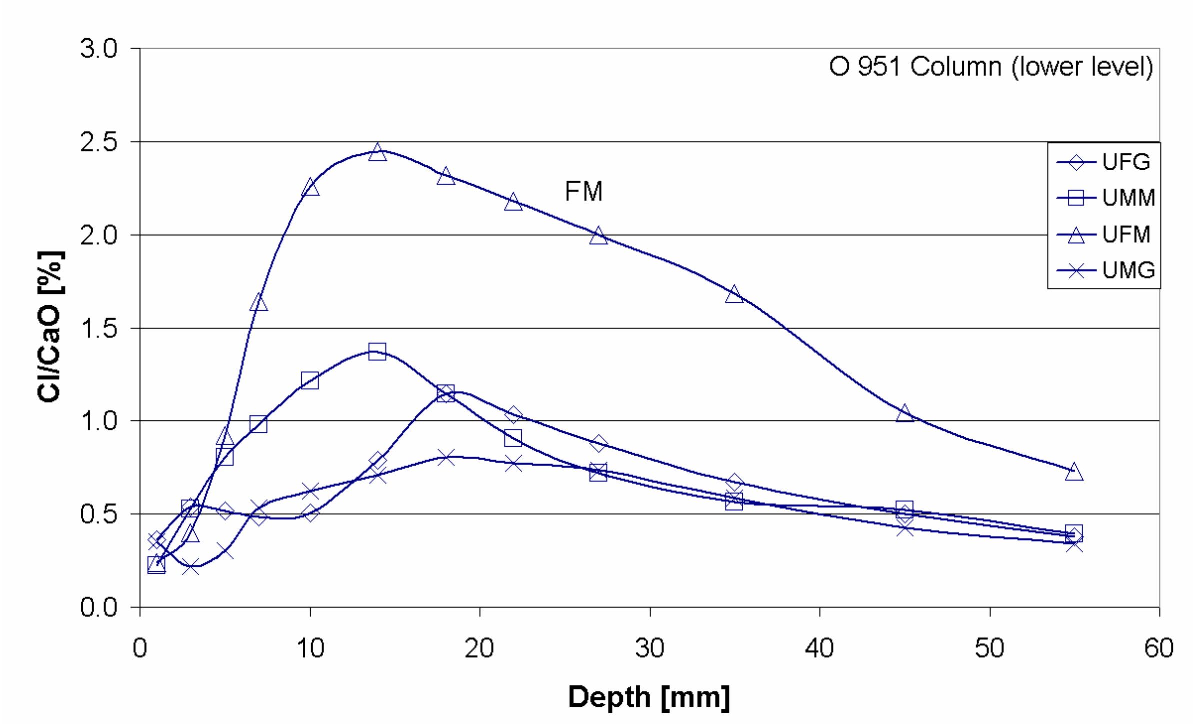

Figure 6 – Chloride penetration profiles from lower level on bridge O 951. The profile in orientation direction FM (facing towards the heavy morning-traffic) has the highest chloride penetration.

