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Improving Durability Performance of Reinforced Concrete Structures with Probabilistic Analysis

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Abstract : In recent years, much research work has been performed on durability design and long-term performance of concrete structures in marine environments. In particular, the development of new procedures for probability-based durability design has been shown to provide a more realistic basis for the analysis. This approach has been successfully applied to several new concrete structures, where requirements for a more controlled durability and service life have been specified. For reinforced concrete structures in a marine environment, it is commonly assumed that the dominant degradation mechanism is the corrosion of the reinforcement due to the presence of chlorides. The design approach is based on the verification of durability limit states, examples of which are: depassivation of reinforcement, cracking and spalling due to corrosion, and collapse due to cross section loss of reinforcement. With this design approach the probability of failure can be determined as a function of time. In the present paper, a probability-based durability performance analysis is used in order to demonstrate the importance of the durability design approach of concrete structures in marine environments. In addition, the sensitivity of the various durability parameters affecting and controlling the durability of concrete structures in a marine environment is studied. Results show that the potential of this approach to assist durability design decisions making process is great. Based the crucial information generated, it is possible to prolong the service life of structures while simultaneously optimizing the final design solution.

Keywords : marine environment, corrosion, durability, reinforcement, temperature, hydrophobation, concrete cover

1. Introduction

In recent years, much research work has been carried out in order to define an approach to long-term performance of reinforced concrete structures due to environmental actions. In particular, the development of new procedures for durability design of reinforced concrete structures has shown to provide a more realistic basis for the durability performance analysis.[1-5] This design approach is crucial in order to obtain more controlled durability performance of new concrete structures; however, it also provides a very valuable basis for condition assessment of existing concrete structures in marine environments.

For reinforced concrete structures in a marine environment, it is commonly assumed that the dominant degradation mechanism is the corrosion of the reinforcement due to the presence of chlorides. In this paper, the modelling of chloride penetration is based on Fick's Second Law of diffusion, adapted to take into account certain modifications that better simulate the real phenomena, such as time dependant diffusion coefficient, varying surface chloride concentration, effects of temperature.[8-10] Since all parameters both for concrete durability and environmental exposure typically show a high scatter, a probability-based approach provides a very powerful basis for durability performance analysis.[1,6,7] The design approach is based on the verification of limit states. Examples of limit states for durability are: depassivation of reinforcement, cracking and spalling due to corrosion, and collapse due to cross section loss of reinforcement.[2] With this design approach the probability of failure can be determined as a function of time. For new concrete structures, this provides an appropriate basis for establishing overall durability criteria for the structure in question.[11] However, for existing concrete structures, where the chloride front has still not reached the embedded steel, the approach can be used for estimating the probability of failure after a certain period of time.[12]

In following paper the approach to durability design of reinforced concrete structures in marine environment applied with a probabilistic method is described and applied in order to demonstrate the sensitivity of the various durability indicators and model parameters affecting and controlling the durability of concrete structures in a marine environment. In addition, the potential for generating crucial information to aid the durability design decision process is demonstrated.

2. Description of model for durability performance analysis

The model presented describes the performance of reinforced concrete structures in marine environment with regards to the serviceability limit state of reinforcement depassivation and consequently corrosion initiation due to the presence of chlorides. There are many models exist, some quite elaborate,[2,3] with different

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parameters and different approaches to corrosion initiation. However, the intention in this paper is not to describe a specific model in detail, but to demonstrate the procedure for durability design and the benefits thereof. For that purpose, a simpler model, with fewer parameters, is used.

For the chosen serviceability limit state the modelling of the chloride penetration into concrete, particularly for marine structures, is performed according to Fick's Second Law of Diffusion:

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

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. By solving this differential equation for predefined boundary conditions,[13] the following equation is obtained:

$$C(x,t) = C_0(C_S - C_0)\left[1 - erf\left(\frac{x}{2\sqrt{D_C \cdot t}}\right)\right] \tag{2}$$

where C_S is the chloride ion concentration on the concrete surface, C_0 is the initial chloride concentration of the concrete mix, and *erf* is the error function.

