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Probabilistic Design for the Durability of Reinforced Concrete Structural Elements Exposed to Chloride Containing Environments†

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ABSTRACT

To obtain structures with long service lives in chloride containing environments, durability design methods should be carried out. In such a design, chloride diffusion must be expressed as a mathematical model and the parameters should be included in this model in a realistic way. The scatter both in the environmental exposure conditions and structural properties should be considered with a probabilistic design. The main objective of this study is the durability design of concrete structures in chloride containing environments. The transport of chlorides into concrete was modeled using Fick's second law of diffusion and a simple software based on Monte Carlo simulation was developed to consider the scatter in the environmental exposure conditions and structural properties. The effects of some important structural parameters affecting corrosion were investigated.

Keywords: *Durability based design, Monte-Carlo analysis, chloride effect, corrosion, probability*

1. INTRODUCTION

Structures such as coastal and harbor structures or bridges require high investments and these structures are expected to carry out their functions with a wide margin of safety throughout their service lives, but, due to durability related problems, their structural performance may decrease with time. Structures are under various environmental exposures which should be considered in the design phase. There are many coastal and harbor structures along the 8300-km long coastline of Turkey. In addition, various structures such as bridge pillars are also exposed to sea water. Even the structures far away from the coast may be exposed to air – borne chlorides from the sea water. It was reported that air-borne droplets of sea water can be carried two kilometers inland by wind. [1]. The de-icing salts used in winter also affect a significant portion of structures such as bridges or viaducts. Corrosion of embedded steel due to penetration of chlorides is one of the most important durability problems. While the cross section area of the reinforcement is reduced due to corrosion, the corrosion products cause cracking of concrete cover which increases the ingress and transport of harmful substances into concrete [2]. As a result, reliability of the structure is reduced and the required service life can not be obtained. The earthquake that

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hit Marmara Region of Turkey in 1999 revealed the durability problems in structures and cracks in the reinforced concrete structures due to corrosion became clearer [3].

One of the factors affecting the durability problems in concrete structures is the scatter in structural properties. Even for a same structural element, the properties may vary from one point to another. If the quality control procedures are not sufficient, the differences in the element properties may not even be noticed and precautions can not be taken [5]. The main reason for the durability problems in structures is the strength based design and assumption that durability is achieved if sufficient compressive strength is obtained.

The main objective of the study presented herein is the durability design of reinforced concrete structures exposed to chlorides. A probability-based durability design considering disparity in structural properties and environmental conditions is used. Chloride transport was modeled using the Fick's second law and a simple software performing Monte Carlo simulations was also developed. In addition, the effects of some material and constructional parameters on the probability of corrosion are evaluated.

2. DURABILITY BASED DESIGN

2.1 Current Design Methods

In the current codes such as TS EN 206 [6] which is in effect in Turkey, or American code ACI 318 [7] and British code BS 8500-2 [8], to ensure sufficient durability in structures, some limitations are given based on the environmental conditions that the structures are exposed to. These limitations are; maximum water/cement ratio, minimum cement content and minimum compressive strength of concrete. However, the concrete composition criteria given in TS EN 206 or other standards are minimum values and, it is very optimistic to assume that structures will have a long service life by only satisfying these criteria.

While one of the causes of durability problems experienced in concrete structures is the factors related to concrete composition, another cause is the deficiencies in the quality of the structure. For example, actual concrete cover depth at the structure may be less that the specified value or concrete chloride permeability may be higher than the requirement in the specification. For the same structure, structural properties and concrete characteristics may differ significantly from one element to other or even within the same element [4]. Scatter in the structural properties is not taken into account in TS EN 206 [6] and specifications for concrete composition such as maximum water/cement ratio and minimum cement content of concrete is considered sufficient. Some concrete cover depths are recommended in TS EN 1992-1 [9] and it is stated that the structure will have a service life of 50-years if these depths are achieved. It is not always true to assume that long service life can be obtained by some pre-defined criteria and durability problems experienced in the existing buildings supports this observation [5]. Therefore, other methods are needed to determine the long-term performance of the structures [10, 11]. In addition to the concrete composition requirements such as water/cement ratio or cement content, properties such as concrete cover depth, transport properties of various ions in concrete, deterioration rate and their scatter should be taken into account and evaluated together with the limit states [12].

