LIFECON DELIVERABLE D 4.1

Definition of decisive environmental parameters and loads

Thomas Carlsson, University of Gävle

Shared-cost RTD project

Project acronym:	**LIFECON**
Project full title:	**Life Cycle Management of Concrete Infrastructures for Improved Sustainability**
Project Duration:	01.01.2001 - 31.12.2003
Co-ordinator:	Technical Research Centre of Finland (VTT) VTT Building Technology Professor, Dr. Asko Sarja
Date of issue of the report	31.12.2003

Project funded by the European Community under the Competitive and Sustainable Growth Programme (1998-2002)

Project Information

CONTRACT N°: G1RD-CT-2000-00378

ACRONYM: **LIFECON**

PROJECT TITLE: Life Cycle Management of Concrete Infrastructures for Improved Sustainability

PROJECT CO-ORDINATOR: Technical Research Centre of Finland (VTT), VTT Building Technology Professor, Dr. Asko Sarja

PARTNERS:

The Finnish Road Administration, Finland

CT LAASTIT Oy Ab, Finland;

Optiroc Oy Ab, Finland

Technische Universität München, Germany

OBERMAYER PLANEN+BERATEN, Germany

Norwegian University of Science and Technology, Norway

Interconsult Group ASA, (Since 01. 01.2003: Interconsult Norgit AS), Norway

Norwegian Building Research Institute, Norway

Kystdirektoratet, Norway

Millab Consult A.S., Norway

Centre for Built Environment, Sweden

Gävle Kommun, Sweden

Ljustech Konsults AB, Sweden

L.Öhmans Bygg AB, Sweden

British Energy Generation Ltd, UK

Heriot-Watt University, UK

Centre Scientifique et Technique du Batiment CSTB, France.

PROJECT DURATION: FROM 01. 01.2001 TO 31. 12.2003

Project funded by the European Community under the Competitive and Sustainable Growth Programme (1998-2002)

Deliverable Information

Programme name:	Growth Programme
Sector:	TRA 1.9 Infrastructures
Project acronym:	LIFECON
Contract number:	G1RD-CT-2000-00378
Project title:	Life Cycle Management of Concrete Infrastructures for Improved Sustainability
Deliverable number:	D 4.1
Deliverable title:	Definition of decisive environmental parameters and loads
Deliverable version number:	Final Report
Work package contributing to deliverable:	WP 4
Nature of the deliverable: (PR/RE/SP/TO/WR/OT)	RE
Dissemination level (PU/RE/CO):	PU
Type of deliverable (PD/WR):	PD Project Deliverable
Contractual date of delivery:	Final Delivery: Month 36
Date of delivery:	31.12.2003
Author(s):	Thomas Carlsson
Project co-ordinator:	Asko Sarja

Nature:

PR - prototype (demonstrator), RE - report, SP - specification, TO - tool, WR - working report OT - other

Dissemination level:

PU - public usage, RE - restricted to project participants, CO - restricted to commission

Type:

PD - project deliverable, WR - working report

Quality Assurance Form

Deliverable ID	D 4.1
Title	Definition of decisive environmental parameters and loads
Deliverable type	FINAL REPORT
Author (s) of deliverable (Name and organisation)	Thomas Carlsson, University of Gävle
Reviewer(s)	Odd Gjørv, Sascha Lay, Erkki Vesikari
Approved by reviewer(s) (Reviewer's name and date)	Sign.: ____ Sign.: ____ Date: ____ Date: ____ Sign.: ____ Sign.: ____ Date: ____ Date: ____
Approved for release WP Leader / Co-ordinator	Sign.: ____ Sign.: ____ Date: ____ Date: ____

Lifecon Deliverables

Deliverable No	Title of the Deliverable
D1.1	Generic technical handbook for a predictive life cycle management system of concrete structures (Lifecon LMS)
D1.2	Generic instructions on requirements, framework and methodology for IT-based decision support tool for Lifecon LMS
D1.3	IT-based decision support tool for Lifecon LMS
D2.1	Reliability based methodology for lifetime management of structures
D2.2	Statistical condition management and financial optimisation in lifetime management of structures • Part 1: Markov chain based LCC analysis • Part 2: Reference structure models for prediction of degradation
D2.3	Methods for optimisation and decision making in lifetime management of structures • Part I: Multi attribute decision aid methodologies (MADA) • Part II: Quality function deployment (QFD) • Part III: Risk assessment and control
D3.1	Prototype of condition assessment protocol
D3.2	Probabilistic service life models for reinforced concrete structures
D4.1	Definition of decisive environmental parameters and loads
D4.2	Instructions for quantitative classification of environmental degradation loads onto structures
D4.3	GIS-based national exposure modules and national reports on quantitative environmental degradation loads for chosen objects and locations
D5.1	Qualitative and quantitative description and classification of RAMS (Reliability, Availability, Maintainability, Safety) characteristics for different categories of repair materials and systems
D5.2	Methodology and data for calculation of life cycle costs (LCC) of maintenance and repair methods and works
D5.3	Methodology and data for calculation of LCE (Life Cycle Ecology) in repair planning
D6.1	Validation of Lifecon LMS and recommendations for further development

Keywords

Lifecon, environmental load, degradation, concrete

Abstract

In this report the decisive input environmental parameters for concrete structures, including supplementary materials, has been defined. For concrete, according to damage mechanisms given in WP3, the DuraCrete degradation models (primarily governing the LMS on the Object Level) and the "Vesikari models" (primarily governing the LMS on the Network Level) has been used.

