

Durability design and quality assurance of major concrete infrastructure

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Abstract. Upon completion of new concrete structures, the achieved construction quality always shows a high scatter and variability, and in severe environments, any weaknesses and deficiencies will soon be revealed whatever durability specifications and materials have been applied. To a certain extent, a probability approach to the durability design can take the high scatter and variability into account. However, numerical solutions alone are not sufficient to ensure the durability and service life of concrete structures in severe environments. In the present paper, the basis for a probability-based durability design is briefly outlined and discussed. As a result, some performance-based durability requirements are specified which are used for quality control and quality assurance during concrete construction. The final documentation of achieved construction quality and compliance with the specified durability are key to any rational approach to more controlled and increased durability. As part of the durability design, a service manual for future condition assessment and preventive maintenance of the structure is also produced. It is such a service manual which helps provide the ultimate basis for achieving a more controlled durability and service life of the given concrete structure in the given environment.

Keywords: achieved construction quality; concrete infrastructure; condition assessment; durability; preventive maintenance; probability-based durability design; quality assurance; reliability; service life; severe environments

1. Introduction

In recent years, deterioration of major concrete infrastructure has emerged as a most severe and demanding challenge facing the construction industry. Public agencies are spending significant and rapidly increasing proportions of their construction budgets for repairs and maintenance of existing concrete infrastructure. Enhanced durability and service life of new concrete infrastructure are not only important from an economical point of view; it also directly affects sustainability (GjØrv 2009).

Although a number of different deteriorating processes may affect the durability and service life of concrete structures in severe environments, extensive experience demonstrates that it is not the disintegration of the concrete itself but rather chloride-induced corrosion of embedded steel

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which poses the most critical and greatest threat to the structures (GjØrv 2009). The increasing amount of de-icing salt has created a special challenge, but de-icing salts are not the only source of problems. Chloride-induced corrosion is also an extensive and costly problem for concrete structures in marine environments. After a comprehensive surveying of concrete structures in U.S. waters, the problem with corrosion of embedded steel was pointed out by Wig and Ferguson already in 1917 (Wig *et al.* 1917). Also in Norwegian waters, chloride-induced corrosion of embedded steel has been the major problem to the operation and safety of a large number of important concrete structures, the first of which was produced already in 1910 (PANE 1936, GjØrv 1968, 1994, 2009).

In order to take the high variability of both achieved construction quality and environmental exposure into account, there has been a rapid international development on probability-based durability design in recent years (Siemes *et al.* 1985, 2000, DuraCrete 2000). However, numerical solutions alone are not sufficient to ensure the durability of concrete structures in severe environments; it is essential also to specify some durability requirements which can be verified and controlled for quality assurance during concrete construction.

In 2004, the combination of probability-based durability design and performance-based concrete quality assurance became the strategy and basis for new recommendations and guidelines for production of more durable concrete infrastructure in Norwegian harbors (NAHE 2004). Since the long-term performance and service life of such structures also very much depend on regular condition assessment and preventive maintenance, the production of a service manual for regular control of the chloride ingress during operation of the structures also became an essential part of the durability design. In the following, current experience with the above recommendations and guidelines for durability design and concrete quality assurance is briefly outlined and discussed.

2. Durability design

2.1 General

For several years, probability-based durability design has been applied to a number of new major concrete structures in many countries (Stewart *et al.* 1998, McGee 1999, Gehlen *et al.* 1999, Gehlen 2007). In Norway, such design was initially based on the guidelines from the European research project “DuraCrete” which were introduced in 2000. During the following years when practical experience with these guidelines was gained, the basis for this design was further developed for more practical applications, but the basic principles remained essentially the same (NAHE 2004). Lessons learned from practical experience with these recommendations and guidelines to new commercial projects were incorporated into subsequent revised editions, the third and last of which from 2009 was also adopted by the Norwegian Chapter of PIANC (PIANC/NAHE 2009), which is the international professional organization for maritime infrastructure.

2.2 Durability analyses

For a given concrete structure in a given environment, the overall durability requirement is based on the specification of a given service period before the probability for onset of corrosion

exceeds a certain upper level, and for this level, a probability of 10% was adopted. In order to calculate the probability of corrosion, durability analyses are carried out, and this provides the basis for selecting proper combinations of concrete quality and cover thickness.