The time dependency of the diffusion coefficient is well known, ever since Takewaka presented an equation to model this behaviour.[8] Much research has been done on this topic,[1,14-18] and, it has shown that the diffusion coefficient variation with time is dependent on various factors, the most important being the w/c ratio of the mix and the cement type and content, and exposure conditions. The time dependent variation of the D_C is introduced by the following equation :[8]

$$D_C(t) = D_0\left(\frac{t}{t_0}\right)^n \tag{3}$$

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

For temperature levels above freezing, the temperature is a decisive factor regarding the rate of certain phenomenon. This factor alone makes warmer climates considerably more aggressive than temperate climates.

The temperature dependence of the viscosity of water is mainly important for other effects such as the concrete's resistivity and diffusion processes. Diffusion processes are strongly dependent on temperature. In the case of chloride diffusion the situation is somewhat more complicated, because in the diffusion process the chemical and physical interaction of chloride with the cement paste must also be taken into consideration.

Based on the Nernst-Einstein relation, values for the diffusion coefficient at ambient temperature (21°C) are correlated to values at standard temperature according to:[19,20]

$$D_C(T) = D_{294K} \cdot \frac{T}{294} \cdot \exp\left[-\frac{E_A}{R}\left(\frac{1}{T} - \frac{1}{294}\right)\right] \tag{4}$$

where T is the temperature in Kelvin, E_A the activation energy, R the gas constant, and D_{294K} the diffusion coefficient at the reference temperature (21°C).

By substituting Eq. (3) and Eq. (4) into Eq. (2), an expression is obtained the model equation for the prediction of chloride penetration based on the time and temperature dependent diffusion coefficient, given by:

$$C(x,t) = C_0(C_S - C_0) \cdot \left[1 - erf\left(x/2\sqrt{D_{0.294K} \cdot \frac{T}{294} \cdot \exp\left[-\frac{E_A}{R}\left(\frac{1}{T} - \frac{1}{294}\right)\right]\left(\frac{t}{t_0}\right)^{\alpha} . t}\right)\right] \tag{5}$$

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 and concerning concrete structures in marine environments, it is assumed that diffusion is a dominating transport process for chloride penetration. However, there is still a lack of relevant data and information on many parameters used in durability design. Therefore, experience with the design procedure is important as well as a critical interpretation of obtained results and sound engineering judgement.

To demonstrate the potential of the probabilistic analysis approach, it is implemented with a Monte Carlo Simulation method.[21] The physical process is simulated directly by use of the modified Fick's Second Law of Diffusion. The only requirement is that all the model parameters be described by a probability density function. Once the probability density functions of the various model parameters are known, the probability of failure i.e. corrosion initiation, is calculated based on the evaluation of the limit state function for a large number of trials. Since the accuracy of the Monte Carlo Method depends mainly on the number of trials undertaken, 1e6 simulation where performed.[22]

3. Influence of model parameters on the durability performance – sensitivity analysis

3.1 Definition of the durability parameter

The objective of the sensitivity analysis is to understand the influence of durability parameter on the probability of corrosion initiation at the end of a 50 years service life. The sensitivity analysis is performed by varying a model parameters over a relevant range of values while maintaining the others constant. The parameters analysed were: diffusion coefficient, D_0; critical chloride ion concentration, c_{CR}; concrete cover of reinforcement, x_C; surface chloride ion concentration, c_S. For comparative purposes a reference case was defined, as shown in Table 1. In addition, the range of variation for the model parameters is also given in Table 1.

3.2 Results and discussion of the sensitivity analysis

Figure 1 shows that as the diffusion coefficient increases, so does the probability of corrosion initiation. This is expected as higher diffusion coefficients indicate easier chloride diffusion through concrete. The probability of corrosion initiation can be reduced by more than 90% if the diffusion coefficient is reduced

Table 1 Range of parameter values for sensitivity analysis.

