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Service Life and Sustainability of Important Concrete Infrastructures

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ABSTRACT

In order to obtain an improved and more controlled durability and service life of important concrete infrastructures, a rapid international development has taken place on both probability-based durability design and performance-based concrete quality control during concrete construction. In the present paper, current experience with such design and concrete quality control is briefly outlined and discussed.

INTRODUCTION

In most countries, concrete structures make up a very large and important part of the national infrastructure, and both the condition and performance of all these structures are very important for the productivity of the society. Since there is a growing amount of deteriorating concrete infrastructures, however, not only is the productivity of the society affected, but it also has a great impact on resources, environment and human safety. The operation, maintenance and repair of all these concrete structures are consuming much energy and resources and are producing a heavy environmental burden as well as large quantities of waste. It is very important, therefore, to produce new concrete infrastructures with an improved and more controlled durability and service life. This is not only important from a technical and economical point of view. This is also a very urgent sustainability issue.

Extensive experience demonstrates that the durability and service life of concrete structures are not only related 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 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 should be applied. Since much of the durability problems can be related 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. Hence, a performance-based concrete quality control during concrete construction with proper documentation of achieved construction quality and compliance with the specified durability should also be carried out. As part of the durability design, a proper service manual for the future operation of the structure should further be produced. It is only such a service manual for a regular condition assessment and preventive maintenance which provides the ultimate basis for achieving a more controlled service life of important concrete infrastructures.

DURABILITY DESIGN

Based on the general technical basis for service life design of buildings and structures developed by the International Organization for Standardization ISO, the European Union already in 1989 produced a Construction Products Directive [EU 1989], where a documentation of achieved durability of buildings and structures was required. Later on, it has been 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 played an important role in the development of a better basis for service life design of concrete structures [Sarja and Vesikari 1996, CEB 1997]. It was not until the European research project DuraCrete was completed in 2000, however, that more general guidelines for a probability-based service life design became available [DuraCrete 2000]. Later on, a model-code for probability-based service life design of concrete structures has also been produced [fib 2006]. 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 such a 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. By completion of such design, however, a proper basis for performance-based concrete quality control during concrete construction is obtained [Gjørv 2003].

Of the various deteriorating processes which can cause problems to concrete structures, proper mathematical models for the above design are currently only available for corrosion of embedded steel, either due to chloride penetration or concrete carbonation. For many important concrete structures, however, it is not the disintegration of the concrete itself but rather electrochemical corrosion of the embedded steel which poses the most critical and greatest threat to the safety, durability and service life of the structures. In particular this is true for concrete structures in chloride containing environments [Gjørv 1975, 2002, Mehta 1996].

In order to control or avoid durability problems for new concrete structures either due freezing and thawing, alkali-aggregate reactions and chemical deterioration or even concrete carbonation, much experience and practical recommendations exist [Gjørv 2002]. For concrete structures in chloride containing environments, however, current experience demonstrates that it may be difficult to avoid steel corrosion within service periods of typically 15 to 20 years even by the use of a high-performance concrete [Gjørv 2008, 2009].

Also for concrete structures which are not necessarily exposed to any chlorides, it is possible to specify performance-based requirements for concrete durability [Goodspeed et al. 1996, Gjørv 2009]. Increasingly, requirements based on chloride diffusivity are being specified for concrete durability. The chloride diffusivity is not only an important parameter for the resistance against chloride penetration, but it does also reflect the general diffusivity and durability properties of the concrete.

In recent years, a probability-based durability design has been applied to a number of important concrete structures in many countries [Stewart and Rosowsky 1998, McGee, R. 1999, Gehlen and Schiessl 1999, Gehlen 2007]. Also in Norway such a durability design has been applied to a number of concrete structures where a high degree of safety, durability and service life has been of special importance [Gjørv 2009]. In Norway, this design was originally based on the results and guidelines from the European research project DuraCrete [DuraCrete 2000], but successively as practical experience with such design was gained, the procedures for the design were simplified and further developed for more practical applications. Thus in 2004, this design was adopted by the Norwegian Association for Harbor Engineers as general recommendations and guidelines for durability design of new concrete structures in Norwegian harbors. Later on, new and revised editions were issued and more recently also adopted by the Norwegian Chapter of PIANC, which is the international professional organization for maritime infrastructures [PIANC Norway/NAHE 2009a,b].