In principle, the probability of corrosion can be calculated by use of several mathematical methods and available software. Based on current experience with durability design of concrete structures in chloride-containing environments, however, a simple combination of a modified Ficks Second Law of Diffusion and a Monte Carlo Simulation has proved to give an appropriate basis for calculating the corrosion probability (Ferreira 2004, Ferreira *et al.* 2004). Although such a combined calculation can also be carried out in different ways, special software “DURACON” for this calculation was developed (Ferreira 2004, Ferreira *et al.* 2004), for which proper information about the following input parameters is needed:

- Environmental loading:
 - Chloride loading (C_S)
 - Age at chloride loading (t')
 - Temperature (T)
- Concrete quality:
 - Chloride diffusivity (D),
 - Time dependence of the chloride diffusivity (α)
 - Critical chloride content (C_{CR})
- Concrete cover (X)

All the procedures and methods for determining and selecting the above input parameters are described and discussed in more detail elsewhere (Gjørsv 2009, PIANC/NAHE 2009). It should be noted, however, that the chloride diffusivity of a given concrete is a very important quality parameter which generally reflects the resistance of the concrete to chloride ingress. Although a low water/binder ratio also reflects a low porosity and a high resistance to chloride ingress, extensive experience demonstrates that selecting a proper binder system may be much more important for obtaining a high resistance to the chloride ingress than selecting a low water/binder ratio. For example, when the water/binder ratio was reduced from 0.50 to 0.40 for a concrete based on pure portland cement, the chloride diffusivity was reduced by a factor of two to three, while incorporation of various types of supplementary cementitious materials such as blast-furnace slag, fly ash or silica fume at the same water/binder ratio reduced the chloride diffusivity by a factor of up to 20 (Thomas *et al.* 2011). Also, while a reduced water/binder ratio from 0.45 to 0.35 for a concrete based on pure portland cement may only reduce the chloride diffusivity by a factor of two, a replacement of the portland cement by a proper blast-furnace slag cement may reduce the chloride diffusivity by a factor of up to 50 (Bijen 1998). By also combining the blast-furnace slag cement with silica fume, extremely low chloride diffusivity can be obtained and hence, a concrete with an extremely high resistance to chloride ingress can be produced.

For major concrete infrastructure, a service period of 100 years or more should always be specified before the probability of corrosion exceeds 10%. For increased service periods of more than 100 years, however, the calculation of corrosion probability gradually becomes less reliable. For service periods of up to 150 years, therefore, the corrosion probability should be kept as low as possible and not exceeding 10%, but in addition, some further protective measures such as partly use of stainless steel should also preferably be required. For service periods of more than 150 years, however, any calculation of corrosion probability is no longer considered valid. For such long service periods, the corrosion probability should still be kept as low as possible and not

exceeding 10% for a 150-year service period, but in addition, one or more additional protective measures should always be required. If there is any risk for early-age chloride exposure during concrete construction before the concrete has gained sufficient maturity and density, special precautions or protective measures should also be required.

It should be noted that the above durability analyses do not provide any basis for prediction or assessment of any service life of the given concrete structure. The above procedures for calculation of corrosion probability should rather be considered a basis for an engineering judgement of some of the most important factors related to the durability of the structure, including their scatter and variability. Hence, a basis for comparing and selecting one of several technical solutions in order to achieve a best possible durability for the given concrete structure in the given environment is obtained. Upon completion of the concrete construction work, new durability analyses are carried out in order to provide documentation of the achieved construction quality and compliance with the specified durability. In this case, the input parameters on both chloride diffusivity and concrete cover are based on the obtained data from the quality control during concrete construction; all the other input parameters are kept the same as that for the original durability analyses. During operation of the structure, further durability analyses are carried out as a basis for the condition assessment and preventive maintenance. For each new condition assessment, the probability of corrosion is then calculated with new input parameters based on data from the real chloride ingress observed. Before this probability of corrosion becomes too high, appropriate protective measures must be implemented.

In the following, a case study is shown demonstrating how durability analyses are used as a basis for the durability design.

