2 nd Int. PhD Symposium in Civil Engineering 1998 Budapest

DURACRETE – PROBABILISTIC PERFORMANCE BASED DURABILITY DESIGN OF CONCRETE STRUCTURES

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SUMMARY

The presented project is a first attempt to make probabilistic performance based durability designs of concrete structures. The performance based durability design is based upon realistic models that describes the future behaviour of the concrete and the environment. To make calculations it is necessary to quantify the parameters included in the chosen models. In this paper two models that describes the behaviour of concrete are presented and it is shown how the environmental parameters in the models are statistically quantified.

Keywords: concrete, durability, environmental influence, carbonation, chloride ingress, statistical quantification

1. INTRODUCTION

The present design with respect to the durability of concrete structures is in large extent empirical. It is in large extent based on deem-to-satisfy rules, where for example minimum concrete cover and maximum water/cement ratio is prescribed. With this approach the structure will have an acceptable long, but not specified lifetime.

If a performance based durability design methodology is used, it is possible to make more accurate estimations of the lifetime of a concrete structure. Performance based means in this respect, that the ability to fulfil relevant functions is quantified. The design methodology is based on realistic and sufficiently realistic environmental and material models capable to predict the future behaviour of a concrete structure. In the performance based durability design methodology the lifetime is determined by probabilistic calculations.

To make probabilistic lifetime calculations it is necessary to find models for the deterioration of concrete and the structural behaviour of deteriorated concrete. In the deterioration models it is important to find the influencing factors, for example concrete properties, curing and the environment, and to quantify them. This is sometimes a hard task, since the quantification of the parameters are based on observations, made in laboratory and field-exposure. Often is little known about the background of the observations, especially from field-observations. This leads to a large scatter when the parameters in the deterioration-models are quantified.

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2. MODELS FOR DEGRADATION

The degradation of concrete is commonly modelled as occurring in two stages defined as “initiation” and “propagation”. The initiation period is the period during which changes in the environment within the concrete continue to take place, normally as a result of interaction with the exposure environment, until, eventually, a limit is reached when damage occurs. The propagation period begins at the moment a certain defined event occurs, e.g. corrosion starts, cracks appears etc, until a specified limit state is reached.

To be able to make predictions of the degradation of reinforced concrete structures there is a need of models that describe the degradation-processes. When studying the degradation of concrete three different types of degradation can be identified: reinforcement corrosion, alkali-aggregate reactions and frost attack. In reality it is only for reinforcement corrosion that models that can be used for predictions exist.

In the following the two models I have chosen to work with are presented. The following degradation process are treated:

- Carbonation-Induced Corrosion.
- Chloride-Induced Corrosion.

2.1 Carbonation-Induced Corrosion

One model to described the carbonation-process in concrete was presented by the CEB Task Group V, 1+2 (1996). The model is mathematically represented as follows:

$$x_c = \sqrt{\frac{2 \cdot k_1 \cdot k_2 \cdot D_{eff} \cdot C_s}{a}} \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^n \qquad (1)$$

where: D_{eff} is the effective diffusion coefficient at a defined execution and environmental conditions, a is the binding capacity for CO_2, t is the time in service, t_0 is a reference period (e.g. 1 year), k_1 is a factor which considers considers the influence of execution of D_{eff} (e.g. influence of curing), k_2 is a factor which considers the influence of the environment on D_{eff} (e.g. influence from moisture and temperature conditions at the surface of the concrete structure) and n is a factor which considers the influence from the environment on the time-evolution of D_{eff} (e.g. shelter against rain and moisture conditions at the surface of the structure).

2.2 Chloride Induced Corrosion

One model to describe the chloride ingress-process in concrete was presented by Mejlbro (1996). The model, rewritten in a convenient from for design purposes, is mathematically represented as follows:

$$C_x = C_{SN} \cdot \left[1 - erf \frac{x}{2 \cdot \sqrt{D_{ce(m)} \cdot f_c \cdot f_e \cdot f_t \cdot \left(\frac{t_m}{t} \right)^n \cdot t}} \right] \qquad (2)$$

where: $D_{ce(m)}$ is the effective diffusion coefficient at a defined execution and environmental conditions measured at time m, n is a factor which considers the influence from the material and the environment on the time-evolution of $D_{ce(m)}$, C_{SN} is the surface chloride level, t is the exposure period, t_m is the reference period (normally 28 days), f_c is a factor that considers the influence from curing on $D_{ce(m)}$, f_e is a factor that considers the differences between different exposure environments, f_t is a factor that considers the test-method and x is the depth.