In general, the basic principles for a probability-based durability design are more or less the same. In the following, however, a short outline of the Norwegian version of such design is given, as it has been applied to a number of important concrete structures in recent years [Gjørv 2009].

Calculation of corrosion probability

It is well known that the transport mechanisms for penetration of chlorides into concrete are rather complex [Poulsen and Mejlbro 2006]. In a very simplified form, however, the rate of chloride penetration into concrete is calculated on the basis of Ficks 2. Law of Diffusion [Collepardi et al. 1970, 1972] in combination with a time-dependent parameter (α) for the chloride diffusivity (D_0) [Takewaka and Mastumoto 1988, Tang and Gulikers 2007]. The effect of temperature (T) is also taken into account [Polder and deRooij 2007]. Since all the input parameters to this calculation show a high scatter and variability, the combination with a probability analysis has proved to be very appropriate. In order to include the uncertainty of the various input parameters, a similar approach as that used for structural design is applied, where the combined analysis is principally based on:

- A serviceability limit state (SLS), which in this case is based on onset of steel corrosion
- The probability for SLS to be reached.

In most codes for reliability of structures, an upper limit of 10 % for probability of failure is often specified. Thus, for a given concrete structure in a given environment, it is possible to calculate a certain service period before a probability of 10 % for corrosion is reached.

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 to the structure is based on the specification of a required service period before 10 % probability of corrosion is reached. For the given environmental exposure, the durability analysis then provides the basis for applying a proper combination of concrete quality and concrete cover. Before the final requirements to 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, C_S
    - Temperature, T
- Concrete quality

    - Chloride diffusivity, D_0
    - Time dependence factor, α
    - Critical chloride content, C_{CR}
- Concrete cover, X

For a concrete structure in a chloride containing environment, the chloride load on the concrete surface is normally based on the surface chloride concentration (C_S), which is the result of a regression analysis of observed data on chloride penetration and curve fitting to Ficks 2. Law. The chloride diffusivity (D_0) of the concrete is a very important concrete property which generally reflects the resistance of the concrete against chloride penetration. Although several methods for the testing of this parameter exist [Schiessl and Lay 2005], the non-steady state migration method or the so-called Rapid Chloride Migration (RCM) method [NORDTEST 1999] has been selected as the basis for determination of this parameter. The further procedures both for determination and selection of all the above parameters are described and discussed in more detail elsewhere [Gjørv 2009]. In principle, the calculation of corrosion probability can be carried out on the basis of several mathematical methods. For the current durability design, however, the calculation of chloride penetration is combined with a Monte Carlo Simulation, a special software for which has been developed [DURACON 2004].

Durability analysis

Based on a proper selection of the above parameters, a calculation of the corrosion probability for the given concrete structure in the given environment is carried out, and as an overall durability requirement to important concrete infrastructures, a service period of 120 years may be specified before a 10 % probability of corrosion is reached. Although the minimum durability requirements according to current concrete codes always must be fulfilled, an improved basis for selecting a proper combination of concrete quality and concrete cover is then obtained. Thus, for a given concrete composition and concrete cover, the effect of different binder systems on the probability of corrosion is demonstrated in Figure 1. In this way, durability analyses provide a basis for comparing and selecting one of several technical solutions in order to meet the specified durability. Based on a number of simplifications and assumptions, however, the obtained “service periods” should not be considered as real service periods for the given structure. Also, such calculations should not be applied for service periods of more than 150 years. However, durability analyses provide a proper basis for an engineering judgment of the most important factors which are considered relevant for the durability, including the scatter and variability of all factors involved.

From the durability analyses carried out, requirements to both chloride diffusivity and concrete cover can be specified, both of which should be regularly verified and controlled during concrete construction. As a result, deviations can be detected and corrected for at an early stage and a final documentation of achieved construction quality and compliance with specified durability obtained as briefly outlined in the following.