2.3 Effect of concrete quality

As an overall durability requirement to a new concrete harbor structure in a typical Norwegian marine environment, a service period of 120 years was specified before 10% probability of corrosion would be reached. In order to select a proper combination of concrete quality and concrete cover which would meet such a requirement, two steps of durability analyses were carried out. In order to evaluate the effect of concrete quality (chloride diffusivity), four different concrete mixtures were produced for which the 28-day chloride diffusivity was determined (NORDTEST 1999). Apart from type of binder system, all these concrete mixtures were the same and fulfilled the minimum durability requirements according to the current concrete codes for a 100-year service life; including a water/binder ratio ≤ 0.40 and a binder content $\geq 330 \text{ kg/m}^3$ (Standard Norway 2003). The various binder systems included four different types of commercial cement in combination with 10% condensed silica fume (CSF) by weight of cement; one high-performance portland cement (Type 1), one fly ash cement with 18% fly ash (Type 2) and two blast-furnace slag cements with 34 and 70% slag (Types 3 and 4), respectively (Table 1).

Based on the obtained 28-day chloride diffusivities, a nominal concrete cover of 70 mm and estimated values for all the other input parameters for the given environment, durability analyses were carried out. Some of the input parameters are shown in Table 1, while for the others, estimated values for chloride loading (C_s) of 5.5;1.4%, age at chloride loading (t') of 28 days and temperature (T) of 10°C were selected.

Although all four concrete mixtures complied with the current code requirements, the service period before 10% probability of corrosion would be reached differed significantly (Fig. 1), ranging from about 30 years for the portland cement type of concrete (Type 1) to about 80 years

for the fly ash cement concrete (Type 2) and to more than 120 years for the two slag cement types of concrete (Types 3 and 4). Thus, only the two types of concrete based on blast-furnace slag cement would meet the specified durability requirement to the given structure.

It may be argued that the above durability analyses were only carried out on the basis of the obtained 28-day chloride diffusivities, while the chloride diffusivity of the various types of concrete based on different types of binder system would develop very differently. Therefore, some additional durability analyses based on values of the chloride diffusivity obtained after longer curing periods were also carried out, but none significantly changed the relative basis for selecting the concrete with the best durability properties.

2.3 Effect of concrete cover

In order to evaluate the effect of increased concrete cover beyond 70 mm, some further durability analyses based on 90 and 120 mm covers were also carried out. These analyses were based on the above type of concrete with portland cement (Type 1), while holding all the other

Table 1 Input parameters for analyzing the effect of concrete quality

Concrete quality	Input parameter		
	D_{28} ($m^2/s \times 10^{-12}$)	α	C_{CR} (% by wt. of binder)
Type 1 (CEM I 52,5 LA + 10 % CSF)	N ¹⁾ (6.0;0.64)	N (0.40;0.08)	
Type 2 (CEM II/A – V 42,5 R + 10 % CSF)	N (7.0;1.09)	N (0.60;0.12)	
Type 3 (CEM II/B - S 42,5 R NA + 10 % CSF)	N (1.9;0.08)		N (0.40;0.10)
Type 4 (CEM III/B 42,5 LH HS + 10 % CSF)	N (1.8;0.15)	N (0.5;0.10)	

¹⁾Normal distribution and standard deviation

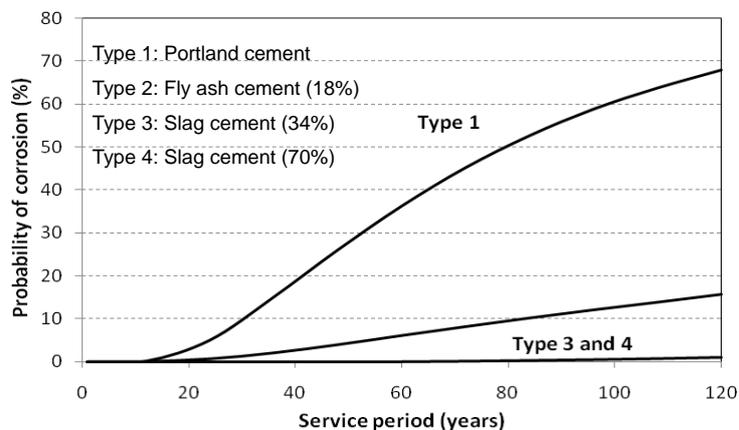


Fig. 1 Effect of cement type on the probability of corrosion (Gjørøv 2009)