Parameters	Base case	Range of values
D_0 (e-12 m^2/s)	N(4.74, 0.47)	[1~20]
c_{CR} (% wt. of concrete)	N(0.48, 0.15)	[0.25~1.25]
x_C (mm)	N(50.0, 5.0)	[40~90]
c_S (% wt. of concrete)	N(3.4, 034)	[1.0~7.0]
t/t_0 (years/days)	50 / 28	Not varied
α	N(0.39, 0.07)	Not varied

FIGURES

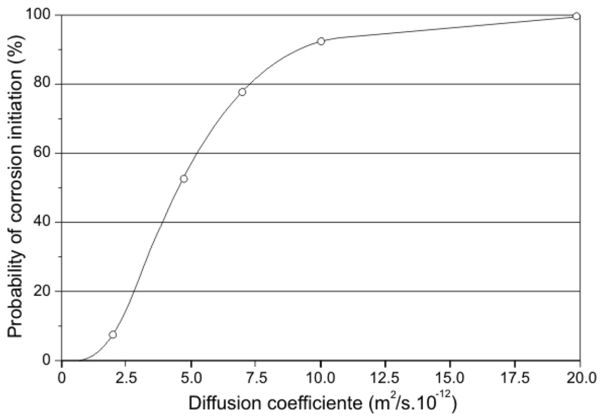

Fig. 1 Sensitivity analysis of the diffusion coefficient on probability of corrosion initiation after a 50 year service life.

from 10.0×10^{-12} m^2/s (moderate resistance to chloride diffusion)[23] to 2.0×10^{-12} m^2/s (extremely high resistance to chloride diffusion).[23] The diffusion coefficient is a very influential parameter. An efficient way of controlling the diffusion coefficient is the proper selection of cement type and water/binder ratio.[13,24]

In Fig. 2, the influence of varying concrete covers on the probability of corrosion initiation is shown. For concrete cover less than 60 mm it appears that the probability of corrosion initiation rapidly increases indicating that concrete cover is also a influential durability parameter. This is obvious as the concrete cover increases the distance the chlorides have to diffuse in order to reach the reinforcement does too. However, to obtain adequate performance large concrete covers are necessary. Whilst improving concrete cover above 60 mm results in small gains in probability of corrosion initiation, an improvement from 40 mm to 60 mm results in an decrease of 50% of the probability of corrosion initiation.

Figure 3 shows that as the surface chloride concentration increases, so does the probability of corrosion initiation. The high chloride concentration on the concrete surface will yield a high driving gradient for the chloride diffusion, and therefore anticipate a shorter diffusion period.

From Figure 4 it can be seen that as the concentration of chloride ions needed to initiate corrosion increases, the probability of corrosion initiation decrease. The need for a higher chloride concentration next to the reinforcement require more time. The critical chloride concentration depends mainly on the binder type.[24,25] The analysis indicates that the critical level of chloride concentration is a sensitive durability parameter, and therefore the choice of binder type is of the utmost importance.

From this analysis, the influence certain parameters have on the durability performance can be better understood. The comprehension of these geometrical, material or environmental parameters has a direct consequence on the durability performance of the reinforced concrete structure.

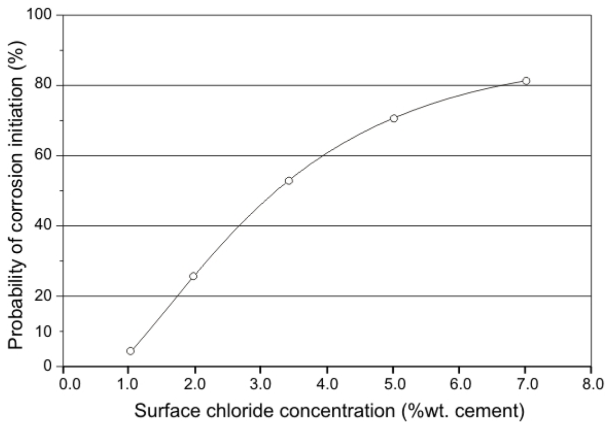

Fig. 3 Sensitivity analysis of the surface chloride concentration on probability of corrosion initiation after a 50 year service life.

