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Durability of concrete structure

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ABSTRACT: The durability of concrete has attracted significant attention over the past several decades and is still a research hotspot until now.Currently, durability of concrete structures is a hot area of civil engineering. Durability of concrete with fly ash as fine aggregate subjected to alternative attacks of freeze-thaw and carbonation, the appearance, mass loss, relative dynamic modulus of elasticity. major durability problems such as alkali aggregate reaction, sulfate attack, steel corrosion and freeze–thaw. Extensive experience demonstrates that the durability of concrete structures is related not only to design and material but also to construction issues. Upon completion of new concrete structures, the achieved construction quality always shows a high scatter and variability, and in severe environments, any weaknesses in the concrete structures.

KEYWORDS: Service life · Durability · Durability design · Probability analysis · Durability requirements · Construction quality · Quality assurance · Condition assessment

I. INTRODUCTION

Internationally, deterioration of concrete infrastructure has emerged as one of the most severe and demanding challenges facing the construction industry . Although corrosion of embedded steel represents the predominant type of deterioration, freezing and thawing and alkali aggregate reactions also represent big challenges to the durability and long-term performance of many concrete structures. Based on current codes and practice, however, it appears to be easier to control such durability problems compared to that of steel corrosion . Thus, for concrete structures in severe environments, it may be difficult to avoid steel corrosion within typical service periods of 15–20 years . . The operation, maintenance and repair of concrete structures are consuming much energy and resources and are producing a heavy environmental burden and large quantities of waste. Thus, poor durability and premature service life of many concrete structures represent not only technical and economic problems; this is poor utilization of natural resources and hence also presents sustainability and ecological problems . In order to obtain an increased and more controlled durability and service life of important concrete infrastructure, a rapid international development on both probability-based durability design and performance-based concrete quality control has taken place, a brief outline of which is presented and discussed in the following. A more complete durability design should also take the various costs (LCC) and environmental impacts (LCA) , but these aspects are not included and discussed in the present paper.

II. DURABILITY DESIGN

2.1 general

In 1989, the European Union produced a Construction Products Directive [14], requiring documentation of achieved durability of buildings and structures. This document was primarily based on the general technical basis for service life design of buildings and structures developed by the ISO. It then was up to the various industrial sectors to come up with more detailed technical procedures and specifications for such documentation. For concrete structures, both RILEM and CEN have put much work into the development of a better basis for service life design of concrete structures. Such a service life or durability design requires, however, that a mathematical model for the given deteriorating process exists, and that the input parameters to the model also can easily be determined. It is further necessary to have some information on both the average values and natural scatter of the various input parameters to the model. , durability and service life of the structures. In particular, this is true for concrete structures in chloride containing environments

2.2 Chloride-Induced Corrosion

Depending on the resistance of the concrete against chloride penetration and the thickness of the concrete cover, it may take many years before the chlorides reach the embedded steel. After the chlorides have reached the steel and the corrosion process starts, however, it may take only a few years before visual damage appears in the form of cracks and rust staining, but it may take a long time before the load carrying capacity of the structure is severely reduced. Schematically, As soon as the corrosion process starts, a very complex system of galvanic cell activities in the concrete structure develops . In this system of galvanic cell activities, the deterioration appears in the form of concentrated pitting corrosion in the anodic areas of the rebar system, while the adjacent cathodic areas act as catchment areas for oxygen. Although larger portions of the rebar system eventually become depassivated, not all of these areas will necessarily corrod. Although it is possible to estimate the time likely to elapse until corrosion starts, this does not provide any basis for estimating the real service life of the structure. As soon as the corrosion process starts, however, the owner of the structure has got a problem, which in an early stage represents only a maintenance and cost problem, but later on develops into a safety problem that is more difficult to control. As a basis for the durability design, therefore, efforts should be made to obtain the best possible control of the chloride penetration during the initial period before corrosion starts. It is in this early stage of the deterioration process that it is both technically easier and much cheaper to take necessary precautions and to select proper protective measures to control subsequent deterioration. In general, the basic principles for probability-based durability design are more or less the same. In the following, however, a short outline of the Norwegian version of such a design is given, as it has been applied to a number of important concrete structures in recent years.