List of Contents

1 Introduction

1.1 Objectives and background

The objectives of the WP4 are "to provide and synthesise the necessary classification of environmental degradation loads for developing and exploiting the models of WP3." WP4 will develop methods and data for assessing, modelling, mapping and classification of environmental risk factors on different geographical levels based on damage functions.

This deliverable, D04.01 gives input as to which environmental parameters are to be included in D04.02 and subsequently into the LMS. The degradation processes and the important parameters are described in WP3 (D03.02).

D04.02 describes and discusses different methods for assessment, modelling, mapping and classification of Environmental Degradation Factors (EDF).

An innovation in the LIFECON project is to create GIS-based national environmental exposure module for quantitative classification on environmental degradation loads onto concrete structures. This is to be described in D04.03. The classified degradation loads should be linked to predictive models of performance factors and residual service life of concrete structures.

The last deliverable, D04.04, is then a generic report on this developed methodology and system for classification environmental loading onto concrete structures

1.2 Degradation of reinforced concrete

The first and general approach to generate data on the degradation agents affecting concrete infrastructures ought to be through utilisation of the climate and weather data normally measured at meteorological sites. This data has to be processed, adapted and modelled to fit the Duracrete Degradation models (primarily governing the LMS on the Object Level) and the "Vesikari models" (primarily governing the LMS on the Network Level).

The Duracrete models are empirical, on a science basis, and a number of the parameters used to adapt the models have pronounced inherent uncertainties. The parameters are, in essence, to be determined via laboratory tests. This is not a general obstacle in a service life design of a new constructed works, but will meet difficulties of varying degree in the LMS application on existing structures.

The proposed model on Network level, is based on a bridge management system. In the initial system the used degradation models are simplified. Penetration of carbonation and critical chloride content, based on the yearly average use of deicing salts, are the only functions that are treated. Effects of temperature is just briefly taken into account by a division into three climatic areas. Other environmental burdens, such as precipitation and solar radiation, are not (for the moment) treated at all.

Moisture and chloride burdens at a regional level are given as an index, 1 or 0. The chloride index 1 corresponds to the amount of chlorides received by unsheltered concrete on top of a bridge deck with the highest winter maintenance class. The chloride index 0 represents the case when no chloride is spread on bridges (depassivation is possible only by carbonation). The moisture index 1 corresponds to the amount of external water (rain, melting, splash) received by unsheltered concrete on top of a bridge deck and moisture index 0 to the amount of external water under a bridge deck provided with a water membrane.

1.3 Degradation of supplementary materials

Beside fitting the degradation models for reinforced concrete, the LMS should include modelling of agents primarily active in the degradation of other materials common in concrete infrastructures, such as steel (with organic and/or zinc coating), coatings, other organic component, repair materials of various kind, e t c. UV-radiation, NO_x, SO_x, and Ozone seem to be the most important. UV is measured at (some) meteorological sites and can in addition within reason be calculated. SO_x measurements are available. NO_x data is also available and can also be estimated (e.g. for bridges) from traffic intensity. Data on ozone is generated at a great number of measurement sites (however, ozone data is not easily transferable from one location to another).

The most important source, when it comes to establishing degradation functions for materials other than concrete, is the UN ECE International Co-operative Programme. The main aim for this programme is to perform a quantitative evaluation of the effects of multi-pollutants such as S and N compounds, O_3 and particles as well as climate parameters on the atmospheric corrosion of important materials.

2 Environmental parameters at the Object level

All equations and definitions that are presented below, are based on the LifeCon deliverable "D3.2 Draft 2, Models for the Prediction of the Residual Service Life" (Sascha Lay, TUM), where also extended equations and explanations can be found.