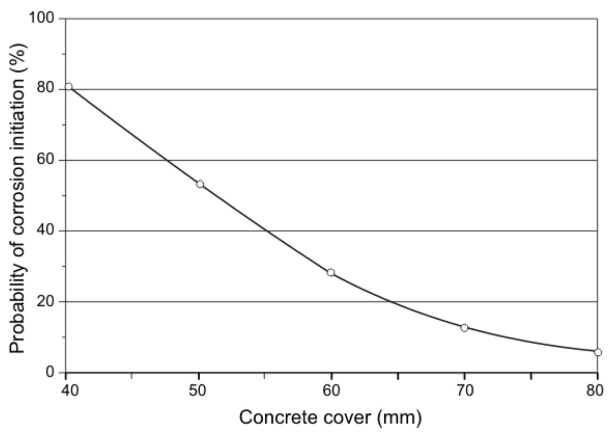

Fig. 2 Sensitivity analysis of the critical chloride concentration of corrosion initiation after a 50 year service life.

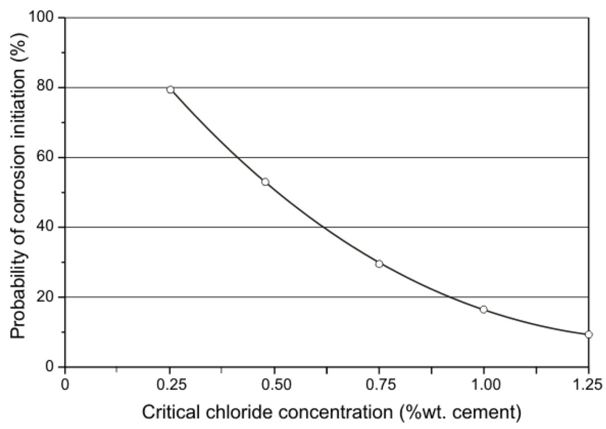

Fig. 4 Sensitivity analysis of the concrete cover on probability of corrosion initiation after a 50 year service life.

4. Evaluating the durability performance of design options

To demonstrate the potential benefit of the design approach, several design scenarios are studied. The designer should select appropriate concrete mixtures and adequate concrete cover in order to fulfil the defined serviceability limit state. In order to obtain the necessary information for the basis of the decision making process, the influence of four different model parameters on the durability performance is studied, for a service life of 50 years the serviceability limit state for corrosion initiation is defined (β = 1.3, $p_F = 10^{-1}$). Material, geometric and environmental parameters are based on published literature.

For the first example, the concrete cover is varied. In the second example, the cement type used in the concrete mixture was analysed whilst in the third example, the influence of temperature is analysed. In the final example, the effect of using surface hydrophobation coatings is analysed.

4.1 Quantifying durability indicators and parameters

The main difficulty associated with the implementation of this approach is the quantification of the model parameters. This is even more noticeable when the parameters are stochastic in nature. The lack of pertinent information can hinder the analysis, however, several proposals for some of the suggested parameters can be found in literature.[1,2,13,24] The designers must rely on their experience, on data obtained from existing structures and from published data, so as to quantify the necessary parameters. Therefore, the model parameters for the durability analysis were quantified considering that:

- the exposure period to the marine environment (service life) was establish at 50;

- the surface chloride concentration was based on measurement on surrounding structures. A normal distribution was assumed with an average value of 3.4 % by weight of cement with a coefficient of variation (CoV) of 10%;[26]

- the nominal reinforcement concrete cover for a XS3 environmental class of exposure according to the EC2[27] is 60 mm. However, taken into account the quality of the workmanship, a normally distributed concrete cover with an average of 50 mm and 10% CoV was adopted;

- the diffusion coefficient was determined based on accelerated laboratory testing,[28] of a concrete with a cement CEM I 42,5 R and approximately 420 kg/m^3 and a water/binder ratio of 0.45, at 28 days. It is normally distributed with an average of 10.5 and 10% CoV;

- the critical chloride concentration is based on existing experience,[24] with a normally distributed value of average 0.48 and standard deviation of 0.15, for the cement type chosen;

- the age factor for time dependence of diffusion coefficient is based on published literature. An average of 0.39 and a standard deviation of 0.07 were adopted, for the cement type chosen;[1]

- the reference temperature is considered deterministic with the value of 21°C.

