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SOFTWARE FOR PROBABILITY-BASED DURABILITY ANALYSIS OF CONCRETE STRUCTURES

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Abstract

In recent years, much research work has been carried out in order to obtain a more controlled durability and long-term performance of concrete structures in chloride containing environment. In particular, the development of new procedures for probability-based durability design has proved to give a more realistic basis for the analysis. Although there is still a lack of relevant data, this approach has been successfully applied to several new concrete structures, where requirements to a more controlled durability and service life have been specified. A probability-based durability analysis has also become an important and integral part of condition assessment of existing concrete structures in chloride containing environment. In order to facilitate the probability-based durability analysis, a simple software named *DURACON* has been developed, where the probabilistic approach is based on a Monte Carlo simulation.

In the present paper, the software for the probability-based durability analysis is briefly described and used in order to demonstrate the importance and sensitivity of the various durability parameters affecting and controlling the durability of concrete structures in chloride containing environment.

1. Introduction

Since all parameters both for concrete durability and environmental exposure typically show a high scatter, a probability-based approach has shown to give a very powerful basis for durability analysis [1-3]. This approach is primarily being applied for obtaining a more controlled durability and long-term performance of new concrete structures, but it also provides a valuable basis for condition assessment of existing concrete structures in chloride containing environment. For the probability approach, a number of statistical methods exist which can be applied for the durability analysis. However, since there is still a lack of relevant data as input to such an analysis and a number of assumptions have to be made, a very simple software program (*DURACON)* based on a Monte Carlo simulation has been developed.

In the following, the software program is briefly described and used in order to demonstrate the importance and sensitivity of the various durability parameters affecting and controlling the durability of concrete structures in chloride containing environment.

2. Model description

For the software program *DURACON - Durability Design of Concrete Structures* [4, 5], the modelling of chloride penetration and time to depassivation is based on Fick's Second Law of Diffusion in combination with a time dependent diffusion coefficient [6]. The software incorporates the stochastic nature of the individual durability parameters which are needed as input to the program. These durability parameters include the diffusion coefficient, which may either be obtained from accelerated laboratory testing or curve fitting of chloride profiles from existing concrete structures, the time dependence of the diffusion coefficient and the critical chloride content for depassivation of embedded steel, both of which may be obtained from existing literature or other experience for the given type of cement and concrete. It further includes the concrete cover and the environmental exposure expressed in the form of surface chloride concentration, which may either be obtained from measurements or previous experience.

As time to depassivation or onset of steel corrosion is used as a basis for the serviceability limit state (SLS), the program can express the probability of failure or risk for SLS to be reached after a certain period of time. For new concrete structures, this provides an appropriate basis for coming up with an overall durability criteria for the structure in question [7], while for existing concrete structures, where the chloride front has still not reached the embedded steel, the program can also be used for estimating the probability of corrosion after a certain period of time [8].

2.1 Rate of chloride penetration

According to Fick's Second Law of Diffusion, we have the following expression:

$$\frac{dC(x,t)}{dt} = D_C \cdot \frac{d^2C(x,t)}{dx^2} \qquad (1)$$

where $C(x,t)$ is the chloride ion concentration at a distance x from the concrete surface after being exposed for a period of time t, and D_C is the chloride diffusion coefficient. By solving this equation for predefined boundary conditions, the following equation is obtained:

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D.t}}\right)\right] \qquad (2)$$

where C_S is the chloride ion concentration on the concrete surface, and *erf* is the error function.

The time dependence of the diffusion coefficient is normally expressed as:

$$D(t) = D_0 \cdot \left(\frac{t}{t_0} \right)^{\alpha} \tag{3}$$

where D_0 is the diffusion coefficient at a given time t_0, and the exponent α represents the time dependence of the diffusion coefficient or the increased ability of the concrete to resist chloride penetration over time.

By substituting eq. 3 into eq. 2, an expression is obtained that permits the prediction of chloride penetration based on the time dependent diffusion coefficient, given by:

$$c_X = c_S \left[1 - erf\left(x / 2.\sqrt{D_0 \cdot t \cdot (t/t_0)^{\alpha}} \right) \right] \tag{4}$$

2.2. Probabilistic approach

The Monte Carlo Method (MCM) can briefly be described as a statistical simulation method, where sequences of random numbers are applied to perform the simulation. In the present application of simulation, the physical process is simulated by use of the modified Fick's Second Law of Diffusion for describing the transport process. The only requirement is that all the input parameters to the equation can be described by a probability density function (PDF). Once the PDF's of the various durability parameters of the system are known, the probability of failure is based on the evaluation of the limit state function for a large number of trials.