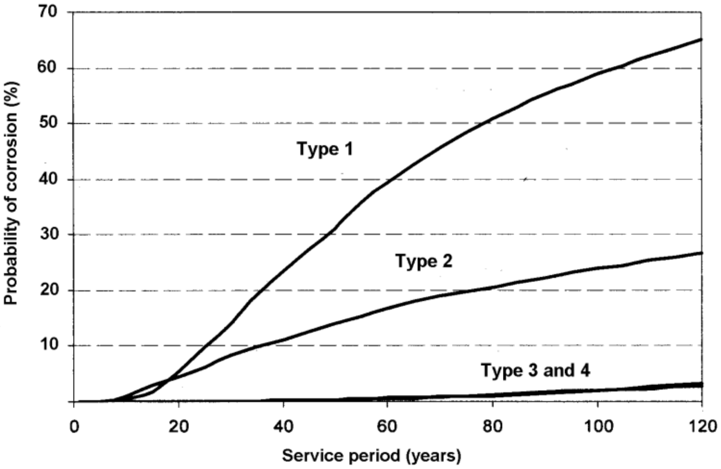

Fig. 1. Probability of corrosion for a given concrete composition with different types of binder system [Gjørv 2009]

PERFORMANCE-BASED CONCRETE QUALITY CONTROL

Although a probability approach to the durability design to a certain extent takes the great variability of construction quality into account, a numerical approach to the durability design alone is not sufficient for ensuring a proper durability. For concrete structures in severe environments, construction quality and variability is a key issue which must be firmly grasped before a more rational approach to a more controlled durability can be achieved [Sommerville 2000].

Even before the concrete is placed in the formwork, the quality of concrete may show a high scatter and variability. Depending on a number of factors during concrete construction, the achieved quality of the finely placed concrete normally shows en even higher scatter and variability. Even for the offshore concrete platforms in the North Sea with a very high quality of both concrete production and concrete construction, most of the durability problems which have been experienced later on can be ascribed due to lack of proper quality control and special problems during concrete construction [Helland et al. 2008, Gjørv 2009].

Probably the best known and well documented quality issue of concrete structures is the failure to meet the specified requirements to concrete cover. In recent years, therefore, improved codes and procedures for achieving the specified concrete cover with more confidence have been introduced. Still, however, the variability of concrete cover appears to be a very difficult problem. Although the specified concrete cover is normally carefully checked and controlled before the concrete is placed, experience demonstrates that significant deviations may still occur during placing of the concrete. The loads during placing of the concrete may occasionally be too high compared to the stiffness of the rebar system, or the spacers may occasionally have been insufficiently or wrongly placed. Even during the sophisticated slip forming work of the offshore concrete platforms for the North Sea, the installed spacers had occasionally to be removed during some critical stages of the slip forming in order to keep the slip forming work going on.

In order to comply with the overall durability requirement to the given structure, a proper quality control of both the specified chloride diffusivity and the concrete cover must be carried out during concrete construction. For both of these durability parameters, average values and standard deviations must be obtained. If cathodic prevention or preparation for such a protective measure also has been specified, a regular quality control of the electrical continuity within the rebar system must also be carried out during concrete construction. In the following, the necessary procedures for measurements and control of both chloride diffusivity and **concrete** cover are briefly outlined and discussed.

Chloride diffusivity

As already described above, all measurements of chloride diffusivity are based on the Rapid Chloride Migration (RCM) method [NORDTEST 1999]. Although the duration of such measurements may only take a couple of days, this is not good enough for a regular quality control during concrete construction. For all porous materials, however, the Nernst–Einstein equation expresses the following general relationship between the ion diffusivity and the electrical resistivity of the material [Atkins and De Paula 2006]:

$$D_i = \frac{R \cdot T}{Z^2 \cdot F^2} \cdot \frac{t_i}{\gamma_i \cdot c_i \cdot \rho} \tag{1}$$

where:
D_i = diffusivity for ion i
R = gas constant
T = absolute temperature
Z = ionic valence
F = Faraday constant
t_i = transfer number of ion i
γ_i = activity coefficient for ion i
c_i = concentration of ion i in the pore water
ρ = electrical resistivity