4.2 Influence of concrete cover on durability performance

A durability analysis was carried out in order to understand out the effect of increased concrete cover above the nominal minimum requirement of 60 mm. The concrete depths of 50 (base case), 60, 70 and 90 mm were analysed. As can be seen from Fig. 5, the concrete cover is of great importance for the probability of corrosion initiation. While a nominal concrete cover of 50 mm would only provide a service life of approximately 5 years, an effective, nominal concrete cover of 90 mm would provide a service period of more than 26 years. This is still not enough to fulfil the required service life of 50 years, and therefore other changes are necessary to improve the durability performance. In practical terms, it may be difficult to used concrete covers larger than 70 mm. A partial replacement of the conventional reinforcement with stainless steel reinforcement could be used in order to obtain a substantial increase of the effective concrete cover. As a result of the durability design, the concrete cover can be changed and therefore the recalculation of the structural design is necessary.

4.3 Influence of cement type on durability performance

In order to study the effect of cement type four different cements were analysed. The durability indicator (diffusion coefficient) for the concrete mixes based on four types of cement is taken from literature.[25] The types of cement included a high-performance portland cement (CEM I 52.5), a blended fly-ash cement (CEM II/A-V 42,5), a blast-furnace slag cement with approximately 70% slag (CEM III/B 42.5), and a high-performance portland cement (CEM I 52.5) mixed with 10% silica fume. The effect of cement type on the observed diffusion coefficient (m^2/s) is shown in Table 2, where the adopted values for *n* are also included.[1,2]

As can be seen from Fig. 6, the type of cement has a significant effect on the probability of corrosion initiation. The large differ-

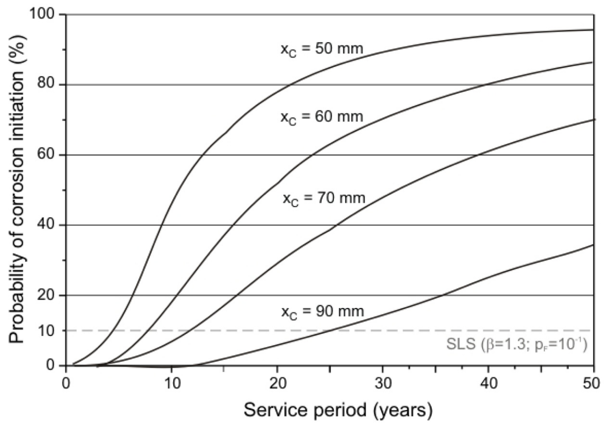

Fig. 5 Influence of concrete cover on the probability of corrosion initiation.

Table 2. Parameter values for different types of cement.

Cement type	CEM I	CEM III/B	CEM II/A-V	CEM I + SF
D_0 (10^{-12} m^2/s)[25]	N(10.5; 0.66)*	N(5.3; 0.59)	N(10.1; 0.81)	N(4.74; 0.51)
N (–)[1,2]	N(0.37; 0.07)	N(0.60; 0.15)	N(0.51; 0.07)	N(0.39; 0.07)

* N- normal distribution (average, standard deviation)

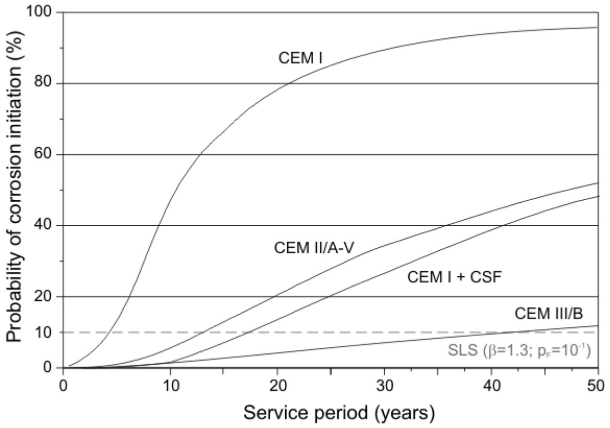

Fig. 6 Influence of cement type on the probability of corrosion initiation.

