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Software for evaluating probability-based integrity of reinforced concrete structures

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Summary

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 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 of the various durability parameters affecting 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 very valuable basis for condition assessment of existing concrete structures in chloride containing environment. For the probability approach 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* [4], the modelling of chloride penetration and time to depassivation is based on Fick's Second Law of Diffusion in combination with a

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time dependent diffusion coefficient [5]. 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, the time dependence of the diffusion coefficient and the critical chloride content for depassivation of embedded steel. The concrete cover and the environmental exposure expressed in the form of surface chloride concentration are also important durability and input parameters to the software program.

As time to depassivation and 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 [6], while for existing concrete structures, where the chloride front has still not reached the embedded steel, the program can be used for estimating the probability of corrosion after a certain period of time [7].

2.1 Rate of chloride penetration

If we solve Fick's Second Law of Diffusion for predefined boundary conditions, the following equation is obtained:

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

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; 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:

$$D(t) = D_0 \cdot \left(\frac{t}{t_0}\right)^{\alpha} \tag{2}$$

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. 2 into Eq. 1, an expression is obtained that permits the prediction of chloride penetration based on the time dependent diffusion coefficient, given by:

$$c_X = c_S\left[1 - erf\left(x/2.\sqrt{D_0 \cdot t \cdot (t/t_0)^{\alpha}}\right)\right] \tag{3}$$

2.2. Probabilistic approach

The probabilistic approach is based on the Monte Carlo Method. In the present application of simulation, the physical process is simulated directly 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, then the contribution to the probability of failure is obtained. The probability of failure is estimated by the following expression:

$$p_f = \frac{1}{N} \cdot \sum_{j=1}^{N} I\left[g\left(r_j, s_j\right)\right] \tag{4}$$

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.

Since the accuracy of the Monte Carlo Method (MCM) mainly depends on the number of trials [8] 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 a dominating transport process for the chloride penetration into concrete. The current software does not take temperature into consideration directly, 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 judgment are important for a proper utilization of the software.

3 Durability design options

In order to demonstrate how the *DURACON* program can be used to select appropriate concrete mixtures or 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.

3.1 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 [9], 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 assumed. 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 assumed.

3.2 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 also the adopted values for c_{CR} 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.conc.)	N(0.05, 0.005)	N(0.06, 0.006)	N(0.065, .0065)	N(0.07, 0.007)

As can be seen from Figure 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 [6]. Regardless of cement content, Figure 1 demonstrates that a probability level of 10% for corrosion will 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.

3.3 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 also the adopted values for c_{CR} and α 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. conc.)	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)

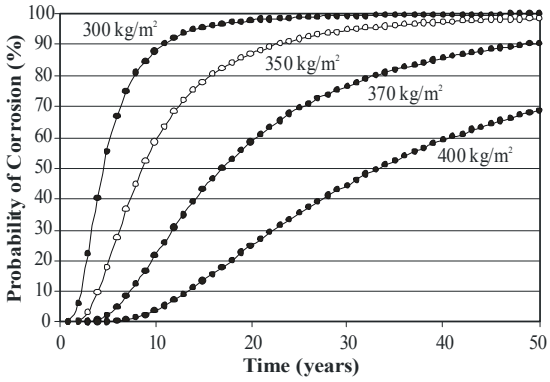

Fig. 1 The effect of cement content on the probability of corrosion.

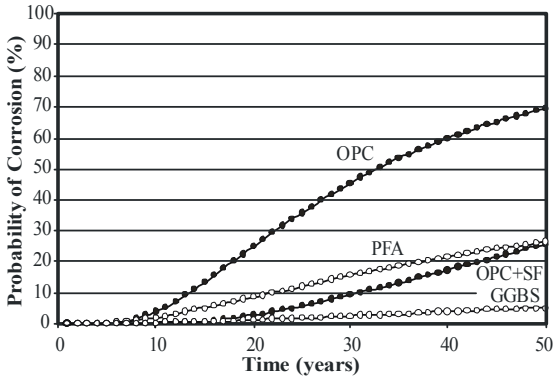

Fig. 2 Effect of cement type on the probability of corrosion.

As can be seen from Figure 2, the type of cement had a significant effect on the probability for corrosion. Figure 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 [10]. 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.

4 Conclusions

For a probability approach to durability analysis, a number of sophisticated statistical methods exist which may be adopted for the analysis. However, since there is still a lack of relevant data as input to a 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 of 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.