2.3 Calculation of Chloride Penetration

C (x, t) = CS 1 − erf x 2 √D(t) · t

(1)

In the above equation, C(x, t) is the chloride concentration in depth x after time t, CS is the chloride concentration at the concrete surface, D is the concrete chloride diffusion coefficient and erf is a mathematical function.

D(t) = D0 1 − α 1 + t t

1−α − t t

1−α t0 t

α · ke (2)

In Eq. 2, D0 is the diffusion coefficient after the reference time t0, and t is the age of the concrete at the time of chloride exposure. The parameter α represents the time dependence of the diffusion coefficient, while ke is a parameter which takes the effect of temperature into account.

ke = exp be 1 293 − 1 T +
273

(3)

In Eq. 3, exp is the exponential function, be is a regression parameter, and T is the temperature. The criterion for steel corrosion then becomes.
C(x) = CCR (4)

where C(x) is the chloride concentration at the depth of the embedded steel, and CCR is the critical chloride concentration in the concrete necessary for onset of corrosion.

2.4 Input Parameters
General

In general, the durability design should always be an integral part of the structural design for the given structure. At an early stage of the design, therefore, the overall durability requirement for the structure should be based on the specification of a certain service period before 10% probability of corrosion is reached. For the given environmental exposure, the durability analysis then provides the basis for specifying a proper combination of concrete quality and concrete cover. Before the final requirements for concrete quality and concrete cover are given, however, it may be necessary to carry out several calculations for various combinations of possible concrete qualities and concrete covers. For all of these calculations, proper information about the following input parameters is needed:

– Environmental loading
– Chloride load, CS
– Temperature, T
– Concrete quality
– Chloride diffusivity, D0
– Time dependence, α
– Critical chloride content, CCR
– Concrete cover, X

All the above parameters may have different distribution characteristics, but if nothing else is known, a statistical normal distribution may be assumed. For each parameter, proper information on both average value and standard deviation is then needed. In the following, the determination and selection of the above input parameters are briefly described and discussed.

Environmental Loading

Chloride Load, CS For a concrete structure in a chloride containing environment. For all concrete structures, therefore, the accumulated surface chloride concentration shows a very high scatter and variability. For the durability analysis, however, it is important to estimate and select a proper value for the surface chloride concentration (CS), one which is as representative as possible for the most exposed and critical parts of the structure. In some cases, it may also be appropriate to select different chlorideloads for different structural parts of the structure and then to carry out separate probability calculations for the various parts.

Temperature, T For a concrete structure in a given chloride containing environment, the rate of chloride penetration also very much depends on the temperature, as shown in Eq. 3. Based on local information on the current temperature conditions, data on average annual temperatures may be used as a basis for the selection of this input parameter.

Concrete Quality

Chloride diffusivity, D0 The chloride diffusivity (D0) of a given concrete is a very important property which generally reflects the resistance of the concrete against chloride penetration. Although a low water/binder ratio generally gives a low porosity and permeability and, hence, a high resistance against chloride penetration, it is well documented that the selection of a proper cement or binder system may be more important for a high resistance against chloride penetration than selecting a low water/binder ratio. Thus, a water/binder ratio reduced from 0.45 to 0.35 for a concrete based on a pure portland cement may reduce the chloride diffusivity to only a small extent compared to that of replacing the portland cement with another type of cement such as blast furnace slag cement.

Time dependence, α Since the chloride diffusivity is a time-dependent property of the concrete, this time dependence (α) is also a very important parameter generally reflecting how the chloride diffusivity of a given concrete in a given environment develops over time. Although the α-value also could be determined on the basis of laboratory testing, this would be time consuming and, at the same time, would not properly reflect how the chloride diffusivity of the given concrete in the given environment develops over time. In order to more realistically reflect field conditions, therefore, empirical α-values for the given type of concrete in the given type of environment are normally used as input parameters to the probability or durability analyses.

Critical chloride content, CCR It is well known that a number of factors affect the depassivation of embedded steel in concrete. Depending on all these factors, the critical chloride concentration in the pore solution of a concrete for breaking the passivity may vary within wide limits. Also, due to the very complex relationship between the total chloride content in a concrete and the passivity of embedded steel, it is not possible to give any general values for critical chloride contents. When certain values for the critical chloride content nevertheless are given in existing concrete codes and recommendations. Based on empirical experience from a wide range of concrete qualities and moisture conditions, an average value of 0.4% by weight of cement is often referred to in current concrete codes and recommendations. Therefore, if nothing else is known, an average value of 0.4% with a standard deviation of 0.1% by weight of cement may be selected as input parameter to the durability analysis. For more corrosion sensitive types of steel, an average value of 0.1% with a standard deviation of 0.03% may be selected. For various types of corrosion resistant steel, however, critical chloride contents of up to 3.5% or even up to 5.0% by weight of cement may be applied.