ence in resistance against chloride penetration between the blast furnace slag cement and the pure Portland cement is in accordance with previous experience.[25,28] For the pure Portland cement, the probability of corrosion initiation would be exceeded within a period of approximately 4 years, while for the blast furnace slag cement, this level of risk of corrosion would only be exceeded within a period of 42 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 13 and 17 years, respectively. For the same concrete mix, varying only the cement type from portland to blast-furnace slag, a 85% improvement in the probability of corrosion initiation is obtain after 50 years.

4.4 Influence of temperature on durability performance

The dependency of most degradation mechanisms on physical and chemical phenomena, which in turn are temperature dependant, should be taken into account in the durability design process. A durability analysis was carried out in order to understand out the effect of temperature on the durability performance of concrete structures in marine environment. The average annual temperature of three locations where taken into account: Bergen, Norway – 8°C, Lisbon, Portugal – 18 °C, and Kuwait City, Kuwait – 25°C. These parameters were used in the analysis deterministically. Figure 7 demonstrates the influence of temperature on the probability of corrosion. Considering the same quality of concrete (same performance in same conditions) but in different environments (subject to different temperature ranges), the variation in performances is significantly different. Designing a reinforced concrete structures at a reference temperature might result in the under-performance of the structure with regards to durability, and consequently the shortening of its service life. On the other hand, for cooler climates, the design might result in an over-performance unnecessarily increasing the cost of construction.

4.5 Influence of surface hydrophobation on durability performance

The influence of surface hydrophobation on durability performance was performed assuming that the efficiency of the hydrophobation coating was effective for 7~10 years. In order to simulate this performance, a gradual decrease of the permeability of the surface coating is simulated. Two situations are analysed: the first in which a single coating is applied, and the second in a second coating is applied 7 years after the first. From Figure 8 it can be seen that the hydrophobation coating delays the degradation for the effective period for the durability performance. This approach in addition with others might prove to be very useful in fulfilling the required service life.

5. Conclusions

The durability design approach described in this paper is applied to a hypothetical situation, however, the parameters are based on published data. This approach is based on models of degradation processes, and as in any similar situation, care should be taken in the interpretation of the results.

With this design approach the probability of failure, i.e. corrosion initiation, can be determined as a function of time. For new concrete structures, this provides an appropriate basis for establishing overall durability criteria for the structure in question. However, for existing concrete structures, where the chloride front has still not reached the embedded steel, the approach can be used for estimating the probability of corrosion initiation for the remaining service life.

The potential benefit of the durability design approach is demonstrated by several design scenarios where useful information for

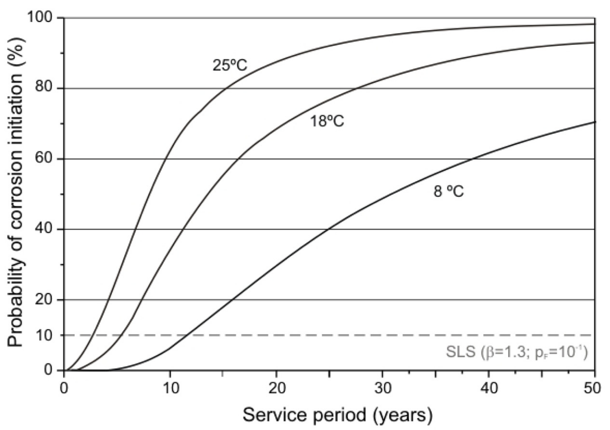

Fig. 7 Influence of temperature on the probability of corrosion initiation.