2.1 Modelling of Carbonation Induced Corrosion

$$X_C = \sqrt{2 \cdot k_{RH} \cdot k_c \cdot (k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot \Delta C_S} \cdot \sqrt{t} \cdot W \quad [\mathrm{m}]$$

X_C carbonation depth [m]

k_{RH} constant considering the influence of the realistic moisture history at the concrete surface [-]

ΔC_S gradient of the CO_2-concentration [kg CO_2/m³]

W weather function [-]

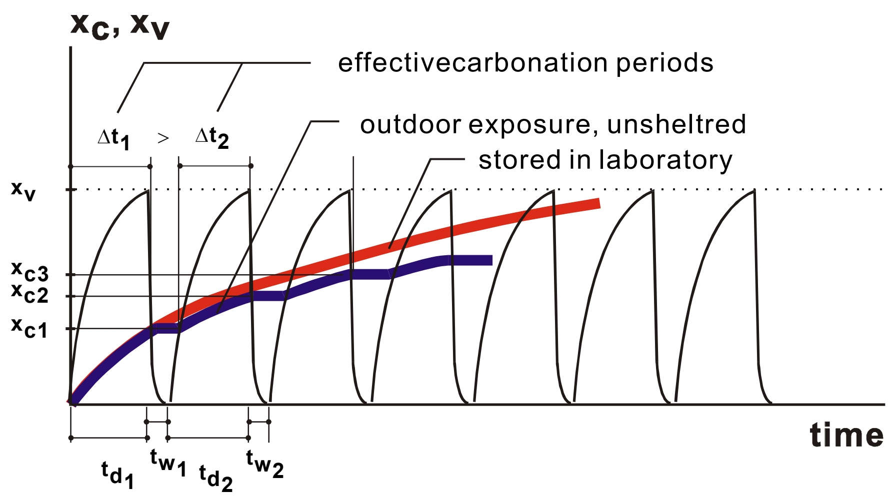

Figure 1: Progress of carbonation of specimens stored under different exposure conditions (laboratory, outdoor-unsheltered)

$$W = \left(\frac{t_0}{t}\right)^w$$

w weather exponent [-]

<u>The weather function</u> considers the derivation of the carbonation process of unsheltered structures from the square-root of time law.

The carbonation evolution depends strongly on the frequency and the distribution of the wetting periods. Since meteorological data is obtainable without a large degree of effort, the parameter "time of wetness TOW" has been introduced.

$$w = a \cdot TOW^b$$

w weather exponent [-]

TOW time of wetness [-]

a, b regression parameters [-]

Using Eq. 3 the weather function may be determined without having data on the carbonation progress at different exposure times, which will seldomly be available. Data of carbonation depths of unsheltered structures have to be related to meteorological data in order to determine values for the regression parameters *a* and *b* of Eq. 3.

To quantify the time of wetness, *TOW*, a criterion has to be found, stating the boundary conditions of a rain event (duration, intensity) to be registered as such. It has to be defined which amount of precipitation is sufficient to impair the carbonation process for a certain period. For reasons of simplicity all days with amounts of rain above 2.5 mm/d is chosen in order to calculate TOW.

$$TOW = \frac{Amount\ of\ days\ with\ h \geq 2{,}5mm}{365}$$

For vertical components the probability of being splashed during a rain event has to be taken into account.

$$w = \frac{(p_{splash} \cdot TOW)^{b_w}}{2}$$

w weather exponent [-]

TOW time of wetness [-]

b regression parameter [-]

p_{splash} probability of a splash event in the case of a decisive rain event, dependent on the orientation of the structure [-]

The parameter k_{RH} describes the effect of the “average” level of humidity. Hereby ($k_{RH} = 1$) for a reference climate, usually considered to be T = +20°C / RH = 65%. The relationship of k_{RH} and the relative humidity can be implemented according to the equation below.

The varying relative humidity of the concrete cover is the decisive input parameter. As a first approximation data of the nearest weather station may be used as input for RH.

$$k_{RH} = \left(\frac{1 - RH^f}{1 - RH_{ref}^f} \right)^g$$

k_{RH} constant considering the influence of the realistic moisture history at the concrete surface [-]

RH relative humidity in the concrete cover, as a first approximation data of the nearest weather station [-]

RH_{ref} reference humidity [-]

f exponent in the range of (1-10) [-]

g exponent in the range of (2-5) [-]

Surface Concentration of Carbon Dioxide ΔC_S

Generally the gradient of the CO_2-concentration of carbon dioxide, ΔC_S, can be assumed to be in the range of 350 ppm, which equals 0,00057 $kgCO_2/m^3$. For tunnels, parking garages or in industrial regions this value may vary and has to be measured.

$$\Delta C_S = C_{S,Atm} + \Delta C_{S,Em}$$

$C_{S,Atm}$ CO_2 concentration of atmosphere [$kgCO_2/m^3$]

$\Delta C_{S,Em}$ local additions, due to special emissions (e.g. in tunnels) must be measured [$kgCO_2/m^3$]