2.2 Probability Based Design Method

For the design of structural elements, the resistance of the element (*R*) being higher than the load (*S*) is the main criterion [13]. This principle can also be used for the durability analysis and it can be formulated as follows;

$$R(t) > S(t) \quad \text{or} \quad g = R(t) - S(t) > 0 \tag{1}$$

where $R(t)$ indicates the resistance variable, $S(t)$ represents the load variable and g is the limit state function. Since the strength and durability of the structure changes with age, both the resistance $R(t)$ and the load effect $S(t)$ are taken as time dependent parameters. Based on these, the failure probability (P_f) can be calculated as shown below;

$$P_f = P[R - S < 0] \quad \text{or} \quad P_f(t) = P[R(t) < S(t)] \tag{2}$$

From the durability point of view, the resistance of the structure $R(t)$ may decrease with time. For example, as the corrosion of the steel reinforcement embedded in concrete ingresses, reinforcement diameter is reduced and due to the higher volume of the corrosion products, concrete cracks and bond between steel and concrete is reduced. As a result, load carrying capacity of the structural element is reduced [14]. The load parameter $S(t)$, however, can remain constant or increase with time. Because the resistance $R(t)$ decreases and the load effect $S(t)$ increases with time, the failure of probability increases with time [12].

There are several methods for determining the reliability of structures [15-17]. Of these methods, Monte Carlo method is a powerful method which can take different parameters into account simultaneously and as a result, it can be used for the durability design of concrete structures. Monte Carlo analysis can be described as a repeated statistical sampling process, by which randomly selected values are used to calculate the limit state function g [16]. These random values, however, should be described as probability density functions. In Monte Carlo analysis, limit state function is calculated using the randomly selected numbers. Sufficient number of iterations is needed to obtain a probability value. For each iteration; a random number based on a given mean and standard deviation is selected and used in the limit state function. In other words, iteration is the repeated solution of the same equation using different values.

The probability of failure $P_f(t)$ obtained by the Monte Carlo analysis is the ratio of the number of iterations that do not confirm the g limit state function, to the total number of iterations. This probability can be shown as below [17].

$$P_f = \frac{1}{N} . \sum_{i=1}^{N} I\left[g(r_i, s_i)\right] \tag{3}$$

where N is the total number of iterations and $I[g(r_i,s_i)]$ indicates the number of iterations resulted in failure ($r < s$ case). To obtain reliable results with Monte Carlo method large number of iterations, i.e., the repeated solution of the same equation is needed, and a software is required for this process. Parameters related to the effect of chlorides in concrete and the limit state function is described below.

3. CHLORIDE EFFECT IN CONCRETE

There are different sources for chloride attack. Chlorides may be present in the concrete mix as part of the constituent materials such as aggregate, cement or admixtures. The maximum permissible values of chloride concentrations in ingredient materials are given in the related standards and specifications. Concrete in marine structures is exposed to sea water or de-icing salts used in winter may be the main sources of external chloride attack. Concentration of the external chloride sources is usually much higher than the chlorides present in the materials, as a result, mostly these free chlorides cause corrosion. The transport of the chlorides into concrete takes place with different mechanisms. For example, at a harbor structure, while diffusion is the main chloride transport mechanism in the submerged parts, capillary absorption will also contribute to the chloride ingress in the splash zones where wetting and drying takes place [14]. For determination of diffusion of chlorides into concrete, concentration vs. depth relationship should be obtained. For this purpose, chloride concentrations of the samples from different depths from the surface are determined to obtain chloride profiles. Chloride concentration in concrete depends on the concrete quality and exposure conditions. The content of chlorides is largest at the exposed surface and it decreases with increasing depth [18].