3. ENVIRONMENTAL PARAMETERS

The general approach of modelling the environmental actions on concrete structures is to separate actions from the response of the structure. This means that the “true environmental actions” in large extent are independent of the choice of concrete. In the following some examples of environmental actions are given.

3.1 Surface temperature

The best way of describing the surface temperature conditions is to use an equivalent surface temperature, see (3). In the expression for the equivalent surface temperature the influences from the temperature of the surrounding air, the solar radiation, convective heat transfer with the ambient air, long wave radiation exchange with the sky and the surroundings, evaporation and heat transferred from the inside of the structure are included.

$$T_{surf} = T_{air} + \frac{I_{sun} \cdot a + \frac{T_i}{M} + a_r \cdot T_{sky} + a_{cv} \cdot T_{air} - h_e \cdot g}{\frac{1}{M} + a_r + a_{cv}} \qquad (3)$$

where: T_{air} is the air temperature, I_{sun} is the solar radiation, a is the solar radiation absorption factor, T_i is the temperature inside the structure, M is the heat resistance for the structure, a_r and a_{cv} are the heat transfer coefficients for radiative and convective heat transfer respectively, T_{sky} is the sky temperature, h_e is the evaporation energy and g is the evaporation rate.

3.2 Surface Humidity

Due to solar radiation the surface humidity differs from the humidity in the surrounding air. Under the assumption of constant vapour content in the air, the surface humidity is predicted with (4).

$$RH_{surf} = \frac{RH_{air} \cdot v_s(T_{air})}{v_s(T_{s,eq})} \tag{4}$$

where: RH_{air} is the relative humidity in the air, $v_s(T_{air})$ being the vapour content of air at saturation at a specific temperature, T_{air} is the air temperature and T_{eq} is the equivalent surface temperature.

3.3 Time of Wetness

The time of wetness for a surface is a summation of the time of wetness due to rain and time of wetness due to surface condensation. This is given in (5).

$$TOW = t_{wet,rain} + t_{wet,cond} \tag{5}$$

where: $t_{wet,rain}$ is the time of wetness due to rain and $t_{wet,cond}$ is the time of wetness due surface condensation.
The time of wetness due to rain and due to surface condensation are however correlated.

- **Precipitation.** A division is made between vertical and driving rain.
- **Surface condensation.** If the equivalent surface humidity exceeds 100% surface condensation will occur, i.e. $RH_{surf} \geq 100\%$.

3.4 Chloride conditions

The true environmental actions in a chloride environment should be described at the concrete surface and include temperature, humidity and chloride concentration. A way should be find to go from these actions to the response by the concrete, e.g. described by a surface chloride content C_s, if empirical models are used. The equation for the C_s-value is described in (6).

$$C_s = \frac{C'_{tot}(C_{env}, w/c, type\, of\, binder, T) \cdot C}{r_{conc}} \tag{6}$$

where: C'_{tot} (% of binder-weight) is given by the chloride binding isotherm at C_{env} and a temperature of $+20\,°C$. The correction factor for T follows from the Arrhenius equation. C is the cement-content in the concrete and g_{conc} is the density of the concrete. The “equivalent chloride concentration”, C_{env}, should be different for a marine or a bridge environment.

4. QUANTIFICATION OF ENVIRONMENTAL PARAMETERS

To be able to make probabilistic lifetime calculations it is necessary to quantify the parameters in the deterioration models. In the following some examples of how the environmental parameters in a carbonation model and a chloride ingress model can be performed.

4.1 Carbonation Induced Corrosion

In the model for carbonation presented above three different environmental factors can be identified. These are:

- k_2. Environmental factor. This factor considers the differences between the conditions in a reference climate and the climate conditions on-site.
- n. Age factor. This factor considers the age-dependency of the diffusion coefficient.
- C_S. Surface concentration of carbon dioxide. This concentration is normally assumed to be equal to the concentration of carbon dioxide in the surrounding air (equal to 358 ppm).