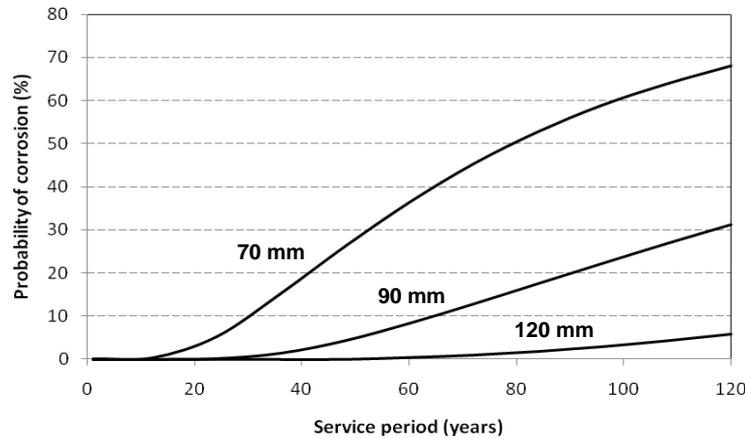


Fig. 2 Effect of concrete cover on the probability of corrosion (Concrete Type 1) (Gjrv 2009)

input parameters constant. Fig. 2 shows how an increased concrete cover also would significantly affect the probability of corrosion. While a nominal cover of 70 mm for the portland cement concrete would give a service period of about 30 years, increased cover of up to 90 and 120 mm would increase the service period by up to more than 60 and more than 120 years, respectively.

It may be argued that increased cover thickness beyond 90 mm would increase the risk for unacceptable crack widths. While this effect to some extent could be mitigated by incorporation of synthetic fibers in the concrete, increased cover would also have some secondary effects such as increased total dead load. Therefore, an alternate solution would be to use stainless steel for the outer layer of the reinforcement, effectively increasing the cover thickness to the remaining black steel reinforcement further in. In this way, durability analyses can also be used as a design tool for quantifying how much of the black steel needs to be replaced by stainless steel reinforcement in order to meet the required safety level against corrosion.

3. Concrete quality assurance

3.1 General

In order to obtain a better control of the high scatter and variability of achieved construction quality, it is essential to have some performance-based durability requirements which can be verified and controlled for quality assurance during concrete construction. Even before the concrete is placed in the formwork, the quality of the concrete may show a high scatter and variability (Gulikers 2011). Depending on a number of factors during concrete construction, the achieved quality of the finely placed concrete may show an even higher scatter and variability. If air-entrained concrete is applied, large variations in the air void characteristics may also occur (Okkenhaug *et al.* 2003). This problem is exacerbated when fly ash cements are used and the carbon content of the fly ash varies (Nagi *et al.* 2007), affecting both the chloride diffusivity and the frost resistance of the concrete.

One of the most common quality problems in concrete construction, however, is the failure to

meet the specified cover thickness to embedded steel (Gjørsv 2009). Although the specified concrete cover is normally carefully checked prior to placing of the concrete, significant deviations can occur during concrete construction, and this does occur. The loads imposed during concrete placement may cause movement of the reinforcement in the form, or the chairs may have been insufficiently or wrongly placed. Even for the offshore concrete platforms in the North Sea, where very high quality standards for the concrete construction were applied, most of the durability problems that later on developed during service can be ascribed due to weaknesses and deficiencies in the achieved construction quality (FIP 1996, Helland *et al.* 2008, Gjørsv 2009). The damage has mostly been related to low concrete cover, but low cover is also often difficult to compact giving concrete covers of reduced quality. During some critical stages of the complex slip forming of these structures, the chairs were occasionally also removed, which contributed to the zones with inadequate and weak concrete cover.

To ensure a best possible construction quality, the specified values of both chloride diffusivity and concrete cover must be properly controlled, which is achieved through ongoing verification and documentation during concrete construction. When unacceptable deviation occurs, immediate actions for correction must be taken.

3.2 Chloride diffusivity

For the testing of chloride diffusivity several test methods exist, a thorough review and discussion of which are given elsewhere (Gjørsv 2009, Luping *et al.* 2012). Although all of these test methods are accelerated methods giving different values for the chloride diffusivity, they all show a good correlation. In order to be suitable for a regular control and quality assurance during concrete construction, however, the Rapid Chloride Migration (RCM) method (NORDTEST 1999) was adopted. This is the only method which can be applied for testing the chloride diffusivity very rapidly, independent of concrete age.