3.1 Modeling of Chloride Diffusion

There are several models available for modeling of chloride penetration into concrete [19]. Of these, the most widely used is Fick's second law of diffusion that is given below [20].

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D_C t}}\right)\right] \tag{4}$$

where $C_{(x,t)}$ is the chloride concentration for a given time and depth, C_S is the surface chloride concentration, *erf* is the error function, x is the depth from the surface, D_c is the chloride diffusion coefficient and t is the time.

Chloride diffusion coefficient D_C is a time dependent parameter and may be expressed as follows.

$$D_C = D_0\left(\frac{t}{t_0}\right)^{\alpha} \tag{5}$$

where D_o is the chloride diffusion coefficient after time t_o and α is a factor that represents the time dependence of the diffusion coefficient.

3.2 Limit States

In a durability design, a limit state for the deteriorating process that marks the end of the service life must be defined. There may be various limit states such as serviceability limit state or ultimate limit state. The serviceability limit state is related to a failure which leads to economic consequences such as onset of steel corrosion or cracking of the concrete cover, while ultimate limit state is the state of collapse or extensive loss of load bearing capacity [21]. Figure 1 schematically shows the deterioration of a reinforced concrete element in the case of corrosion [22]. Corrosion damage can be divided into two parts. At the first stage there is no physical damage in the element. However, transport of chlorides into concrete takes place during this initiation period. At the end of this stage, the chloride content reaches a critical level at the depth of the embedded reinforcement and passivisation layer around the steel is damaged (de-passivisation). From this point on, it may be assumed that corrosion starts, cracking and other physical damages in the structural element start to appear and they increase in time. The increase in the slope of the curve in Figure 1 indicates the increase in the damage rate. At the second stage known as propagation stage, when the damage exceeds a specific level, it may be accepted that load bearing capacity of the element is lost. Such a damage level, however, may not be generalized for all the structures or structural elements; different levels may exist for different types of elements such as beams, columns or concrete walls. Even only one type of element, for example, only columns are taken into account, reinforcement amounts and locations, loads acting on the columns may differ significantly. Due to these reasons, reinforcement loss that culminates in the loss of the load bearing capacity depends on the structural system employed and loading conditions of the structure, and can only be determined by modeling the structure as a whole.

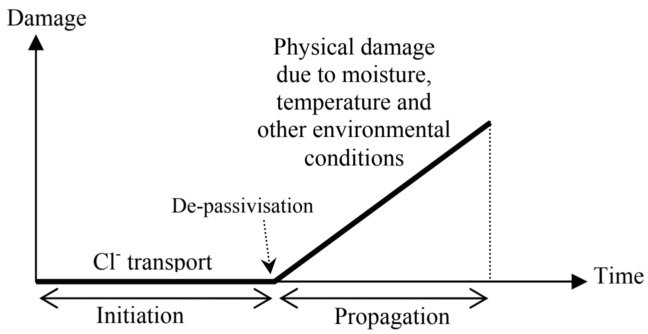

Figure 1. *Deterioration in structural element due to corrosion of embedded reinforcement*

For a new construction, it may be accepted that; when the chloride content at the depth of reinforcement is equal to a critical value, serviceability limit state is reached [4, 19], because after this point maintenance and repair costs increase substantially and safety of the structure begins to decrease. In addition, determination of this point is relatively easy; by obtaining the chloride penetration depth through electrochemical methods, and the state of the structure from the point of corrosion can be clearly identified [23].