The quantification of the factors is made with data from a 16-year exposure test on 27 concrete mixes and for three different exposure conditions, indoors (LAB), outdoors sheltered (OS) and outdoors unsheltered (OUS). The results from the exposure test are presented in Wierig (1984).

The quantification is made in such way that a reference climate is defined. Normally the indoor climate is used as a reference climate. In this reference climate the environmental parameter, k_2, is equal to 1 and the age factor, n, is equal to 0. The quantification is made in the following way:

1. The n-parameter is quantified by making a linear regression analysis in a log-log diagramme, with the carbonation-depth on one axis and the time on the other axis.
2. The k_2-parameter is quantified by comparing the carbonation-depths in different climates for the same concrete-mix and the same execution.

The result of the quantification can look like in figure 1a, where the k_2-factor is plotted against the surface humidity, and figure 1b, where the n-parameter is plotted against rain time. Due to lack of field-observation at different climates, data from calculations made with a micro-level carbanation model, used in CEB TG V/1+2. The model is presented in CEB Bulletin 238.

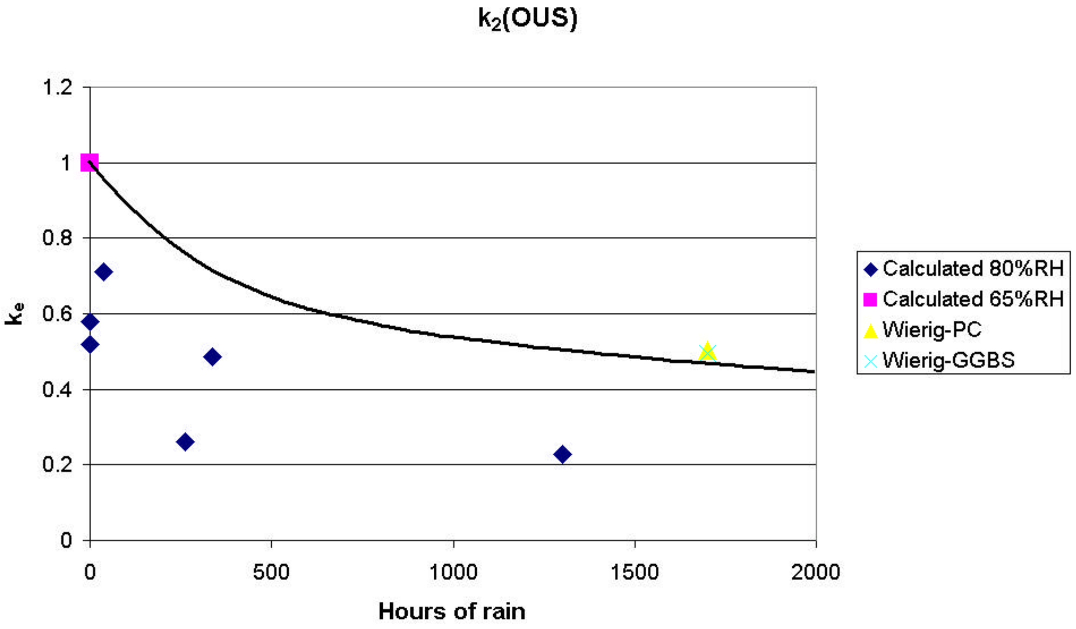

Figure 1a: The result of the quantification of the environmental parameter, k_2*, for OPC- and GGBS-concrete exposed in an OUS-environment.*