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Paulo J.V. Oliveira; Paulo A.L.F. Coelho; Luís J.L. Lemos

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Organizer:

Professor Koichi Hashiguchi

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Frederic Barlat; Jeong-Whan Yoon

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Takashi Okayasu; Koichi Hashiguchi; Toshiyuki Ozaki; Daiki Yajima; Shingo Ozaki

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Toshiyuki Ozaki; Takashi Okayasu; Koichi Hashiguchi; Daiki Yajima

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Hideki Setouchi; Koichi Hashiguchi; Takeshi Shikanai; Takashi Okayashu

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Mohammed Saiful Alam Siddiquee; Tadatsugu Tanaka

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Professor Luigi Morino & Professor Wesley Harris

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Organizers:

Professor Pinhas Bar-Yoseph & Professor Alexander Gelfgat

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Pinhas Z. Bar-Yoseph; Alexander Yu. Gelfgat

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A. Bergeon; E. Knobloch

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Morten Brons; Anders Bisgaard

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C. H. Bruneau

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Jacob Cohen; D. Mourtazin

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Nuno P. Costa; Rodrigo Jorge Maia

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R. Hollerbach

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B. C. Houchens; John S. Walker

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S. Hoyas; H. Herrero; A. M. Mancho

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Eliezer Kit; Alexander Yu. Gelfgat

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Janis Priede; Gunter Gerbeth

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Gregory J Sheard; Mark C Thompson; Thomas Leweke; Kerry Hourigan

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J. M.M. Sousa

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Hermann Wilke; Andrew Cliffe; J. A. Pojman

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Dr. Frederick W. Brust, Professor Wen-Hwa Chen, & Professor Hidekazu Murakawa

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Dean Deng; Hidekazu Murakawa

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Professor A. Tom Scarpas & Professor Patrick Selvadurai

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Erich Bauer; Jacek Tejchman

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Annamaria Cividini; Giancarlo Gioda

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Behrouz Gatmiri; Hasan Ghasemzadeh

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Nuno Costa Guerra; Manuel Matos Fernandes; António Silva Cardoso; António Gomes Correia

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Niki Kringos; A. Tom Scarpas

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Markus Oeser; Sabine Werkmeister; Bernd Möller; Frohmut Wellner

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Luis Picado Santos; Rosa Conceição Luzia

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Organizers:

Professor Carlos Alves, Professor C.S. Chen,
Professor Vitor Leitão, & Professor Thanh Tran-Cong

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C. G. Biniaris; A.I. Kostaridis; D.I. Kaklamani

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Andreas Karageorghis; C.S. Chen; Y.-S. Smyrlis

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Professor Hanchen Huang, Professor Nobutada Ohno,
Professor Hiroshi Okada, Dr. Deepak Srivastava,
Dr. Vinod Tewary, Professor Yoshiro Tomita,
& Professor Priya Vashishta

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Priya Vashishta; Rajiv K. Kalia; Aiichiro Nakano

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H. S. Wijesinghe; Nicolas G. Hadjiconstantinou

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Organizer:

Professor Demos Polyzos

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D. G. Aggelis; T. P. Philippidis; S. V. Tsinopoulos; D. Polyzos

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Mohsen Asghari; Artan Sheshmani

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Pavel Kuklík; Michal Šejnoha; Jarosla Vacek

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Jiri Nemecek; Pavel Padevet; Zdenek Bittnar

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Bending Design of RC Circular Cross Sections according to ENV 1992 Standard for strains ec2>1.35 %
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Hongying Fei; Abdelhakim Artiba ; Chengbin Chu

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Adelino Jorge Ferreira; Gerardo W. Flintsch

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Luis Filipe Figueiredo; Mário Freire

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Francesco Giambanco; Luigi Palizzolo; Alessandra Caffarelli

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Andrew J. Goupee; Senthil S. Vel

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José Luis Carrasco Gutierrez; Celso Romanel

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Andrej Kotar; Pino Koc; Boris Stok

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Silvio J.P.S. Mariano; Luis A.F.M. Ferreira

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Kazunari Momose; Yoshikatsu Sawada; Hideo Kimoto

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Marcos Noronha; Ch. Duenser; G. Beer

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Orlando Camargo Rodríguez; Sérgio Machado Jesus

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Sabrina B.M. Sambatti; Haroldo F. de Campos Velho; Leonardo D. Chiwiacowsky; Stephan Stephany; Airam J. Preto

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Wigand Stransky; Bernd Möller; Wolfgang Graf

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Rolf Vargas; L.C. Gadelha DeSouza; Helio K. Kuka

Chapter 19

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Organizers:

Professor Masanori Kikuchi, Professor Seung Jo Kim,
Professor Toshihisa Nishioka, Dr. Larry Russell,
& Professor Kunigal Shivakumar

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A. Blázquez; J.F. Kalthoff; I. Palomino; A. Fernandez-Canteli

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Bin Chen; Z.H. Gao; X.H. Peng; J.H. Fang

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Victor M. F. Évora; Nitesh Jain; Arun Shukla

Software for Evaluating Probability-Based Integrity of Reinforced Concrete Structures
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Takehiro Fujimoto; Toshihisa Nishioka

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Influence of Semi-Rigid Joints on the Behaviour of Steel Beam-Column Structures
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Andreas Sebastian Kompalka; Stefanie Reese

Fracture Mechanics of the Interface Crack in a Bimaterial Piezoelectric Wedge under Antiplane Deformation
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