3.3 Determination of Corrosion Probability

For durability design of a new concrete construction, two assumptions were made in this study; i) de-passivisation (the onset of corrosion) is the serviceability limit state for a new concrete construction, and ii) the probability of de-passivisation defines the service life. After the de-passivisation the corrosion starts within a short period or may take several years depending on several factors. In this study, however, it is accepted that de-passivisation occurs and corrosion starts when the chloride concentration is equal to the critical chloride content. Based on these assumptions, for the probability of damage due to chloride action, the limit state function can be expressed as:

$$P_f = P(C(x,t) \geq C_{cr}) \tag{6}$$

where $C(x,t)$ is the chloride ion concentration at a distance x from the concrete surface for a time of t, and C_{cr} is the critical chloride concentration that causes de-passivisation.

In this study, the probability of failure (P_f) was obtained by Monte Carlo method. Monte Carlo method depends on a random number generation; the outcome of each generation is stored and compared with the limit state. For this purpose, parameters (C_S surface chloride concentration, x depth from the concrete surface, D_C chloride diffusion coefficient) were determined randomly based on the probability distribution functions. Then, chloride concentrations calculated using these random numbers were compared with the critical chloride contents (Equation 6). By using the results obtained from iterations, probability of de-passivisation was determined according to Equation 3.

Large numbers of iterations are needed to obtain reliable results in Monte Carlo analysis. For this purpose; simulations were carried out to investigate the effect of iteration number on the probability of de-passivisation and the results obtained are shown in Figure 2. All the parameters were kept the same for these simulations, except the iteration number. For each of these iteration numbers, 20 simulations were carried out and dispersal of the results are evaluated.

As seen from Figure 2, as the number of iterations increased, the scattering of the obtained results decreases. For example, for an iteration number of 10, the coefficient of variation was 52 %, while it was only 10%, 2.4 % and 0.6 % for 1000, 10 000 and 100 000 iterations. As the number of iterations increase, the results obtained approach a constant value which indicates that more reliable results are obtained. For example, for an iteration number of 10^6, the coefficient of variation was as low as 0.2%. Increasing the iteration number, however, also increases the time necessary to obtain the results. Based on these results, it may be concluded that the number of iterations should be at least 10,000. In this study, however, since reliable results with a coefficient of variation of 0.6% are obtained and computing time is not very long, 100 000 iterations were used for all the analysis and results presented below were obtained using this number.

Effects of various parameters on the probability of de-passivisation of reinforcement are given below for some cases. It was assumed that all the parameters selected have normal distributions and can be expressed with an average value and standard deviation. If experimental results are available and actual probability distribution functions are known, these values can be used in the above-mentioned design method. However, if there is not enough data for these parameters, assuming normal distributions may provide sufficient approximation for new constructions.