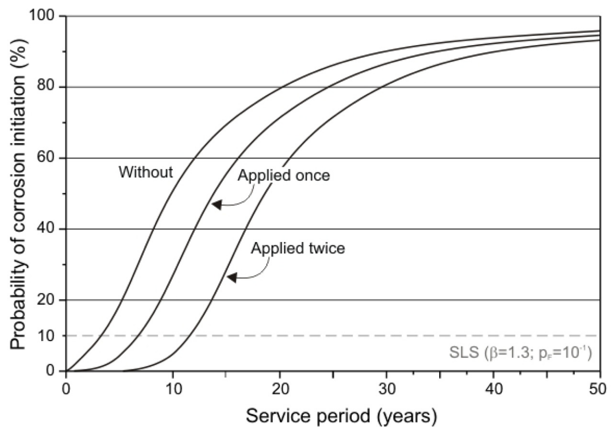

Fig. 8 Influence of hydrophobation coatings on the probability of corrosion initiation.

the decision making process is obtained. The influence of four different parameters on the durability performance is studied: concrete cover, cement type, temperature and surface hydrophobation coatings.

The results show that, for the serviceability limit state for corrosion initiation adopted, the type of cement directly influences the durability indicator (diffusion coefficient) and therefore the probability of failure. Changing from Portland cement to slag cement for the same composition results in an improvement of 85% in the probability of failure.

It is also shown that larger concrete covers benefit the durability performance. However, concrete covers greater then 60 mm result in small improvements in the durability performance for the defined service life.

In addition, the effect of temperature on durability design is demonstrated by the variation of the probability of failure by an interval of 10 years. Durability design should take into consideration the effect of temperature. If not, for warmer structures under performance could result in premature degradation, while in cooler climates, over performance results in unoptimized solutions for the structure.

It is also shown that the hydrophobation coatings can benefit the service life for as long as they are efficient. This option can be optimized in combination with other solutions to prolong the service life.

In conclusion, it is demonstrated that the durability design can benefit from applying this approach to different design scenarios and how the information generated can provide the designer with useful design options. Only by performing the different scenario simulations can an overall view of the structural durability performance be obtained.

References

1. *DuraCrete: General Guidelines for Durability Design and Redesign*, The European Union-Brite EuRam III, Project No. BE95-1347: "Probabilistic Performance Based Durability Design of Concrete Structures," Document R 15, February 2000, 109 pp.

2. *fib Bulletin No. 34*, Model Code for Service Life Design, FIB, 2006, 2006 pp.

3. Tang, L.; Chloride Transport in Concrete-Measurement and Prediction. Department Building Mateirals, Chalmers University of Technology, 1996, Pub-96.6.

4. Bamforth, P. B., The Derivation of Input for Modelling Chloride Ingress from Eight-year UK Coastal Exposure Trials, Magazine of Concrete Research, 51-nº2, 1999, pp.87~96.

5. *DURACON: Probability-Based Durability Analysis of Concrete Structures – Software Manual.* University of Minho, Department of Civil Engineering, Guimarães, Portugal, 2004.

6. Gehlen, C. and Schiessl, P., *Probability-Based Durability Design for the Western Scheldt Tunnel*, *Structural Concrete*, No. 2, 1999, pp. 1~7.

7. McGee, R., *Modelling of Durability Performance of Tasmanian Bridges*, Proceedings, The 8th International Conference on the Application of Statistics and Probability, Sydney, Australia, 1999.

8. Takewaka, K. and Mastumoto, S., *Quality and Cover Thickness of Concrete based on the Estimation of Chloride Penetration in Marine Environments*, ACI SP 109-17, *American Concrete Institute*, 1988, pp. 381~400.

9. Nilsson, L.O., Massat, M., et al., The Effect of Non-Linear Chloride Binding on the Prediction of Chloride Penetration into Concrete Structures. 3rd Int. Conference on Durability of Concrete, Nice, France, ACI SP-145, 1994, pp. 469~486.

10. Page, C.L.; Short, N.R.; Holdon, W.R.; The influence od different cements on chloride induced corrosion of reinforcing steel. Cement and Concrete research, Vol 16, nº 1, 1986, pp. 79~86.

11. Gjørv, O. E., *Durability Design and Construction Quality of Concrete Structures*, Fourth International Conference on Concrete Structures under Severe Conditions: Environment and Loading", Seoul, Korea, 2004.