2.2 Modelling of Chloride Induced Corrosion

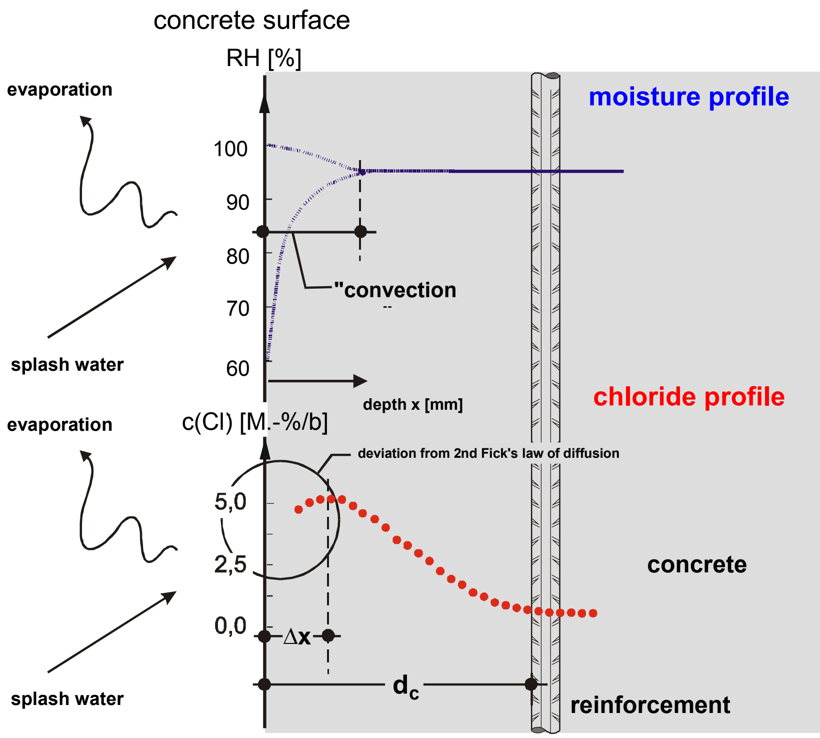

Figure2: Distribution of the moisture content and the chloride concentration, as commonly observed in the splash-zone

$$C(x,t) = C_{s,\Delta x} \cdot \left[1 - erf\left(\frac{x - \Delta x}{2\sqrt{t \cdot D_{eff}(t)}}\right)\right]$$

$$D_{eff}(t) = k_{RH} \cdot D_{RCM,0} \cdot k_t \cdot k_T \cdot \left(\frac{t_0}{t}\right)^n$$

$C(x,t)$	chloride concentration at depth x at age t in e.g. [M.-%/c]
$C_{s,\Delta x}$	chloride concentration in depth Δx [M.-%/c]
k_{RH}	environmental parameter accounting for the moisture influence on D_{eff} [-]
k_T	temperature parameter [-]

A formulation of a factor k_{RH} in dependence of the relative humidity as it has been stated for the carbonation model is still lacking for the chloride ingress model.

The temperature parameter, k_T, may be taken into account by using the Arrhenius equation.

$$k_T = \exp\left(b_T\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$$

k_T	temperature parameter [-]
b_T	regression parameter (b_T=3500 to 5900) [K]
T_{ref}	reference temperature [K]
T	temperature of the environment (micro climate) [K]

The chloride surface concentration C_S, and the chloride concentration $C_{S,\Delta x}$ in the depth ΔX, are parameters depending on the concrete composition and on the environmental conditions.

The most important environmental variables influencing the chloride surface concentrations are the equivalent chloride concentration C_{equ} of the chloride source and the distance of the concrete surface from this chloride source.

For off-shore structures the chloride load can be considered to be equal to the chloride content of the sea water.

$$C_{equ} = C_{sea}$$

C_{equ}	average content of the chloride source [g/l]
C_{sea}	chloride content of sea water [g/l]

The chloride load of structures in a road environment is controlled by the de-icing salt applications.

$$C_{equ} = C_{road} = \frac{n \cdot C_R}{h_S}$$

C_{road}	average concentration of the chloride containing water on a street [g/l]

n	quantity of de-icing salt application incidents [-]
C_R	average amount of de-icing salt for each application incident [g/m²]
h_s	precipitation (rain, snow) during salt application period [l/m²]

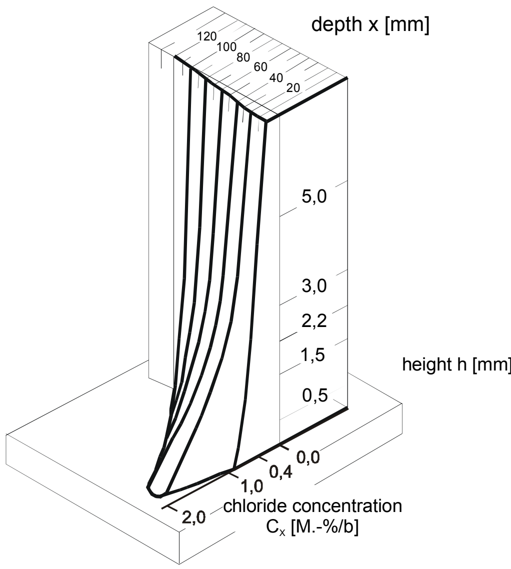

Figure 3: Chloride concentration in dependence of the distance from the street.