For most durability analyses, the 28-day chloride diffusivity is normally used as input parameter; although the chloride diffusivity obtained after longer curing periods can also be applied. It may be argued that both from a transport mechanism and theoretical point of view, such a strongly accelerated test method as the RCM method is questionable (Yuan 2009, Gulikers 2011). It should be noted, however, that the above 28-day chloride diffusivity only is a simple, relative index reflecting the general mobility of ions in the pore system and hence, both the resistance to chloride ingress as well as the general durability properties of the concrete. Thus, the 28-day chloride diffusivity may be comparable to that of the 28-day compressive strength, which is also only a very simple, relative index primarily reflecting the compressive strength but also reflecting the general mechanical properties of the concrete.

Although the RCM method is a very rapid test method which provides data on the chloride diffusivity already within a few days, this is not good enough for the regular quality control during concrete construction. However, based on the Nernst-Einstein equation expressing the general relationship between diffusivity and electrical resistivity of all porous materials (Atkins *et al.* 2006), a calibration curve as that shown in Fig. 3 is established. Such a calibration curve relating the two tests must therefore be established for the given concrete before concrete construction starts. Measurements of the electrical resistivity are then carried out as a quick, non-destructive test on the same concrete specimens as that being used for the regular control of the 28-day compressive strength (Gjørsv 2003). All control measurements of the electrical resistivity are carried out immediately before the compressive strength testing, either by use of the two-electrode

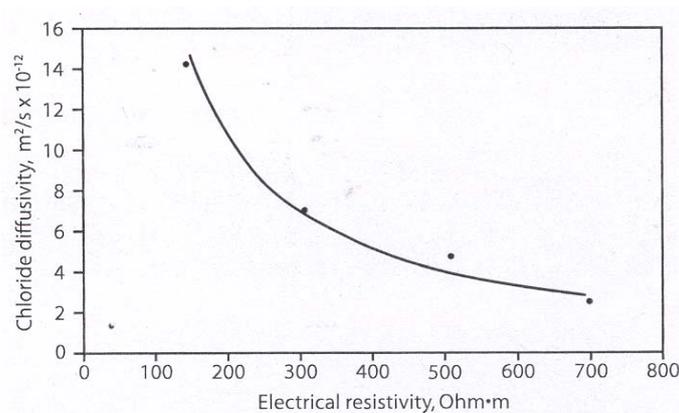


Fig. 3 Typical calibration curve for control of chloride diffusivity based on electrical resistivity measurements (Gjrv 2009)

or the four-electrode method (Wenner) (Sengul and Gjrv 2008, Gjrv 2009). Although the two-electrode method is a more well-defined and accurate test method, both methods are being applied for a simple and rapid quality control during concrete construction.

3.3 Concrete cover

In severe environments, the concrete cover is normally very thick, and the reinforcement is often highly congested, making it difficult to measure cover thickness very accurately based on conventional cover meters. The use of stainless steel reinforcement may further complicate such measurements, although cover meters based on pulse induction can then be used. However, also more sophisticated systems for control of achieved concrete cover based on image scanning exist. With such equipment available, there should be little excuse for allowing low cover in new concrete structures, yet this seems to continue to be a problem on many construction sites.

Often, a more pragmatic approach to the control of cover thickness is applied, where manual readings of the cover thickness on protruding bars in construction joints during concrete construction are carried out (Fig. 4). If the amount of such control measurements is sufficiently high to produce reliable statistical data, such a simple approach may be considered sufficiently accurate for the regular control and quality assurance during concrete construction. As long as an ongoing control and documentation of the achieved concrete cover are required, experience has shown that the increased focus and attention on achieved concrete cover also is very important for an increased quality of workmanship (Gjrv 2009).