When a simulation method is used for calculating the probability of failure, the failure function is calculated for each outcome. If the outcome is in the failure region, a contribution to the probability of failure is obtained. Thus, the probability of failure can be estimated by the following expression:

$$p_f = \frac{1}{N} \cdot \sum_{j=1}^{N} I\left[g\left(r_j, s_j \right) \right] \tag{5}$$

where N is the number of simulations, $I\,[g(r_j,s_j)]$ is the indicator function, and $g(r_j,s_j)$ is the limit state equation, where s represents the environmental load and r is the resistance of the concrete against chloride penetration.

The standard error for the probability of failure is estimated by [9]:

$$s = \sqrt{\frac{p_f(1-p_f)}{N}} \qquad (6)$$

Since the accuracy of the Monte Carlo Method (MCM) mainly depends on the number of trials [10] and the method is easy to implement, a simulation based on MCM appears to be both simple and intuitive.

2.3 Assumptions and limitations

It should be noted that the rate of chloride penetration may also be controlled by other mechanisms such as capillary suction or crack penetration. However, based on current knowledge, it appears that diffusion is the dominating transport process for the chloride penetration through the concrete cover. Since the rate of diffusion is also controlled by temperature, however, and the current software does not take temperature into consideration, this may also represent a limitation. This may not be so important for a durability analysis of an existing structure, since the input parameter for the diffusion coefficient D_o then will also reflect the prevailing temperature conditions for the given structure. This may also be the case for the input parameter α, which reflects the time dependence of the diffusion coefficient. However, there is still a lack of relevant data and information on the various input parameters. Therefore, a critical interpretation of obtained results and sound engineering judgement are important for a proper utilization of the software.

3. Durability design options

3.1 General

In order to demonstrate how the *DURACON* program can be used for selecting an appropriate combination of a concrete mixture and concrete cover for obtaining a more controlled durability, the effects of two different concrete variables on the durability analysis are shown in the following. In the one example, the effect of varying cement content in the concrete mixture was investigated, while in the other example, the type of cement was varied.

5.1 Input durability parameters

As input to the durability analysis, the following durability parameters were used:

- t - exposure period to the chloride containing environment. In both cases, an exposure period of 50 years was selected.
- c_S - surface chloride concentration. In both cases, a normal distribution of surface chloride concentration with an average of 0.60 % by wt. of concrete and a coefficient of variation (CoV) of 10% were adopted.
- x_C - concrete cover of reinforcement. In both cases, a normal distribution of concrete cover with an average of 50 mm and a 5 mm standard deviation were

adopted.

- D_0 - diffusion coefficient at time t_0. For each concrete mixture, this coefficient was determined based on accelerated laboratory testing [11], assuming a normal distribution with a 10% CoV.
- t_0 - the age at which the diffusion coefficient D_0 was determined. For all types of concrete, this age was 28 days.
- c_{CR} - critical chloride ion concentration. Based on existing experience, a value for each type of concrete depending on both content and type of cement was adopted. For all types of concrete, a 10% CoV was also adopted.
- α - exponent for time dependence of diffusion coefficient. Based on existing experience for each type of cement, appropriate values for both the exponent and CoV were adopted.

5.2 Effect of cement content

In order to study the effect of cement content, four different types of concrete with a constant water to cement ratio but a varying content of an ordinary portland cement were produced. The varying cement content included 300, 350, 370 and 400 kg/m^3, and the effect of the cement content on the observed diffusion coefficients is shown in Table 1, where the adopted values for c_{CR} also are included.

Table 1. Parameter values for varying cement content (kg/m ^{3}).

Cement content	**300**	**350**	**370**	**400**
D_0 (e-12 m^2/s)	N(15.70, 1.57)	N(11.70, 1.17)	N(8.00, 0.80)	N(5.50, 0.55)
c_{CR} (% wt. of concrete)	N(0.05, 0.005)	N(0.06, 0.006)	N(0.065, .0065)	N(0.07, 0.007)

As can be seen from Fig. 1, the increasing cement content distinctly decreased the probability of corrosion at any given time of exposure. It is also important to note that the smaller the cement content, the more rapidly the probability of corrosion increased. In most codes for reliability of structures, however, an upper level of 10% for probability of failure is normally accepted [7]. Regardless of cement content, Fig. 1 demonstrates that a probability level of 10% for corrosion would be exceeded already within a period of approximately 5 to 15 years. For concrete structures in chloride containing environment, therefore, another type of cement should be used.