Since most of the factors in eq. 1 are physical constants, the above relationship can for a given concrete with given temperature and moisture conditions be simplified to:

$$D = k \cdot \frac{1}{\rho} \tag{2}$$

where D is the chloride diffusivity, k is a constant and ρ is the electrical resistivity of the concrete. Since the electrical resistivity of the concrete can be measured in a much more rapid and simple way than the chloride diffusivity, it is primarily a regular quality control of the electrical resistivity of the concrete which provides the basis for an indirect quality control of the chloride diffusivity during concrete construction [Gjørv 2003]. Therefore, as soon as the type of concrete is given, the above relationship between chloride diffusivity and electrical resistivity for the given concrete must be established. This is done by producing a certain number of concrete specimens, on which parallel testing of both chloride diffusivity and electrical resistivity at different periods of water curing are carried out. After the relationship between the chloride diffusivity and the electrical resistivity has been established, this relationship is later on used as a calibration curve for an indirect control of the chloride diffusivity based on regular measurements of the electrical resistivity during concrete construction. Since the testing of electrical resistivity is a rapid and non-destructive type of test, these measurements are carried out on the same concrete specimens as that being used for the regular quality control of the 28 day compressive strength during concrete construction.

Concrete cover

For concrete structures in severe environments, the specified concrete cover is normally very thick, and the reinforcement system may also be very congested. For such structures, therefore, it may be difficult to obtain reliable control data on the achieved concrete cover based on conventional cover meters and procedures. It may also be difficult to apply conventional cover meters if the reinforcement is based on stainless steel, which does not respond to magnetic measurements. In such a case, cover meters based on a pulse-induction technique may be used. In both cases, however, extensive experience has shown that straight manual readings of the concrete cover on protruding bars in casting joints during concrete construction may provide a sufficiently accurate basis for the regular quality control of achieved concrete cover. However, the extent of measurements must be sufficient in order to provide reliable statistical data both on average values and standard deviations.

ACHIEVED CONSTRUCTION QUALITY

From the performance-based concrete quality control as briefly described above, average values and standard deviations both for chloride diffusivity and concrete cover are obtained. Upon completion of the concrete construction, these data are used as input parameters to a new durability analysis which provides the documentation of compliance with the specified durability.

Since the specified chloride diffusivity is only based 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 of achieved chloride diffusivity on the construction site should also be provided. At the end of concrete construction, such a chloride diffusivity in combination with the achieved concrete cover are used as input parameters for a new durability analysis and hence, a 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 should also be provided. Such a chloride diffusivity in combination with the achieved concrete cover provide the basis for documentation of the potential durability of the given structure.

Upon completion of the concrete structure, a proper documentation of the achieved construction quality should always be provided before the structure is formally handed over to the owner from the contractor. For the owner, such documentation may have implications both for the future operation and expected service life of the structure. In the following, the procedures for providing such documentation are briefly described.

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 has to be carried out based on the average values and standard deviations obtained from the quality control of both the chloride diffusivity and the concrete cover 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 result of the achieved chloride diffusivity and concrete cover during concrete construction, including the observed scatter and variability. Hence, the new durability analysis provides the basis for documentation of compliance with the specified durability.

Durability on construction site

In principle, any documentation of achieved chloride diffusivity from 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, however, one or more un-reinforced concrete elements should be separately produced on the construction site at an early stage of concrete construction, from which most of the concrete coring takes place during the construction period. In addition, a certain extent of coring from the real concrete structure must also be carried out, but only from locations where the coring will not weaken the structure.

All separately produced concrete elements which could either be a wall or slab type of element or both, should be produced and cured as representative as possible for the real concrete structure or various parts of the concrete structure. From these elements, a number of concrete cores are later on removed at various ages, and immediately upon removal sent to the laboratory for testing of achieved chloride diffusivity. In order to obtain a proper curve for the development of chloride diffusivity on the construction site, the cores should be removed and tested after various periods of up to at least one year. In addition, supplemental data on achieved chloride diffusivity are also obtained from the testing of a certain number of concrete cores removed from the real concrete structure during concrete construction.