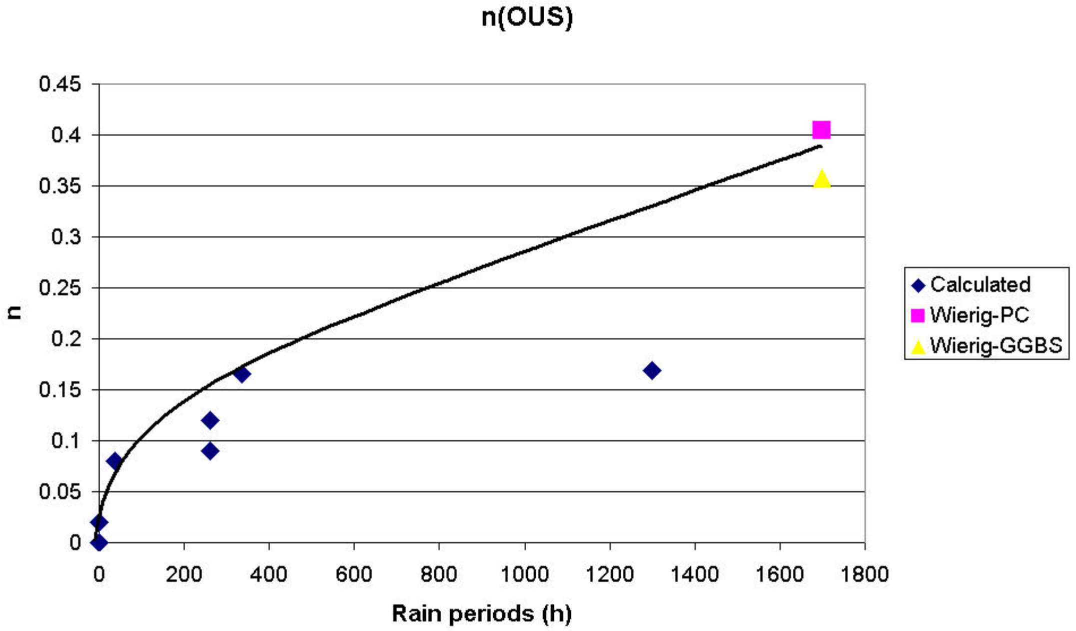

Figure 1b: The result of the quantification of the age factor, n, for OPC- and GGBS-concrete exposed in an OUS-environment.

In figure 1a and 1b the result of the quantification of the field observation are given as mean-values. To each of these mean-values the following statistical distribution function are attached:

- Environmental factor: LogNorm(0.48;0.26) (OPC-concrete) and LogNorm (0.50; 0.12) (GGBS-concrete).

- Age-factor: Beta(0.283; 0.184; 0; 0.5) (OPC-concrete) and Beta(0.319; 0.124; 0; 0.5) (GGBS-concrete).

4.2 Chloride Induced Corrosion

In the model for chloride ingress presented above three different environmental parameters can be presented:

- f_e. Environmental factor. This factor considers the differences between the conditions in a reference climate and the climate-conditions on-site.
- n. Age-factor. This factor considers the age-dependency of the apparent diffusion coefficient.
- C_{SN}. Surface chloride concentration. This factor describes the driving potential of chlorides into the concrete structure.

The quantification of the parameters is made with data from Nilsson et al (1997), where 15 different concrete mixes are studied in a 2-year exposure programme in a marine environment on the Swedish west coast. Three different zones in the marine environment have been studied: the submerged zone (S), the splash zone (Sp) and the atmospheric zone (A).

The quantification is made in the following steps:

1. The age factor, n, is quantified by making a linear regression analysis in a log-log diagram, with the apparent diffusion coefficient as a function of time.
2. Using the result from the quantification of the age factor an apparent diffusion coefficient for 28 days is calculated.
3. The environmental factor, f_e, is quantified by comparing the calculated apparent diffusion coefficient for 28 days, in the different environments, with a diffusion coefficient achieved in laboratory.
4. The surface chloride concentration, CSN, is quantified by writing the surface chloride concentration as a function of w/b.

The result of the quantification can look like in figure 2a, where the statistical distribution functions for n for OPC-concrete in the submerged and splash zones are given, and in figure 2b, where the statistical distribution functions for the f_e for OPC-concrete in S, Sp and A are given, and in figure 2c, where C_{SN} is given for OPC-concrete as a function of w/b in S, Sp and A.