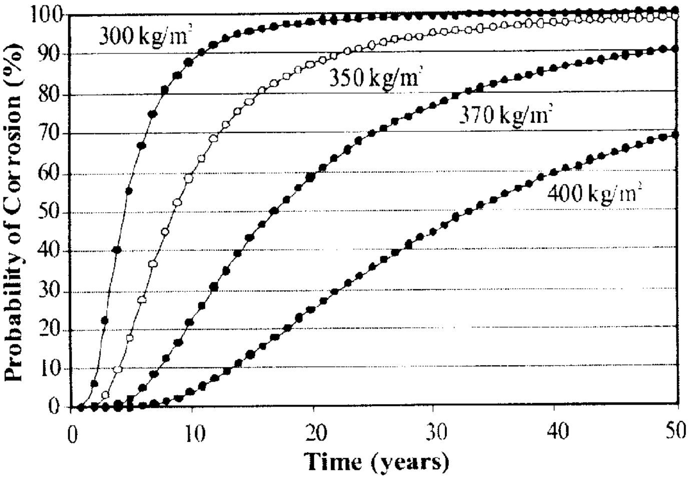

Fig. 1. The effect of cement content on the probability of corrosion.

5.3 Effect of cement type

In order to study the effect of cement type, four concrete mixtures with four different types of cement were produced, where the type of cement was the only variable. The different types of cement included an ordinary portland cement (OPC), a granulated blast furnace slag cement (GGBS), a blended portland cement with 20% fly ash (PFA) and a combination of the ordinary portland cement with silica fume (OPC+SF). The effect of cement type on the observed diffusion coefficient is shown in Table 2, where the adopted values for c_{CR} and α also are included.

Table 2. Parameter values for different types of cement.

Cement type	**OPC**	**GGBS**	**PFA**	**OPC+SF**
D_0 (e-12 m^2/s)	N(5.50, 0.55)	N(6.70, 0.67)	N(12.80, 1.28)	N(5.00, 0.50)
c_{CR} (% wt. of concrete)	N(0.07, 0.007)	N(0.12, 0.012)	N(0.10, 0.010)	N(0.07, 0.007)
α	N(0.37, 0.07)	N(060, 016)	N(0.57, 0.10)	N(0.40, 0.07)

As can be seen from Fig. 2, the type of cement had a significant effect on the probability for corrosion. Fig. 2 clearly demonstrates the big difference in resistance against chloride penetration between the blast furnace slag cement and the pure portland cement, which is in accordance with previous experience [12]. For the pure portland cement, the probability level of 10% for corrosion would be exceeded within a period of approximately 15 years, while for the blast furnace slag cement, this level of risk for corrosion would not be exceeded within the considered period of 50 years. For the fly ash cement and the combination of the portland cement with silica fume, the corresponding risk for corrosion would be exceeded within a period of approximately 20 and 30 years, respectively.

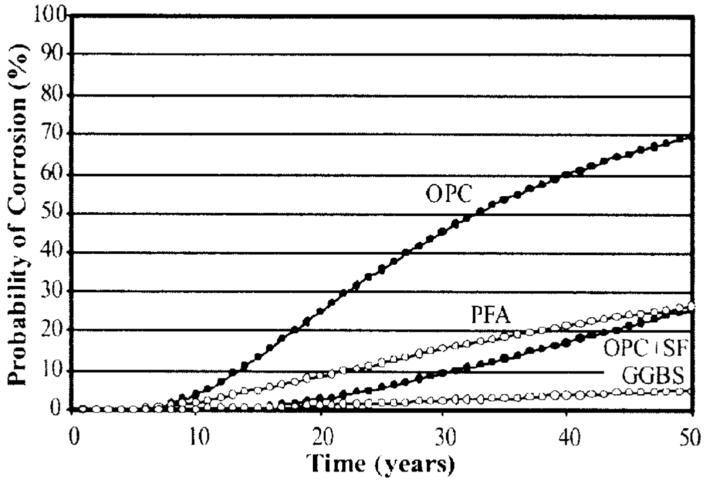

Fig. 2. Effect of cement type on the probability of corrosion.

4 Sensitivity analysis

4.1 Method of sensitivity analysis

The objective of the sensitivity analysis was to observe the variation of probability of corrosion for the individual durability parameters after a service period of 50 years. The analysis was performed by varying the various parameters involved over a relevant range of values while maintaining the other parameters constant. Some typical results are shown in the following. For comparative purpose, a base case was also defined, the values for which together with the range of the parameters analysed are shown in Table 3.

4.2 Sensitivity of durability parameters

If the diffusion coefficient increases, it can be seen from Fig. 3 that so does the probability of corrosion. This should be expected, since the larger the diffusion coefficient, the more penetrable the concrete is. For the base case values chosen, however, it can be seen that the probability of corrosion can be reduced by more than 95% if the diffusion coefficient is reduced from 5e-12 m^2/s to 1e-12 m^2/s, and hence, the diffusion coefficient appears to be a very sensitive parameter. A most efficient way of controlling the diffusion coefficient, is a proper selection of cement type as previously shown in Fig. 2.