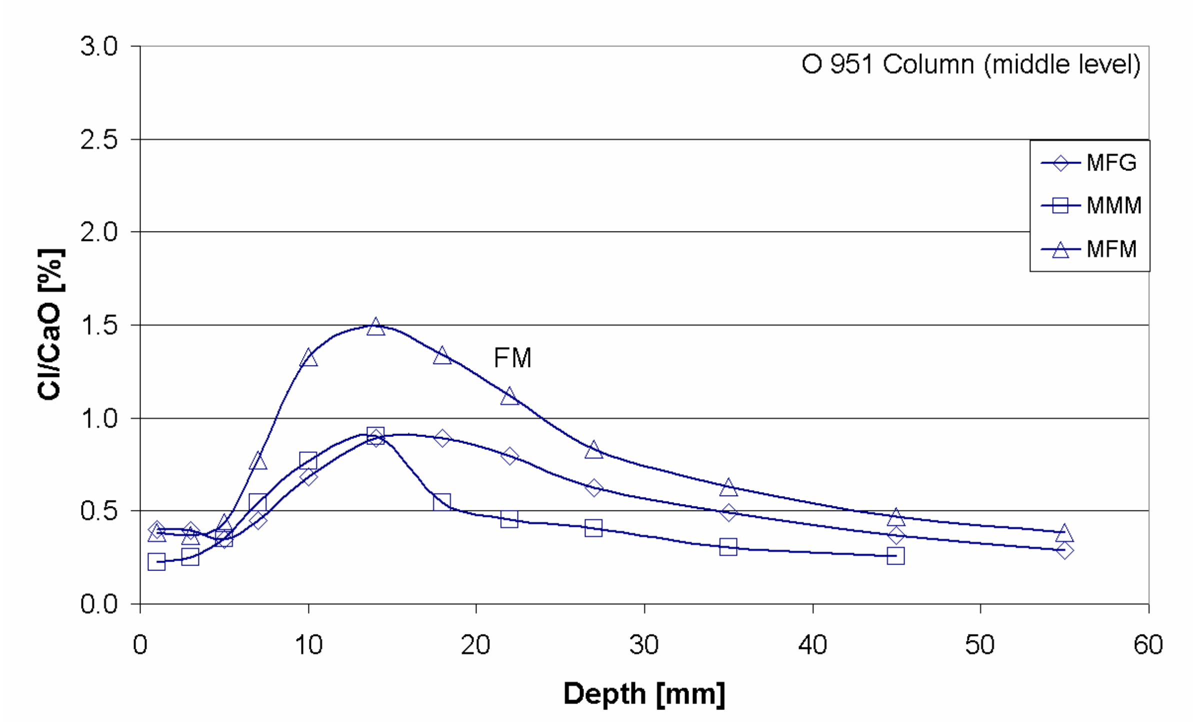

Figure 6 – Chloride penetration profiles from middle level on bridge O 951. The profile in orientation direction FM (facing towards the heavy morning-traffic) has the highest chloride penetration.

6. CONCLUSIONS

The following conclusions can be drawn:

- **Conditions for chloride penetration**. The chloride penetration into concrete is governed by the exposure conditions (chloride- and moisture-conditions) and the concrete properties. From the shape of the chloride penetration profiles it is possible to assess the exposure mechanism for chlorides.
- **Significance of the exposure environment**. The exposure environment has been found to have a large influence on the chloride penetration into a concrete structure. Large variations in the chloride penetration have been found even in one single structure. This implies that the environmental actions on a concrete structure should be determined as surface conditions, to get an as accurate description as possible.
- **Variations in response between bridges**. The results from the survey of the seven bridges have shown that each bridge should be treated separately when the chloride penetration is investigated. This is due to the fact that the chloride penetration is not only influenced by the environmental actions but also the execution during construction, the concrete mix proportions and possible surface treatments, e.g. hydrophobic treatments. This means that before the chloride penetration and moisture conditions in a concrete bridge are evaluated the concrete properties and the effect of possible surface treatments have to be assessed.
- **Quantification of environmental actions**. The statistical quantification in the DuraCrete-project has shown on the difficulties to quantify the environmental actions in mathematical prediction models. It is hard to find data on the same concrete composition exposed in different environments (both marine and road conditions), which makes it hard to quantify differences between different environments. Thus there is need for good data where the same concrete composition is exposed in different environments.

7. FUTURE RESEARCH

The following is proposed for future research:

- **Differences between different marine environments**. Further study how the chloride penetration varies in different marine environments. To avoid effects from execution and concrete composition the same concrete composition should be exposed in different environments. To get well-defined environmental conditions the marine submerged zone should be used for the exposure.
- **Investigate and map the road environment**. Further study how the chloride penetration in bridges varies with the environmental actions. To examine the environmental actions around a bridge, mortar disks can be used. The mortar disks should be used to get a well-defined and homogeneous material.
- **Execution during construction**. Further study the effects that insufficient execution of the concrete during construction has on the durability. To examine this effect the chloride penetration in two bridges, built with board and steel moulds, along the same road can be examined. The chloride penetration profiles are then compared and analysed and the influence from the type of mould can be evaluated.
- **The influence surface treatments**. Further study the effects that surface treatments have on the durability of concrete. To examine this effect chloride penetration profiles from treated and untreated can be compared. The profiles should be taken as close as possible to each other.