The approach above neglects the effects, that:

- salt may be removed from the street by wind and driving cars and
- salt containing water and snow slush will be drained,

hereby reducing the salt concentration C_{equ}. For durability design purposes the above mentioned approach is on the safe side. The average amount of salt spread C_R depends on:

- climatic conditions
- road maintenace policy

and must thus be based on data provided by the nearest road adminstration office. Data should be collected for the longest period available, as the scatter of annual data is extremely high. If no data is available from nearby stations, empirical models can be applied which link meteorologic data and salt spread data, as e.g.:

$$C_{R,\,FR} = 1000\cdot(-9{,}56+0{,}52\cdot SF+0{,}38\cdot SL+0{,}14\cdot FD-0{,}20\cdot ID)/w \qquad [g/m^2]$$

Index FR indicates federal roads

$C_{R,FR}$	average amount of de-icing salt for each application incident on federal roads[t/km]
SF	number of days per month with snow fall above 0,1 mm [-]
SL	number of days per month with a layer of snow above 1,0 cm [-]
FD	number of days per month with average daily temperature below 0°C

ID number of days per month with ice on road surface [-]

w average spread width (can be set equal to average street width) [m]

The correlation between salt spread data for federal roads (FR) and highways (HW) was found to be:

$$c_{R,HW} = 1{,}51 + 0{,}235 \cdot C_{R,FR} \qquad [g/m^2]$$

2.3 Modelling the Propagation of Corrosion

The corrosion rate V_{corr} can be expressed in terms of the current density i_{corr} [$\mu A/cm^2$] (corrosion current I_{corr} related to the steel surface area). V_{corr} may be constant along the propagation period or vary following different events suffered by the structure (environmental changes). There are numerous parameters related to the concrete quality and the environment influencing $V_{corr.}$

$$V_{corr} = i_{corr} \cdot 0{,}0116 \ [mm/a]$$

or

$$V_{corr} = V_{corr,a} \cdot ToW$$

$Vcorr$ corrosion rate [mm/a]

ToW wetness period given as the fraction of the year [-]

$V_{corr,a}$ mean corrosion rate when corrosion is active [mm/year]

$$i_{corr} = \frac{k_0}{\rho(t)} \cdot F_{Cl} \cdot F_{Galv} \cdot F_{Oxide} \cdot F_{O_2}$$

i_{corr} corrosion rate [$\mu A/cm^2$]

k_0 constant regression parameter [$\mu V/cm$]

$\rho(t)$ actual resistivity of concrete at time t [Ωm]

$$\rho(t) = \rho_0 \cdot k_c \cdot k_t \cdot k_T \cdot k_{RH} \cdot k_{Cl} \cdot \left(\frac{t}{t_0}\right)^n$$

ρ_0 potential concrete resistivity for a reference concrete and defined environment (T=+20°C; 100% RH) [Ωm]

k_T temperature factor [-]

k_{RH} relative humidity factor [-]

The model for corrosion rate contains two main environmental and material dependent parameters k_0 and $\rho(t)$. A reasonable approach to model the material and environmental effects on the concrete resistivity $\rho(t)$ is to introduce a potential resistivity ρ_0 for a reference concrete and defined environmental conditions (20°C/ 100% RH). This material parameter can be obtained with a low amount of effort and is already quantified for numerous concrete compositions. The difference in environmental conditions is covered by a number of environmental parameters. Since the potential resistivity is measured at an age of 28 days, an age factor n, analogous to the chloride ingress model is introduced.

For sheltered concrete structures the humidity factor, k_{RH}, can be derived by comparing the resistivity of the concrete at different relative humidities with a reference humidity (100% RH). A reasonable assumption is to estimate RH from the annual average air humidity close to the structure.

For unsheltered conditions the time of wetness, TOW, i.e. the duration of rain and condensation at the concrete surface, must be considered.

It is a common approach to use the Arrhenius-equation to model the temperature factor, k_T, and its effect upon the electrolytic resistivity. Data on the resistivity at different temperatures with a reference temperature (+20°C) has to be compared.

2.4 Modelling of Alkali-Aggregate Reaction

The principal common conclusion regarding the alkali aggregate reaction (AAR) is that no credible predictive mathematical model exists until now and that avoidance is almost universally accepted as the best philosophy.

The AAR is governed by the interaction of numerous effects, for instance the following environmental parameters.