Table 3. Range of parameter values for sensitivity analysis.

Parameters	**Base case**	**Range of values**
D_0 (e-12 m^2/s)	N(2.00, 0.20)	1.00, 3.00, 4.00, 5.00
c_{CR} (% wt. of concrete)	N(0.05, 0.005)	0.10, 0.15, 0.20
x_C (mm)	N(50.0, 5.0)	40.0, 55.0, 60.0, 70.0
c_S (% wt. conc)	N(0.60, 0.06)	0.45, 0.53, 0.68, 0.75
t/t_0 (years/days)	50 / 28	Not varied
a	N(0.35, 0.035)	Not varied

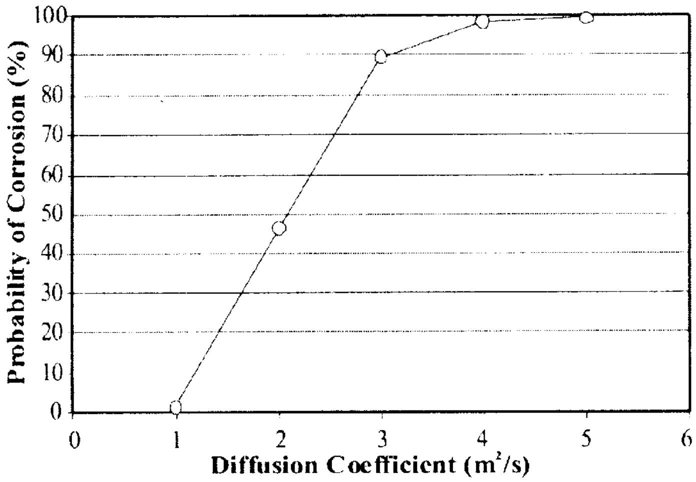

Fig. 3. Effect of the diffusion coefficient on probability of corrosion.

In Fig. 4 the sensitivity of varying concrete cover for the probability of corrosion is shown. For decreasing concrete cover below 60 mm, it appears that the probability of corrosion rapidly increases in a linear way, and hence, concrete cover is also a very sensitive durability parameter.

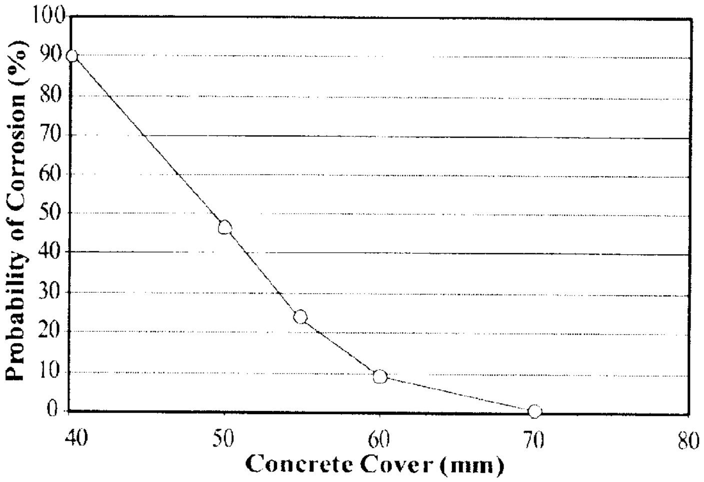

Fig. 4. Effect of concrete cover on probability of corrosion..

5. Conclusions

For a probability approach to the durability analysis, a number of statistical methods exist which may be adopted for the analysis. However, since there is still a lack of relevant data as input to such an analysis and a number of assumptions have to be made, a very simple software program based on a Monte Carlo simulation has been developed, some results of which are demonstrated in the present paper.

As part of the durability design options, it was shown that increased contents of a pure portland cement did not change very much the probability of chloride-induced corrosion compared to that of selecting a more proper type of cement. Thus, for the pure portland cement, a probability level of 10% for corrosion would be exceeded within a period of approximately 15 years, while for the blast furnace slag cement, such a risk for corrosion would not be exceeded within the considered period of 50 years. For the fly ash cement and the combination of the portland cement with silica fume, the corresponding risk for corrosion would be exceeded within a period of approximately 20 and 30 years, respectively. In the sensitivity analysis of the various durability parameters, it was further shown that a reduced chloride diffusivity of the concrete from 5e-12 m^2/s to 1e-12 m^2/s would reduce the probability of corrosion by more than 95% over a service period of 50 years. Hence, the chloride diffusivity of a concrete is a very sensitive and important durability parameter for concrete structures in chloride containing environment.

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