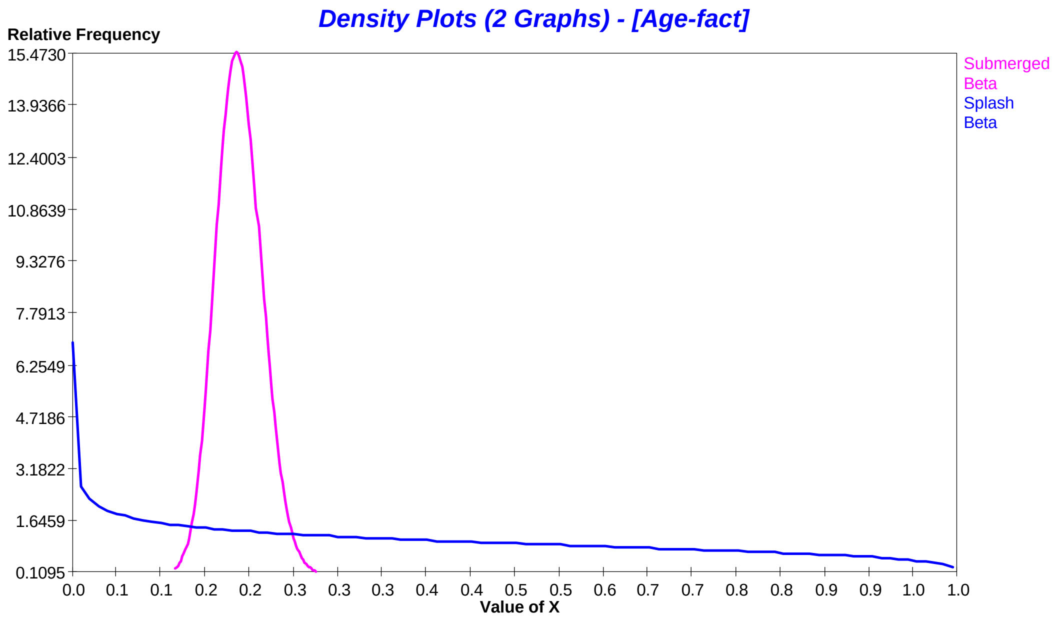

Figure 2a: The result of the quantification of the age-factor, n, for OPC-concrete exposed in the submerged, splash and atmospheric zones.

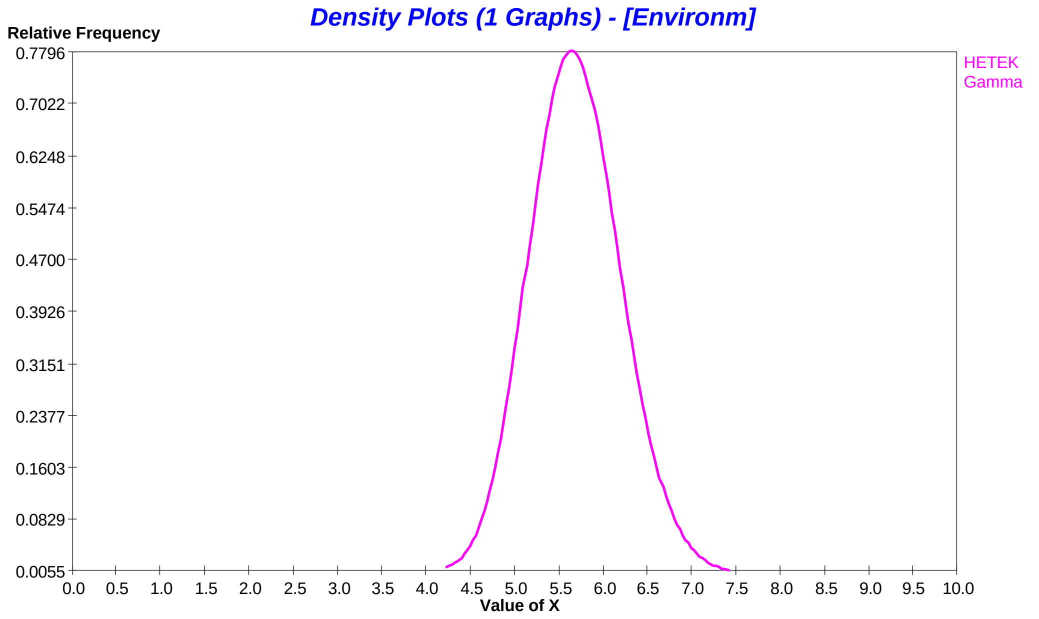

Figure 2b: The result of the quantification of the environmental factor, f_e, for OPC-concrete exposed in the submerged zone.