REFERENCES

1. Lindvall, A., “Environmental Actions and Response – Reinforced Concrete Structures exposed in Road and Marine Environments”, Publication P-01:3, Department of Building Materials, Chalmers University of Technology, Göteborg, 2001, 320 pp.
2. DuraCrete, “General Guidelines for Durability Design and Redesign”, Document BE95-1347/R15, The European Union – Brite EuRam III, Contract BRPR-CT95-0132, Project BE95-1347, CUR, Gouda, 2001.
3. Tang, L., “Chloride transport in concrete – Measurement and Prediction”, Publication P-96:6, Department of Building Materials, Chalmers University of Technology, 1996.
4. DuraCrete, “Statistical quantification of the Variables in the Limit State Functions”, Document BE95-1347/R9, The European Union – Brite EuRam III, Contract BRPR-CT95-0132, Project BE95-1347, CUR, Gouda, 2000.
5. Poulsen, E., Details of the Mejlbro-Poulsen model, *Chapter 3* in Frederiksen et al (1997), HETEK-report No. 83, Danish road directorate, Copenhagen, 1997.
6. Högberg, A., “Microclimate Description – To Facilitate Estimating Durability and Service Life of Building Components Exposed to Natural Outdoor Climate”, Publication P-98:5, Department of Building Physics, Chalmers University of Technology, Göteborg, 1998.
7. WMO – World Meteorological Organization, “Guide to meteorological instruments and methods of observations”, Secretariat of the World Meteorological Organization, Geneva, 1983.
8. Harderup, E., “Klimatdata för fuktberäkningar – Väderdata från tio meteorologiska mätstationer i Sverige” (Climate data for moisture calculations – Weather data from ten meteorological stations in Sweden), Report 3025, Department of Building physics, Lund Institute of Technology, Lund, 1993. (in Swedish).
9. Oke, T.R., “Boundary Layer Climates”, Routledge, Second edition, London, 1987.
10. Mehta, P.K., “Concrete in the Marine Environment”, Elsevier applied science, London, 1991.
11. CEB – Comité Euro International du Béton, “Durable Concrete Structures”, Bulletin 182, Comité Euro-International du Béton (CEB), Lausanne, 1989.
12. Andersen, A. & Paulsson, J., “Measurements of Seasonal and Diurnal Variations of Environmental Conditions Surrounding a Heavily Trafficked Bridge Structure”, Proceedings International Conference on “Repair of concrete structures – From Theory to Practice in a Marine Environment”, Svolvær, 1997. pp. 143-152.
13. Blomqvist, G., “Impact of De-Icing Salt on Roadside Vegetation – A Literature Review”, VTI rapport 427A, Swedish National Road and Transport Research Institute, Linköping, 1998.
14. Eliasson, Å., ”Spridning av vägsalt kring vägar (The spread of de-icing salts around roads)”, Project work 20p, Naturgeografiska institutionen, Göteborgs universitet, Göteborg, 1996. (in Swedish).
15. Wallbank, E.J.H., “The performance of concrete in bridges – A survey of 200 motorway bridges”, HSMO publication, prepared for the Department of Transport, London, 1989.
16. Lindvall, A. & Andersen, A., “Undersökning av kloridinträngning, armeringskorrosion, frysning och fukttillstånd på sju brokonstruktioner exponerade för tösalter” (Investigation of chloride ingress, reinforcement corrosion, frost and moisture conditions on seven bridge-constructions exposed to thaw-salts), Publication P-00:8, Department of Building

Materials, Chalmers University of Technology, Göteborg, 2000. (in Swedish). 141 pp.

17. NT Build 492, Concrete. Mortar and cement based repair materials: Chloride migration coefficients from non-steady state migration experiments", NORDTEST, Approved 1999-11.
18. NT Build 376, "Concrete testing – Hardened concrete: Frost resistance", NORDTEST, Adopted 1991-09. 6 pp.
19. Andersen, A., "Investigations of chloride penetration into bridge columns exposed to de-icing salt", HETEK-report No. 82, Danish road directorate, Copenhagen, 1997.
20. Nilsson, L.-O., Andersen, A., Luping, T. & Utgennant, P., "Chloride ingress data from field exposure in a Swedish road environment", Publication P-00:5, Department of Buildings Materials, Chalmers University of Technology, Göteborg, 2000. 31 pp.