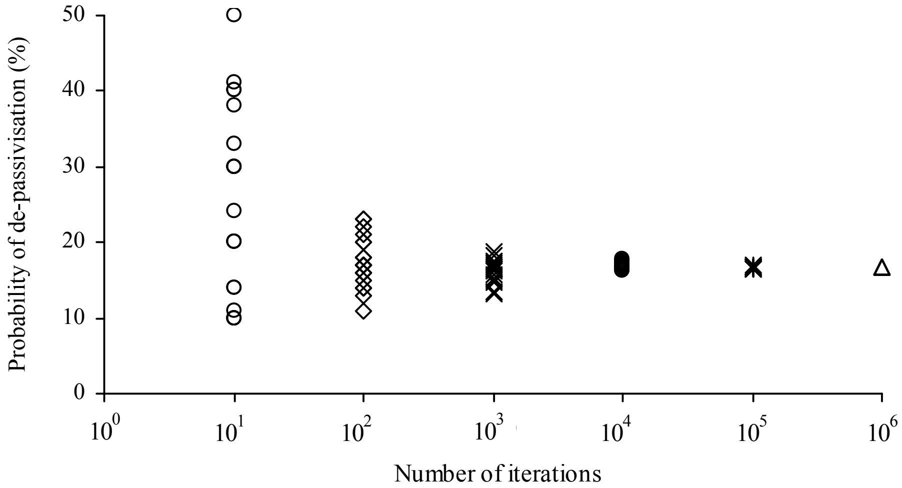

***Figure 2**. Effect of iteration number on the probability of de-passivation*

4. RESULTS AND DISCUSSION

4.1 Effect of Chloride Diffusion Coefficient

Effect of chloride diffusion coefficient on the probability of de-passivation is shown in Figure 3. An average cover depth of 50 mm, average surface chloride concentration of 4%, and average critical chloride concentration of 1% was used but chloride diffusion coefficient ranging from 2 x 10^{-12} m^2/s to 20 x 10^{-12} m^2/s were selected for the simulations. In all these analyses, the standard deviation was assumed to be 10 % for all the parameters.

As shown in Figure 3, for a given time, as the chloride diffusion coefficient increases, probability of de-passivation also increases. Chloride diffusion coefficient indicates the transport of chlorides in concrete and it is one of the factors determining the service life of structures [24]. As shown in Figure 3, although all the other parameters were kept constant, the increase in the chloride diffusivity increased the probability of corrosion, thus, for a given probability, the time needed for corrosion to set in is reduced, which affects the service life of structure. Higher chloride diffusivity indicates that the transport of chloride ions in concrete is faster [19]. For the same concrete cover thickness, longer time is required for the chloride ions to reach the embedded steel as concrete quality increases. The results confirm once again that in order to obtain a concrete structure with a long service life, concrete having low chloride permeability, i.e. high quality concrete must be used. Factors such as water/cement ratio, cement type, use of pozzolans, and degree of hydration affect chloride diffusion coefficient [25-27]. For improving the quality of concrete cover, i.e., reducing the diffusion coefficient, necessary care should be given also to curing.

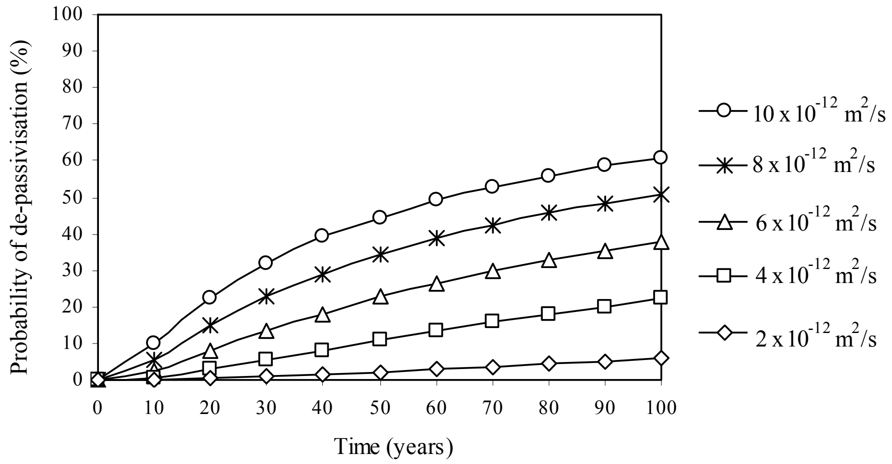

***Figure 3**. Effect of chloride diffusivity on the probability of de-passivisation*

4.2 Effect of Concrete Cover Thickness

To investigate the effect of concrete cover thickness on the probability of de-passivisation in a reinforced concrete structure, a simulation was carried out in which the average chloride diffusion coefficient of $6x10^{-12}$ m^2/s was used and while the other parameters were selected as in 4.1, different values were used only for the thickness of concrete cover. The results obtained are given in Figure 4.