Somewhat depending on type of binder system, the obtained development of chloride diffusivity on the construction site often tends to level out after a period of approximately one year (Figure 2). Based on the achieved chloride diffusivity on the construction site after one year, therefore, a new durability analysis is carried out. In combination with the achieved data on concrete cover, this new durability analysis provides the basis for documentation of achieved durability on the construction site during concrete construction.

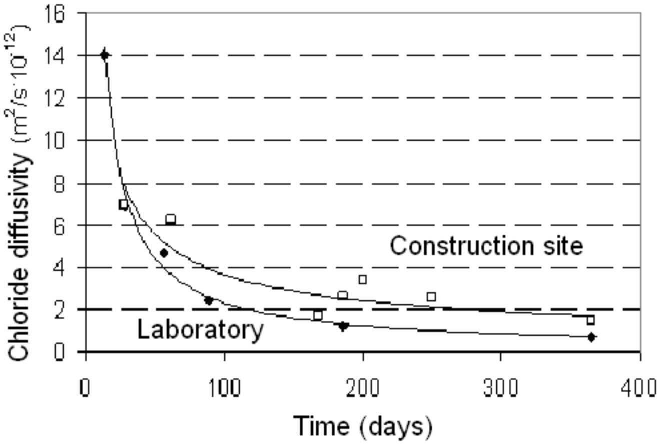

Fig. 2. Development of achieved chloride diffusivity on the construction site and in the laboratory during the construction period [Gjørv 2009]

Potential durability

For establishing the 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 concrete specimens after curing periods of up to at least one year, a further development of the chloride diffusivity as that shown in Figure 2 is obtained. 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 also typically tends to level out after approximately one year. Hence, the observed chloride diffusivity after one year of water curing in the laboratory is used as input parameter to a new durability analysis. In combination with the achieved data on concrete cover, this analysis provides the basis for documentation of the potential durability of the given structure. Also for this new analysis, the other input parameters are the same as that used in the original durability analysis.

CONDITION ASSESSMENT AND PREVENTIVE MAINTENANCE

For most concrete structures, the typical situation during operation is that maintenance and repairs are mostly reactive, and the need for taking appropriate measures is mostly realized at a very advanced stage of deterioration. For chloride-induced corrosion, repairs at such a stage are then both technically difficult and disproportionately expensive compared to that of carrying out regular condition assessments and preventive maintenance. Therefore, for all concrete structures where high safety, performance and service life are of special importance, regular condition assessments and preventive maintenance should be carried out.

For all important concrete structures in chloride containing environments, special procedures for monitoring and control of chloride penetration during operation of the structures are needed. To establish such procedures should always be an important and integral part of the durability design [Gjørv 2009].

For the regular control of chloride penetration during operation of the structure, it is very important to have a detailed plan for the given structure showing the selected locations in which the future control of chloride penetration should take place. These locations which should be as representative as possible for the most exposed and critical parts of the structure, provide the basis for assessment of the future rates of chloride penetration. Based on the observed chloride penetration, new durability analyses are carried out in order to predict the future probability of corrosion. Before this probability becomes too high, proper protective measures should be considered and selected [Gjørv 2009]. Depending on type of protective measure, the observed rate of chloride penetration can either be reduced or completely stopped. If the chlorides have not reached too deep through the concrete cover, a proper surface treatment or coating may slow down the further rate of chloride penetration. If the chlorides have already reached too deep, however, a cathodic prevention is the only protective measure that can stop the further chloride penetration and thus avoid onset of steel corrosion.

CONCLUDING REMARKS

Extensive experience demonstrates that the durability and service life of concrete structures are not only related 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 hence, a probability approach to the durability design should be applied. Since much of the durability problems can be related 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.

From all the new commercial projects to which the above procedures for durability design and concrete quality control have been applied so far, the increased focus on achieved construction quality has proved to be very important. For the owners of the structures it has been very important to receive a proper documentation of the achieved construction quality and compliance with the specified durability. Also, it has been very important to receive this information before the structures have formally been handed over from the contractors. To receive the structures with an improved and more controlled durability is not only important from a technical and economical point of view. This is also a very urgent sustainability issue [Gjørv and Sakai 2000].

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