Concrete cover x

In current concrete codes, requirements for both minimum concrete cover (Xmin) and tolerances for the given environment are given. Thus, the nominal concrete cover(XN)is always given with a certain value of tolerance (X), and different values for Xmay be specified. For a tolerance of ± 10 mm, the minimum requirement for concrete cover then becomes: $X_{min} = X_N - 10$ (7) Although the specified concrete cover primarily gives the required concrete cover to the structural steel, additional mounting steel for ensuring the position of the structural steel during concrete construction is also often applied. Since the penetrating chlorides do not distinguish between structural and mounting steel, however, the nominal concrete cover should preferably be specified for all embedded steel including the mounting steel in order to avoid any cracking of the concrete cover due to premature corrosion. For all structural design, great care are always made to avoid any cracking of the concrete.

2.5 Durability Analysis
General

A durability design of a given concrete structure in a given environment can be carried out based on the procedures briefly described above. For important concrete structures, a service period of 120 years before 10% probability of corrosion is reached may be specified as an overall durability requirement. Always, however, the minimum durability requirements according to the current concrete codes must be fulfilled. Several durability analyses may be carried out as a basis for selecting a new and improved combination of concrete quality and concrete cover, some typical results of which are briefly demonstrated in the following.

Effect of Chloride Diffusivity

These analyses were based on the 28 day chloride diffusivity obtained from the four types of concrete produced with the four different binder systems (Types 1–4). For the analyses, some estimated values were selected for the other input parameters for a severe marine environment as discussed above. Apart from type of binder system, the composition of all the concrete mixtures was the same, and this composition also met all durability requirements according to the current concrete codes for a 100 year service period both with respect to water/binder ratio (≤0.40) and binder content (≥360 kg/m3). A minimum concrete cover of 70 mm was also adopted with a tolerance according to the current concrete code.

Effect of Concrete Cover

Further durability analyses based on increased concrete covers of up to 90 and 120 mm, respectively, were also carried out in order to evaluate the effect of increased nominal concrete cover beyond the minimum requirement of 70 mm used in the above analyses. For these analyses, all the other input parameters were the same as those used for the above analysis of Type 1 concrete. cover also has a significant effect on the obtained probability of corrosion. While a nominal cover of 70 mm for a concrete quality of Type 1 would give a service period of only about 25 years, increased concrete covers of up to 90 and 120 mm would increase the service period up to about 50 and 120 years, respectively, before 10% probability of corrosion would be reached.

Results and Discussion of Results

As shown above, durability analyses can be used to compare and select one of several technical solutions in order to obtain the best possible durability for a given concrete structure in a given environment. For evaluation of the obtained results, however, it should be noted that a number of simplifications and assumptions were made in the above procedures for the calculation of corrosion probability. Although diffusion is the predominant transport mechanism through thick concrete covers in chloride containing environments, only a very simple diffusion model for the calculation of chloride penetration rates was applied. It should also be noted that the diffusion behavior of chloride ions in concrete is a much more complex transport process than that which can be described by Fick's Second Law of Diffusion. Under more realistic conditions in the field, other transport mechanisms for chloride penetration than pure diffusion also exist. The characterization of the resistance of the concrete against chloride penetration was further based on a rapid migration type of testing, where the chloride penetration is very different from that which takes place under more realistic conditions in the field. However, the chloride diffusivity obtained by such an accelerated test method should be considered only as a relative index reflecting the ability of the concrete to resist chloride penetration in the same way as the compressive strength also is a relative index reflecting the ability of the concrete to resist mechanical loading. The durability analyses were further based on a number of other input parameters for which there is a lack of reliable data and information. In particular, this is true for the input parameters such as the chloride loads (CS) and the aging factors (α) for the chloride diffusivities. Although a selection of these parameters should preferably be based on current experience from other similar concrete structures in similar environments, such information is not necessarily available. Therefore, the selection of these parameters is normally based on general experience. The temperature is also another important factor, a proper value for which may also be difficult to select.