4. Achieved construction quality

4.1 General

Upon completion of the concrete construction work, the obtained data from the quality control of both chloride diffusivity and concrete cover are used as input parameters to new durability analyses for documenting the achieved construction quality. Since the specified chloride



Fig. 4 Control of cover thickness on protruding bars in construction joints during concrete construction

diffusivity is based on small and separately produced concrete specimens cured in the laboratory for only 28 days, however, this chloride diffusivity may be quite different from that obtained on the construction site during concrete construction. Therefore, some additional documentation of achieved chloride diffusivity on the construction site must be provided. Since neither the 28-day chloride diffusivity from the laboratory nor the achieved chloride diffusivity on the construction site reflects the potential chloride diffusivity of the concrete, additional documentation of the long-term diffusivity must further be provided. For the owner of the structure, a proper documentation of achieved construction quality may have implications both for the future operation and expected service life of the structure.

4.2 Compliance with specified durability

As a result of the durability design, a required service period with a probability for corrosion of less than 10% is specified. To show compliance with such a durability requirement, a new durability analysis must be carried out based on the achieved average values and standard deviations of both the 28-day chloride diffusivity and the concrete cover from the quality control as new input parameters. For this durability analysis, all the other previously assumed input parameters from the original durability analyses, which may have been somewhat difficult to select, are kept the same. Hence, this documentation primarily reflects the results obtained from the regular quality control during concrete construction including the scatter and variability

involved.

4.3 In situ quality

The achieved chloride diffusivity on the construction site during the construction period is primarily based on the testing of a number of concrete cores removed from the given structure under construction. In order not to weaken the structure too much by coring, however, one or more representative dummy elements are also produced on the construction site, from which a number of additional cores are removed and tested during the construction period. Based on the achieved chloride diffusivity on the construction site after one year combined with the site data on cover thicknesses as new input parameters, a new durability analysis is carried out. Also here, all the other previously assumed input parameters from the original durability analyses are held constant. Hence, this analysis provides documentation of the achieved in situ quality during the construction period.

4.4 Potential quality

For most binder systems, the development of chloride diffusivity tends to plateau after about one year of water curing at 20°C in the laboratory. Therefore, to estimate the potential construction quality and durability of the structure, the chloride diffusivity is also determined on separately produced and water cured specimens in the laboratory for a period of up to one year. This chloride diffusivity in combination with the achieved site data on concrete cover as new input parameters provides the basis for documenting the potential construction quality of the structure. Also here, all the other originally assumed input parameters to the durability analysis are held constant.

5. Condition assessment and preventive maintenance

Even if the strongest requirements to both concrete quality and concrete cover have been specified and achieved during concrete construction, extensive experience demonstrates that for all concrete structures in chloride containing environments, a certain rate of chloride ingress will always take place during operation of the structures. Upon completion of the given structure, therefore, the owner must be provided with a service manual for regular control of the real chloride ingress taking place. It is such a service manual which helps provide the ultimate basis for obtaining a more controlled and increased service life of the given concrete structure in the given environment. For each new condition assessment of the structure, new estimates for the probability of corrosion are developed using input parameters based on data from the observed chloride ingress (Gjrv 2009). Before this probability of corrosion becomes too high, appropriate protective measures must be implemented.

6. Practical applications

6.1 General

For many years, when concrete was mostly based on pure portland cements and simple

Table 2 Chloride diffusivity of concrete typically being applied for new marine concrete construction along the Norwegian coastline (Gjørsv 2009)

Construction site	Chloride diffusivity ($\times 10^{-12} \text{ m}^2/\text{s}$)									
	Age (days)									
	14	28	60	90	180	365	400	460	640	730
“Container Terminal No.1” Oslo (2002)	13.5	6.0	4.4	3.8	3.0	-	-	-	-	-
“Gas Terminal” Aukra (2005)	17.6	6.8	4.3	2.3	-	-	1.5	-	-	-
“Eiksund Bridge” Eiksund (2005)	14.1	4.4	3.8	3.4	3.1	-	-	3.0	-	-
“Container Terminal No.2” Oslo (2007)	14.0	6.9	4.6	2.4	1.2	0.7	-	-	-	0.7
“Sea Spaced City Development” Oslo (2010)	4.7	1.6	0.4	0.4	0.3	0.2	-	-	0.2	0.2

procedures for concrete production, the concept of water/cement ratio was the fundamental basis both for characterizing and specifying concrete quality. In recent years, however, there has been a rapid development of new types of cement and supplementary cementitious materials which are increasingly controlling the concrete properties. Also, the concrete properties are increasingly being controlled by use of processed concrete aggregate, new concrete admixtures and more sophisticated equipment for concrete production. As a result, the old and very simple terms “water/cement ratio” or “water/binder ratio” for characterizing and specifying concrete quality have successively lost their meaning. As a consequence, performance-based specifications for concrete quality must be applied. In particular, this is essential for characterizing and specifying concrete durability.