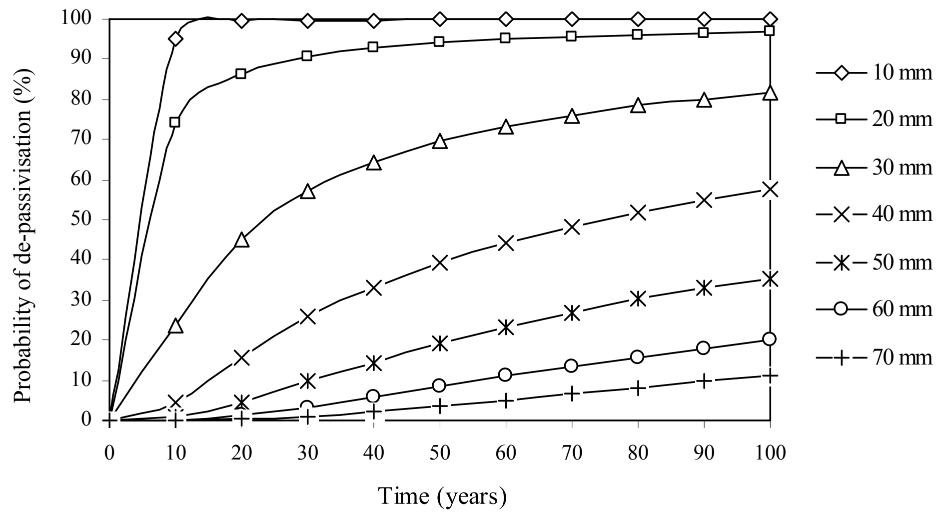

***Figure 4**. Effect of concrete cover thickness on the probability of de-passivisation*

As the concrete cover thickness increases, time to reach a given probability of de-passivisation increases as expected. For example, if the maximum limit for the probability is selected as 10 % and concrete cover thickness is 10 mm to 30 mm, this probability is reached within the first few years. However, when the cover thickness is taken as 50 mm, this period is approximately 30 years and for 70 mm, it is 90 years. For the initiation of corrosion, external chlorides should be transported from the concrete surface, pass through the concrete cover and reach the embedded steel [18, 24]. For this reason, thickness of the cover is one of the most important parameters affecting the service life of structures. As seen in Figure 4, when concrete cover thickness increases, the time necessary for chlorides to reach the steel becomes longer and as a result, service life of the structure increases. However, in order to obtain structures with long service lives; in addition to increasing cover thickness, permeability should also be taken into account as shown in Figure 3 and to obtain a concrete cover without cracks, special attention should be given to factors such as proper curing. In case of a crack on the cover, chlorides can be transported very rapidly, thus, for a given time; chloride concentration in the cracked regions is much higher compared to crack-free regions. As a result of the high chloride concentrations in these cracked parts, corrosion occurs much earlier. In addition, because the transport of other aggressive ions and water through the cracks is faster, they can damage concrete more easily.

4.3 Effect of Surface Chloride Concentration

For studying the effect of surface chloride concentration on the probability of de-passivisation, concrete properties were selected as above, but surface concentration values varying from 2% to 10% were used to obtain the probabilities. Results are shown in Figure 5.