- moisture availability
- temperature
- external chloride sources
- alkali concentration effects (wet-dry cycles, wick action)

A further factor is the moisture content of the concrete. A higher alkali content is necessary to initiate a deleterious expansion in drier concretes. Threshold values for the relative humidity may be defined below which AAR will not occur. These range between 75 to 90% RH.

2.5 Modelling of Internal Frost Damage

The limit state function of the initiation phase of the internal frost process can be given as a function of the capillary saturation, S_{cap}, and a critical value of saturation, S_{cr}. The capillary saturation degree depends on the material and the environmental conditions. One approach to account for environmental conditions is to perform capillary rise tests in the laboratory and apply correction factors to compensate for the difference between absorption behavior in the test and the exposure environment.

$$P_f(t) = P(S(t) > S_{cr})$$

P_f failure probability [-]

S_{cr} critical degree of saturation [-]

$S(t)$ degree of saturation [-]

The function for the time dependent moisture ingress can be determined by laboratory capillary suction tests. The maximum value of the degree of saturation, S_{max}, within a given time period can be given as.

$$S_{\max}(t) = \left(S_k + b \cdot t_{\max}{}^{c}\right)$$

S_k break point in the graph of the degree of saturation vs. the square root of time, being reached in a relatively short period

b, c regression parameters obtained from capillary suction tests

t_{max} length of the longest wetting period of the structure within the considered period

In order to determine t_{max} three different environments have to be distinguished

1. An environment in which the drying of the concrete is negligible. For this case the longest period of wetting is equal to the age of the structure.

2. Drying brings the degree of saturation below the break point S_k. The longest period of wetting is equal to the duration of rain events, determined by meteorological data.

3. An environment leading to an degree of saturation being intermittently above/ below the break point for certain periods. Here, an equivalent period of wetting has to be determined. The most simple approach is to set the longest period of wetting equal to $k \cdot t$, with t being the construction age.

2.6 Modelling of Frost Induced Scaling

$$n = \sum_{i=1}^{N} \frac{T_i^{\,2}}{T_{ref}^{\,2}}$$

n equivalent number of cycles [-]

N number of freeze-thaw cycles where the water content in the surface layer of the concrete is high enough for damages to occur [-]

T_i lowest temperature in a cycle [K]

T_{ref} reference temperature [K]

It is assumed that the number of cycles where the degree of saturation is harmful, N, can be determined as.

$$N(t)=k \cdot m(t)$$

k describes the environment [-]

$m(t)$ total number of cycles [-]

The environmental factors that has to be determined are:

- T_{max}, T_{min}, = temperature (min/ max) [K]
- n_C = changes of temperature [-]
- n_T = number of wet/ dry cycles [-]
- W = wind: intensity, direction [m/s²]
- U = sun: intensity, radiation [MJ/m²s]
- RH = air humidity [-]

3 Environmental parameters at the Network Level

The model on Network level introduced into the LifeCon projekt by Vesikari, ”Degradation models for a project level bridge management system” (Vesikari, VTT, WP3-5 meeting Oslo 2001), is based on a bridge management system initially developed for the Finnish Road Administration. In the initial system the used degradation models are simplified. Penetration of carbonation and the critical chloride content, based on the yearly average use of deicing salts, are the only functions that are treated. Effects of temperature is just briefly taken into account by a division into three climatic areas (southern Finland, middle Finland and northern Finland). Other environmental burdens, such as precipitation and solar radiation, are not treated at all.

The LifeCon LMS needs a more refined treatment of the environmental parameters. This means, in principal, that the same parameters as used on the Object level should be considered also on the Network level. However, the Network level is intended to give a status overview of the total object population of an owner.

3.1 Modeling of reinforcement corrosion

This presentation is principally based on ”Degradation models for a project level bridge management system” (Vesikari, VTT, WP3-5 meeting Oslo 2001).

Based on the results obtained from computer simulation, the degradation in both the depassivation phase and the active corrosion phase was given a simple model function of the following form:

Depassivation:

$$f_0 = a_0 \cdot t^{n_0}$$

where

f_0 is penetration of carbonation or critical chloride content in relation to the concrete cover

t time from the manufacture of the structure

a_0 constant coefficient

n_0 exponent of time

Active corrosion:

$$f_1 = a_1 \cdot t^{n_1}$$

where

f_1 is	depth of corrosion of reinforcing steel in relation to the critical depth of corrosion causing cracking of concrete cover
t	time from depassivation
a_1	constant coefficient
n_1	exponent of time

In the depassivation phase the function f_0 starts from 0 at the beginning of service life and attains the value 1 at the moment of depassivation (when carbonation or the critical chloride content reaches the depth of reinforcement). In the active corrosion phase the function f_1 starts immediately after depassivation and attains the value 1 when the concrete cover cracks as a result of corrosion.