12. Ferreira, R. M., Jalali, S., *et al., Probability-based Durability Analysis of Concrete Harbour Structures.* CONSEC 04, 4th International Conference on Concrete under Severe Conditions: Environment and Loading, Seoul, Korea, June 27-July 1, 2004. pp. 999~1006.

13. Ferreira, R. M.; *Probabilistic-Based Durability Analysis of Concrete Structures in Marine Environment*, Doctural Thesis, Universidade do Minho, Guimarães, Portugal. ISBN 972-8692-16-1, 2004, 321 pp.

14. Maage, M.; Helland, S.; Carlsen, J.E.: Chloride Penetration in High Performance Concrete Exposed to Marine Environment. Proc of RILEM International Workshop on Durability of High Performance Concrete, Wien, February 14-15 1994, ed. by H. Sommer, pp. 194~207.

15. Mangat, P.S., Molloy, B.T.: Predicting of Long Term Chloride Concentration in Concrete. Materials and Structures, Vol. 27, 1994, pp. 338~346.

16. Bamforth, P. B., A New Approach to the Analysis of Time-Dependent Changes in Chloride Profiles to Determine Effective Diffusion Coefficients for Use in Modelling of Chloride Ingress, in RILEM International Workshop on Chloride Penetration into Concrete, St Remy-les-Chevreuse, France, Oct 1995, Paper 21, pp. 195~205.

17. Gjørv, O.E., Durability and Service Life of Concrete Structures, Proceedings, The First fib Congress 2002, Session 8, V. 6, Japan Prestressed Concrete Engineering Association, Tokyo, pp. 1~16.

18. Ferreira, R.M.; Liu, G.; et al., Blast furnace slag for concrete durability. Report nº. BML-200130, Universidade Norueguesa de Ciência e Tecnologia, Trondheim, 2002.

19. Pruckner, F., Corrosion and Protection of Reinforcement in Concrete Measurements and Interpretation, University of Vienna, Faculty of Natural Sciences and Mathematics, Doctoral Thesis, 232 pp.

20. Jooss, M. and Reinhardt, H.W., Permeability and Diffusivity of Concrete as Function of Temperature Cement and Concrete Research, Vol. 32, No. 9, 2002, pp. 1497~1504.

21. Ferreira, R.M. and Jalali, S. Software for Probability-Based Durability Analysis of Concrete Structures. Proceedings of International Conference on Concrete Repair, Rehabilitation and Retrofitting ICCRRR, Alexander (eds.), Taylor & Francis, Cape Town, South Africa, 21-23 November, 2005, 117 pp.

22. Di Sciuva, M. and Lomario, D., *A Comparison between Monte Carlo and FORMS in Calculating the Reliability of a Composite Structure*, *Composite Structures,* Vol. 59, 2003, pp. 155~162.

23. Gjørv, O.E.; Controlled Service Life of Concrete Structures and Environmental Consciousness, Proceedings, International Workshop on Concrete Technology for a Sustainable Development in the 21st Century, ed. by O.E. Gjørv and K. Sakai, E & FN Spon, London and New York, 2000, pp. 1~13.

24. HETEK 53, Chloride Penetration into Concrete. State of the Art. Transport Processes, Corrosion Initiation, Test Methods and Prediction Models, Report No. 53, 1996.

25. Ferreira, R. M., Liu, G., Nilsson, L., et al., *Blast-Furnace Slag Cements for Concrete Durability in Marine Environment.* CONSEC 04, 4th International Conference on Concrete under Severe Conditions: Environment and Loading, Seoul, Korea, June 27-July 1, 2004. pp 109~116.

26. Lindvall, A., Environmental Actions on Concrete Exposed in Marine and Road Environments and Its Response - Consequences for the Initiation of Chloride Induced Reinforcement Corrosion. Doctoral Thesis CTH, pp. 1~233, 2003.

27. EN 1992-1-1:2004 Eurocode 2: Design of Concrete Structures. Part 1-1: General Rules and Rules for Buildings. CEN, 2004.

28. Bijen, J., "Blast Furnace Slag Cement for Durable Marine Structures," NC/BetonPrisma, The Netherlands, 1998, 62 pp.