In order to obtain some general information about the durability properties of concrete typically being applied for new marine concrete construction along the Norwegian coastline, samples of the concrete from some recent construction sites were collected for testing the chloride diffusivity based on the RCM method. For most of these cases, the specified concrete durability was based on current concrete codes for a 100-year service life, including a water/binder ratio of ≤ 0.40 and a binder content of $\geq 330 \text{ kg/m}^3$. From Table 2 it can be seen that the chloride diffusivity of the various types of concrete varied widely.

For some of the above concrete structures, a probability-based durability design and performance-based concrete quality assurance according to the current recommendations and guidelines from the Norwegian Association for Harbor Engineers were also carried out (NAHE 2004). One of these concrete structures was part of a new container terminal in Oslo Harbor completed in 2007 (“Container Terminal No. 2”), while others were part of a new sea spaced city development in the harbor region of Oslo City (Tjuvholmen). The following is a brief summary of experience gained from these projects. As a reference project, a container terminal in Oslo Harbor completed in 2002 (“Container Terminal No. 1”) is also included.

6.2 “Container Terminal No. 1”, Oslo (2002)

This concrete harbor structure consists of an open concrete deck on driven steel tubes filled with concrete. At the time of construction, the above recommendations and guidelines for durability design from the Norwegian Association for Harbor Engineers were not available. The durability specifications for a 100-year service life were therefore based on the then-current concrete codes with some additional requirements:

- Water/binder ratio: 0.40 ± 0.03
- Minimum cement content: 370 kg/m^3
- Silica fume: 6-8% by wt. of cement
- Air content: $5.0 \pm 1.5\%$
- Cover to the structural steel: $75 \pm 15 \text{ mm}$

Although no probability-based durability design was carried out, the owner of the structure required a best possible documentation of the achieved construction quality during the construction period. Therefore, a quality control similar to that later on recommended by the Norwegian Association for Harbor Engineers was carried out.

6.3 "Container Terminal No. 2", Oslo (2007)

From 2005 to 2007, the first part of a new container terminal in Oslo Harbor was constructed. This structure having a water front of about 300 m also consists of an open concrete deck on driven steel tubes filled with concrete. As minimum durability requirements to the structure, all requirements in the current concrete codes for a 100-year service life had to be fulfilled; including a water/binder ratio of ≤ 0.40 , a minimum binder content of 330 kg/m^3 and a minimum concrete cover of 60 mm. For frost resistance, a total air content of 4 to 6% was also specified. In order to obtain an increased and more controlled durability of the given structure, however, the owner required that a durability design and quality assurance according to the current recommendations and guidelines from the Norwegian Association for Harbor Engineers were also carried out. Therefore, a new durability design was carried out based on a 100-year service period with a probability of corrosion not exceeding 10%. Since the durability analyses carried out showed that chloride diffusivity (D_{28}) of $5.0 \times 10^{-12} \text{ m}^2/\text{s}$ in combination with a concrete cover of 90 mm would satisfy this requirement, these values were adopted for the concrete construction work. From Fig. 5 it can be seen that in the deck of such an open concrete harbor structure, there is much steel that needs a proper protection against corrosion.

6.4 "Sea spaced city development", Oslo (2010)

In 2005, a new sea spaced city development on Tjuvholmen in Oslo City began. This development project includes a number of concrete substructures in seawater with depths of up to 20 m, on top of which a number of business and apartment buildings have been built (Fig. 6). All these concrete substructures were finished by 2010, most of which include large underwater parking areas in up to four levels. In the shallower water, the structures typically include a solid concrete bottom slab on the sea bed, surrounded by external concrete walls partly protected by riprap or wooden cladding and partly freely exposed to the tides. In the deeper water, some structures include an open concrete deck on columns of driven steel pipes filled with concrete. In the deepest water, four large concrete caissons were prefabricated in dry dock, moved into position



Fig. 5 In the deck of an open concrete harbor structure, much steel needs a proper protection against corrosion



Fig. 6 The new sea spaced city development on Tjuvholmen in Oslo City (Photo: Terje Løchen)



Fig. 7 Section showing how large prefabricated concrete caissons after installation provide up to four levels of submerged parking on Tjuvholmen in Oslo City (Courtesy of Skanska)

and submerged in water up to 20 m deep. Three of these structures provide up to four levels of submerged parking (Fig. 7).