The constant coefficient (a) and the exponent of time (n) in both the depassivation phase and the active corrosion phase are assumed to be dependent on many factors as follows:

(a) depends on nominal strength, air content of concrete, geographical location,

vertical/horizontal surface, thickness of concrete cover

(n) depends on nominal strength of concrete

3.2 Environmental effects

The environmental burdens depending on geographical location, is taken into account by applying the weather data at different locations, which are selected to represent different area climatic conditions.

The quantities a_0, n_0, a_1 and n_1 are first determined for four basic cases of moisture and chloride burden:

1. moisture index 0/ chloride index 0
2. moisture index 1/ chloride index 0
3. moisture index 0/ chloride index 1 and
4. moisture index 1/ chloride index 1

The chloride index 1 corresponds to the amount of chlorides received by unsheltered concrete on top of a bridge deck with the highest winter maintenance class. The chloride index 0 represents the case when no chloride is spread (depassivation is possible only by carbonation). The moisture index 1 corresponds to the amount of external water (rain, melting, splash) received by unsheltered concrete on top of a bridge deck and moisture index 0 to the amount of external water under a bridge deck provided with a water membrane.

4 Summary of needed environmental data

In chapters 2 and 3 the degradation mechanisms at different levels has been presented. A course summary of the needed environmental data is found in Table 1. A detailed presentation of the parameters are to be found in Table 2 to 8, where also time periods and possible data sources are proposed.

Table 1

Deterioration mechanism	RH	Temp.	CO_2	Precipi-tation	Wind	Radia-tion	Chloride Conc.	Freeze -thaw cycles	$[SO_2]$	$[O_3]$
Reinforced concrete (DuraCrete models)										
Carbonation induced corrosion	X	(X)	X	X	X					
Chloride induced corrosion	X	X		X			X			
Propagation of corrosion	X	X		X			X			
Alkali-aggregate reaction	No model									
Frost attack internal/scaling	(X)	X		X	(X)	(X)	(X)	X		
Supplementary materials (Dose-response functions)										
Galvanised steel/zink coating	X	X		X			X		X	
Coil coated steel	X	X		X					X	
Sealants/bitumen	No function									
Polymers	No function									
Aluminium				X			X		X	X

Table 2

Degradation model

Carbonation depth

$$X_c = \sqrt{2k_{RH}k_c\left(k_t R_{ACC}^{-1} + \varepsilon_t\right)\Delta C_s}\,\sqrt{t}\left(\frac{t_0}{t}\right)^w$$

Input parameter (primarily)	**Sub model**		**Input data**	**Time period**	**Data source**
KRH, influence of moisture at the concrete surface [-]	$K_{RH} = \left(\frac{1-RH^f}{1-RH_{ref}^f}\right)^g$		RH, relative humidity [%]	Daily mean	Nearby meteorological station
			RHref, relative humidity, reference [%]		
w, weather exponent taking into account the micro climate [-]	Horisontal $w = a_W TOW^{b_w}$	Time of wetness [-] ToW = (hrain > 2.5 mm/day)/365	Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
	Vertical $w = \frac{\left(P_{splash} TOW\right)^{b_W}}{2}$	Time of wetness [-] ToW = (hrain > 2.5 mm/day)/365	Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
		Psplash, probability of a splash event [-] Psplash = sum{d(w+r)}/ sum{d(r)}	d(w+r), days with wind in considered direction during a rain event of hrain > 2.5 mm [-]	Yearly	Nearby meteorological station
			d(r), days with rain events of hrain > 2.5 mm [-]	Yearly	Nearby meteorological station

Table 2 continued..

ΔC_S, CO_2 concentration of the atmosphere [kg CO_2/m^3]	$$\Delta C_S = C_{S,ATM} + \Delta C_{S,Em}$$		$C_{S,atm}$ back ground level of CO_2 concentration [kg CO_2/m^3]	Yearly mean	Environmental research institute
			$\Delta C_{S,em}$ local addition [kg CO_2/m^3]	Yearly mean	Local measurements

Table 3

Degradation model **Chloride concentration at depth x at age t [g/l]**	$C(x,t) = C_{s,\Delta x} \cdot \left[1 - erf\left(\frac{x - \Delta x}{2\sqrt{t \cdot D_{eff}(t)}}\right)\right]$					
Input parameter (primarily)	**Sub-model**			**Input data**	**Time period**	**Data source**
C_s, chloride concentration on surface [g/l]	Off-shore structures $C_s = C_{sea}$			C_{sea}, chloride content of seawater [g/l]	Yearly	Hydrological Institute
	Roads Cs = Croad	Croad = nCr/hs		n, number of de-icing salt application incidents [-]	Monthly	Road administration office
				Hs, precipitation during salt application period [l/m²]	Monthly	Nearby meteorological station
			Cr = 1000(-9.56+0.52SF +0.38SL+0.14FD-0.20ID)/w Average amount of de-icing salt for each application incident [g/m²]	SF, number of days with snow fall > 0.1 mm [-]	Monthly	Nearby meteorological station
				SL, number of days with a snow layer > 100 mm [-]	Monthly	Nearby meteorological station
				FD, number of days with a average daily temperature > 0° C [-]	Monthly	Nearby meteorological station
				ID, number of days with ice on road surface [-]	Monthly	Road administration office
				w, average spread width (street width) [m]	Monthly	Road administration office

Table 3 continued..