III. ACHIEVED CONSTRUCTION QUALITY

3.1 general

Because the specified chloride diffusivity is based only on the testing of small, separately produced concrete specimens water cured in the laboratory for 28 days, such a chloride diffusivity may be quite different from that achieved on the construction site. During concrete construction, therefore, some additional documentation on the achieved chloride diffusivity on the construction site must also be provided. At the end of concrete construction, this chloride diffusivity and the achieved concrete cover are used as input parameters for a new durability analysis and, hence, documentation of achieved durability on the construction site. Since neither the 28 day chloride diffusivity from small laboratory specimens nor the achieved chloride diffusivity on the construction site during concrete construction reflects the potential chloride diffusivity of the given concrete, further documentation on the long-term chloride diffusivity of the given concrete is also provided. Such a chloride diffusivity in combination with the achieved concrete cover provides the basis for documentation of the potential durability of the given structure.

3.2 Compliance with Specified Durability

As a result of the durability design, an overall durability requirement based on a required service period with a probability for corrosion of less than 10% has been specified. In order to show compliance with such a durability requirement, a new durability analysis must be carried out based on the average values and standard deviations of both the chloride diffusivity and the concrete cover obtained from quality control during concrete construction. Although it may have been difficult to select proper data for several of the other input parameters to the original durability analysis, these input parameters are now the same for the new durability analysis. Therefore, the new durability analysis primarily reflects the achieved values for chloride diffusivity and concrete cover during concrete construction, including the scatter and variability observed. Hence, the new durability analysis provides a basis for the documentation of compliance with the specified durability.

3.3 Durability on Construction Site

Documentation of achieved chloride diffusivity on the construction site should preferably be based on the testing of a number of concrete cores removed from the concrete structure under construction. In order not to weaken the structure too much, however, one or more un-reinforced concrete elements should be separately produced on the construction site, from which most of the concrete coring can take place during the construction period. In addition, a certain extent of coring from the real concrete structure should also be carried out, but only from locations where the coring does not weaken the concrete structure. Separately produced concrete elements, which could be wall or slab types of elements, or both, should be produced and cured as representatively as possible for the real concrete structure or various parts of the concrete structure. From these separate dummy elements, which are produced at an early stage of concrete construction, a number of concrete cores are later on removed at various ages. Immediately upon removal these should be wrapped in plastic to avoid drying out and sent to the laboratory for testing of achieved chloride diffusivity.

3.4 Potential Durability

For establishing the necessary calibration curve, the chloride diffusivity is determined on separately cast concrete specimens after certain periods of water curing in the laboratory of up to approximately 60 days. By a continued testing of the chloride diffusivity on a few additional specimens after curing periods of up to at least 1 year, a further development of chloride diffusivity is obtained, as shown in Fig. 7. Although it may take a long time before a final and stable value of the chloride diffusivity is reached, this development curve for most types of concrete tends to level out after approximately 1 year. Hence, the observed chloride diffusivity after 1 year of water curing in the laboratory is used as an input parameter to a new durability analysis. In combination with the achieved data on the concrete cover, this analysis provides a basis for the documentation of the potential durability of the given concrete structure. Also for this new analysis, the other input parameters are the same as those used in the original durability analysis.

IV. CONCLUDING REMARKS

In recent years, an extensive amount of research has been carried out in order to better understand and control several of the most important deterioration mechanisms for concrete structures in severe environments, and never before has so much basic information and knowledge about concrete durability been available. The great challenge to the profession is, therefore, to utilize and transform more of all this existing knowledge into good and appropriate engineering practice. Extensive experience demonstrates that the durability of concrete structures is related not only to design and material but also to the execution of the concrete construction work and the achieved construction quality. Upon completion of new concrete structures, the construction quality achieved always shows a high scatter and variability, and in severe environments, any weaknesses in the concrete structures will soon be revealed, whatever specifications and constituent materials have been applied. In order to better take all this variability into account, a probability approach to the durability design as outlined and discussed in the present paper should be applied. Since many of the durability problems also can be attributed to poor quality control as well as special problems during concrete construction, the issue of construction quality and variability must also be firmly grasped before any rational approach to a more controlled durability can be achieved.

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