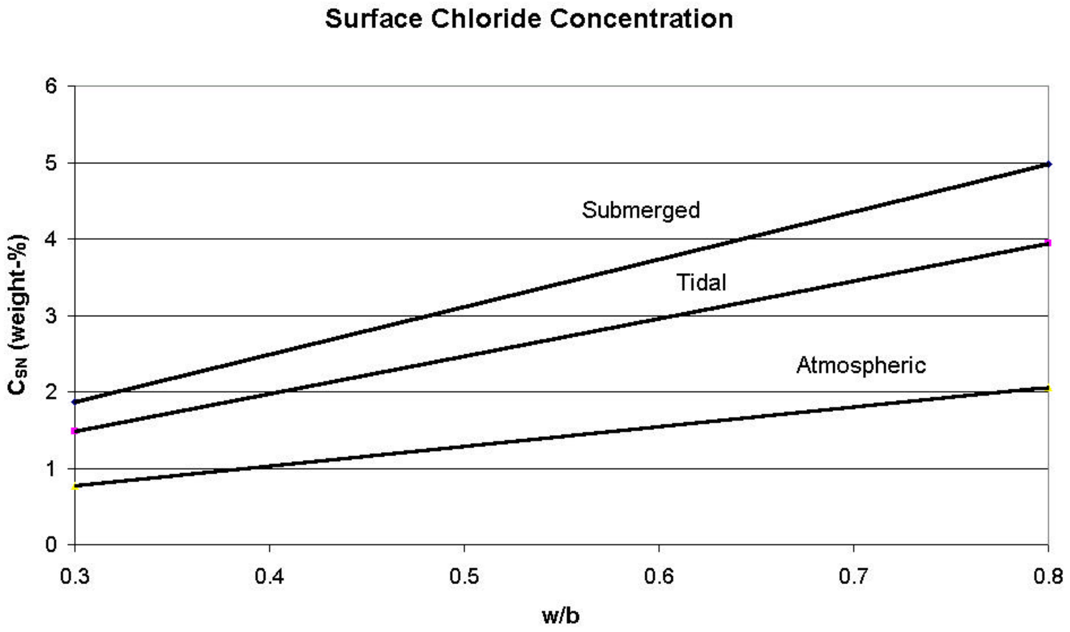

Figure 2c: The result of the quantification of the surface chloride concentration, CSN, for OPC-concrete exposed in the submerged, splash and atmospheric zones.

5. PROJECTS

In the last couple of years there have been some projects, where this new probabilistic approach to durability problems has been applied. On the project, where the author of this paper has been involved, is DuraCrete[2].

5.1 Duracrete

DuraCrete is a European project financed by the European Union. The project is a joint project between 12 different partners, companies, institutes and universities, in the EU-member states. The project is divided into eight different sub-tasks. In each sub-task between two and eight different partners are involved.

Within the DURACRETE-project calculations will be made where the lifetime for a number of different concrete structures will be estimated. The input data for the designs are achieved from the quantification made in the project. The quantification is based on observation made in the project and found in literature.

The end of the lifetime is decided by the chosen limit-state. A limit-state is for example when the reinforcement starts to corrode, when cracks occur or when the structure collapse due to corroding reinforcement. This means if for example the last limit-state is selected the limit-state function has to include everything that happens with the structure until the collapse. Consequently the limit-state function has to include the

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[2] Brite-Euram Project BE95-1347: DuraCrete - Probabilistic Performance Based Design of Concrete Structures. Partners: COWI (DK), CUR (NL) (coord.), CTH (S), Geocisa (E), HBG (NL), IBAC (D), IETCC (E), Intron (NL), Schwenk (D), RWS (NL), Taywood (UK) and TNO (NL).

initiation and propagation of corrosion on the reinforcement and the structural consequences of the corrosion.

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