Deff, effective diffusion coefficient of concrete at the time of inspection [m²/s]	$D_{eff}(t) = k_{RH} \cdot D_{RCM,0} \cdot k_t \cdot k_T \cdot \left(\frac{t_0}{t}\right)^n$		kRH, moisture influence on Diffusion coefficient		
		$k_T = \exp\left(b_T\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right)$	T, temperature [K]	Monthly	
			Tref, reference temperature [K]		

Table 4

Degradation model **Propagation of corrosion, loss of rebar diameter [mm]**	$P(t) = V_{Corr}\alpha t$						
Input parameter	**Sub model**				**Input data**	**Time period**	**Data source**
Vcorr, corrosion rate [mm/year]	$V_{Corr} = 0{,}0116 * i_{Corr}$	Icorr, corrosion current [mA/cm²] $i_{Corr} = \frac{k_0}{\rho(t)} F_{Cl} F_{Galv} F_{o^2}$	ρ(t), resistivity of concrete at time t [Ωm] $\rho(t) = \rho_0 k_C k_t k_{R,T} k_{R,RH} k_{R,Cl} \left(\frac{t}{t_0}\right)^n$	Kr,t temperature factor [-] $K_{R,T} = \frac{1}{1 + K(T-20)}$	T, temperature [K]	Monthly mean	Nearby meteorological station
				Kr,rh humidity factor [-] $k_{R,RH} = \left(\frac{100}{RH}\right)^a$	RH, relative humidity [%]	Monthly mean	Nearby meteorological station
				Kr,cl chloride factor [-] Kr,cl = 1-{(1-a)/2}Ccl	Ccl, chloride content [g/l]		Local measurements
	$V_{Corr} = V_{Corr,a} TOW$	ToW, time of wetness [-] ToW = (hrain > 2.5 mm/day)/365			Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station

Table 5

Degradation model **Frost attack (internal damage), failure probability [-]**	$Pf(t) = P\{S(t) > Scr\}$			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
S(t), actual degree of saturation [-]	Smax(t), maximum degree of saturation within a given time [-] Smax(t) = Sk+btmax	tmax, longest wetting period within the considered period [-]	Monthly	Nearby meteorological station

Table 6

Dose-response function **Zinc coated galvanised steel**	$ML = 1,4[SO_2]^{0,22}\exp\{0,018Rh + f(T)\}t^{0,85} + 0,029Rain[H^+]t$			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
f(T), temperature dependency [-]	f(T) = 0.062(T-10) when T<10°C	T, temperature [°C]	Yearly, mean	Nearby meteorological station
	f(T) = -0.021(T-10) when T ƒ10°C			
SO2		SO2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
RH		RH, relative humidity [-]	Yearly, mean	Nearby meteorological station
Rain		Rain, precipitation [m]	Yearly	Nearby meteorological station
[H+]		[H+], concentration at surface [g/l]	Yearly, mean	Environmental research institute

Table 7

Dose-response function **Coil coated steel**	$\mathbf{(10\text{-}ASTM) = (0{,}0084[SO_2] + 0{,}015Rh + f(T))t^{0{,}43} + 0{,}00082Rain \cdot t^{0{,}43}}$			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
f(T), temperature dependency [-]	$f(T) = 0.040(T-10)$ when $T<10°C$	T, temperature [°C]	Yearly, mean	Nearby meteorological station
	$f(T) = -0.064(T-10)$ when T ƒ10°C			
SO2		SO2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
RH		RH, relative humidity [-]	Yearly, mean	Nearby meteorological station
Rain		Rain, precipitation [m]	Yearly	Nearby meteorological station

Table 8

Dose-response function (4-year) **Aluminium**	4ML = 0.85 + 0.028 ToW [SO2] [O3] (unshelted) 4ML = -0.03 + 0.053 ToW [SO3] [O3] + 74 [Cl-] (shelted)			
Input parameter (primarily)	**Sub model**	**Input data**	**Time period**	**Source**
ToW	Time of wetness [-] ToW = (hrain > 2.5 mm/day)/365	Hrain, days with rain > 2.5 mm [-]	Yearly	Nearby meteorological station
[SO2]		SO2, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
[O3]		O3, atmospheric concentration [µg/m³]	Yearly, mean	Environmental research institute
[Cl-]		Cl-, atmospheric deposition [mg/m², day]	Yearly, mean	Environmental research institute