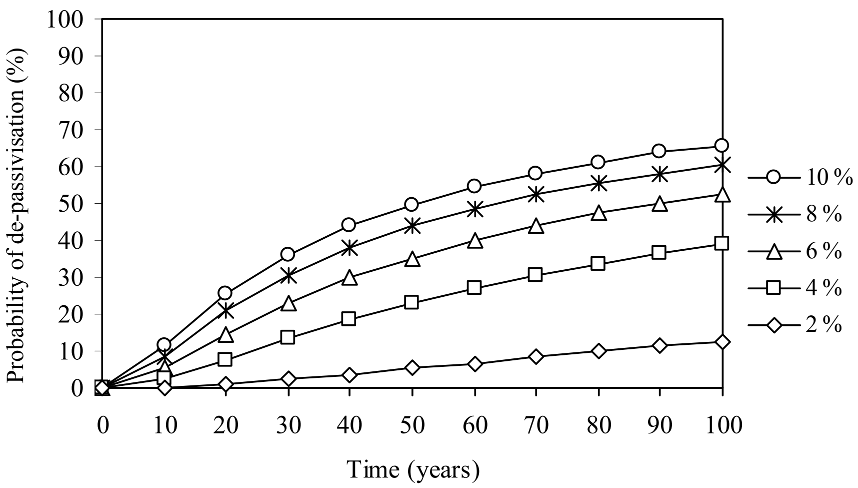

***Figure 5**. Effect of surface chloride concentration on the probability of de-passivisation*

As seen from the figure given above, probability of de-passivisation increases when the surface chloride concentration is higher. For example; when the surface chloride concentration is 2%, the probability of de-passivisation in 50 years is 5%, but the probability increases to 35% if the concentration is 6%. Since high surface chloride content increases the concentration difference between the surface and inner sections of the concrete, the transport of chlorides increases [24]. As a result, exceeding the critical chloride concentration is also easier. Surface chloride content is an indication of the period that the concrete has been under the effect of chlorides from the environment. It is a time dependent parameter and factors such as chloride content of the sea water, porosity of the concrete surface or wetting – drying periods affect the surface chloride content of concrete [29]. Surface chloride concentration may differ significantly also due to the local conditions that the structure is exposed to. For example, in bridge and viaduct piers exposed to sea water, surface chloride concentration is highest at the sea level, but it decreases at higher points of the pier in question. In structural elements exposed to continuous wetting and drying cycles, surface chloride concentration is higher due to progressive build up of chlorides [30]. For new constructions, surface chloride contents obtained from neighboring structures can be used for design purposes. If there is no such data available, results from similar climates and environments can also be used.

4.4 Effect of Critical Chloride Concentration

Figure 6 shows the effect of critical chloride concentration on the probability of de-passivisation. These results were obtained using the concrete type mentioned above, hower various critical chloride concentrations were used.

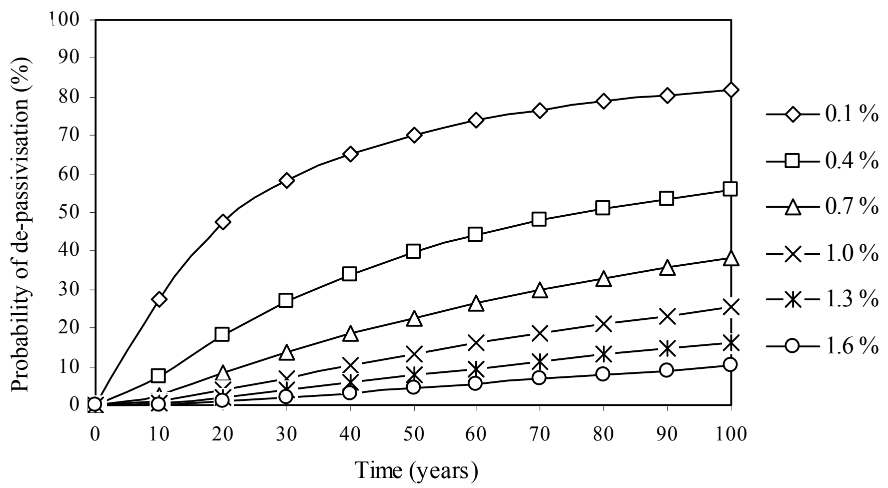

Figure 6. *Effect of critical chloride concentration on the probability of de-passivisation*

As seen from the figure, the probability of de-passivisation decreases with increasing critical chloride concentration. In this study, probability of de-passivisation was obtained by comparing the critical chloride content with the chloride content at the depth of the reinforcement. As the critical chloride concentration is reduced, the probability of the chloride content obtained by the calculations being higher than this critical level, increases. Critical chloride concentration depends on various factors such as water/cement ratio, cement type, pozzolanic materials, and type of steel used [31-34]. Water and oxygen is needed for corrosion and when one of these factors is not present corrosion does not occur. If the relative humidity is very low or very high, the critical chloride content to initiate corrosion is higher [35].

5. CONCLUSIONS

For durability design, structural properties and environmental conditions that the structure is exposed to should be investigated in detail. Using this information, it is possible to model the damage that may occur and predict the service life of the structure. Since both structural properties and environmental exposure conditions show high scatter, the analysis must have a probability based approach incorporating this variability. Such a durability design method depends on the same principles of structural design to achieve the required performance. In this study, penetration of chlorides into concrete was modeled using Fick's second law of diffusion. To consider the scatter in structural properties and environmental conditions, probability based Monte Carlo analysis was used and a simple software was prepared for this purpose. Several assumptions were made in this study. For example; it was assumed that corrosion starts when the chloride concentration at the depth of the reinforcement is equal to the critical value and chloride transport takes place only by diffusion. In this study, the effects of the factors related to chloride transport on the probability of de-passivisation was investigated for some example situations.

The results obtained show the importance of the parameters used in chloride diffusion model. Number of iterations should be sufficiently high to obtain reliable results in Monte Carlo method and the number of iterations was determined as at least 10 000 in this study. The results obtained clearly show the importance of the chloride diffusion coefficient of concrete. As seen in the simulation results, quality and thickness of the concrete cover significantly affect the probability of de-passivisation. Increased surface chloride concentration is a factor that increases the probability of de-passivisation. Reduction of the critical chloride concentration, however, causes de-passivisation to occur easier. As seen from the results obtained, the probability of de-passivisation increases with time as expected. Chloride diffuses into concrete with time and when the chloride concentration at the depth of the reinforcement exceeds a critical value, it may be assumed that de-passivisation takes place. Since the chloride concentration at a given depth increases, the probability of de-passivisation increases over time. This study was made based on the same type of concrete and the same environmental effects. However, similar results were also obtained even in the case of different concrete properties. When concretes with different characteristics were used, i.e. when concretes with low and high chloride diffusion coefficients were compared, for a given time, corrosion probability is lower for the concrete with the lower diffusivity. When the concrete is in a more harmful environment, that is, when the chloride concentration in the environment is higher, the probability of corrosion increases.

Service life of a structure may be described as the duration at which time structural properties or load bearing capacity reaches a defined limit state [36]. For example, abrasion on an industrial concrete floor or excessive deflection of a slab causes the termination of its service life. As mentioned above, for a new structure it may be assumed that the probability of de-passivisation is equal to the serviceability limit state. This method can also be used to evaluate the durability performance of existing structures [37]. Parameters such as chloride diffusion coefficient, concrete cover thickness, surface chloride concentration may be obtained from the existing structure, and together with the electrochemical methods such as half-cell potential and electrical resistance, the current condition of the structure can be evaluated.

For the durability design of a new structure, a realistic selection of these parameters is very important to obtain reliable results. In a durability design, the main point considered is the determination of a suitable concrete type and cover thickness. However, if the selected concrete properties can not provide the required service life, additional protective measures must be taken. Necessary importance should be assigned to curing conditions and a crack-free cover should be obtained for a concrete with low chloride diffusion coefficient and required characteristics. During the construction stage, using the concrete properties obtained from the structure, differences compared to design stage can be determined. Information on the parameters used for the probability-based durability design is not sufficient yet and various assumptions are being made. However, use of this design method can become widespread as more information from long term tests is obtained.

Symbols

C	: chloride concentration in concrete
C_S	: surface chloride concentration
C_{cr}	: critical chloride concentration
D_C	: chloride diffusion coefficient
D_0	: chloride diffusion coefficient at time t_o
erf	: error function
g	: limit state function
$I[g(r_i,s_i)]$	: indicator function
N	: total number of iterations
P_f	: probability of failure
R	: resistance
$R(t)$	: resistance variable
S	: load
$S(t)$	: load variable
t	: time
x	: cover thickness
α	: age factor

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