For all the concrete substructures, the owner and developer of the project required a service life of 300 years, which means that a highest possible durability and long-term performance of the given structures were required. For all the concrete substructures in the first four parts of the project, a durability design and concrete quality assurance according to the recommendations and guidelines from the Norwegian Association of Harbor Engineers were carried out. However, since any calculation of corrosion probability for a service period of up to 300 years was not considered valid, a probability of corrosion as low as possible and not exceeding 10% for a 150-year service period was specified, and in addition, some special protective measures were also required. Based on a number of durability analyses carried out, chloride diffusivity (D_{28}) of 2.0×10^{-12} m²/s in combination with a concrete cover of 100 mm were specified for the first concrete structure. For this structure, which was based on black steel reinforcement, provisions for future cathodic prevention in combination with embedded probes for future chloride control were also specified. For all the other concrete structures for which a replacement of the outer layer of the black steel reinforcement stainless steel was specified, the concrete cover was reduced to 85 mm, while the 28-day chloride diffusivity was kept the same.

6.5 Results and discussion

For a more complete durability design of concrete structures in severe environments, also other potential durability problems than chloride-induced corrosion must be properly considered and taken into account. The same is true for control of early-age cracking. Based on the above procedures for durability design and concrete quality assurance, however, the specified durability and the results obtained on achieved construction quality for all the above case structures are briefly summarized in Table 3. Since the risk for corrosion is primarily related to those parts of the structures which are located above water, the results from the structures in the “Sea spaced city development” in Table 3 only include these parts of the structures.

Table 3 Specified service periods and achieved construction quality based on corrosion probability (Gjørsv 2009)

Project	Specified service period (years)	Achieved construction quality (Corrosion probability %)		
		Compliance	In situ quality	Potential quality
“Container Terminal No.1” Oslo (2002)	100 years: Current concrete codes	-	After 100 years: Approx. 80%	After 100 years: Approx. 60%
“Container Terminal No.2” Oslo (2007)	100 years: Probability of corrosion \leq 10%	OK Approx. 2%	After 100 years: Approx. 0.05%	After 100 years: < 0,001%
“Sea Spaced City Development” Oslo (2010)	150 years: Probability of corrosion \leq 10%	OK 0.02- < 0.001% ¹⁾ Approx. 2% ²⁾	After 150 years: < 0,001% ¹⁾ < 0.001% ²⁾	After 150 years: < 0,001% ¹⁾ < 0,001% ²⁾

¹⁾ Stainless steel

²⁾ Black steel

Again it should be noted that the above procedures for durability design do not provide any basis for prediction or assessment of service life of the given structures. Beyond onset of corrosion, a very complex deteriorating process starts with many further critical stages before the final service life is reached. As soon as the first chlorides have reached embedded steel and corrosion starts, however, the owner of the structure has got a problem, which at an early stage only represents a maintenance and cost problem but later on may also gradually develop into a more difficult controllable safety problem. As a basis for the durability design, therefore, efforts should be made to obtain a best possible control of the chloride penetration during the initiation period before any corrosion starts. It is in this early stage of the deteriorating process that it is both technically easier and much cheaper to take necessary precautions and select proper protective measures for control of the further deteriorating process. Such control has also shown to be a very good strategy from a sustainability point of view (Gjørsv 2009).

Since the above calculations of corrosion probability are based on a number of assumptions and simplifications, it should also be noted that the obtained “service periods” with a corrosion probability of less than 10% should neither be considered as real service periods for the given structures. However, for all the case structures where the above procedures for durability design were applied, the durability analyses supported an engineering judgment of the most important parameters related to the durability, including their scatter and variability. Hence, a proper basis for comparing and selecting one of several technical solutions for achieving a best possible durability of the given structure in the given environment was obtained. As a result, durability requirements could be specified which were possible to verify and control for quality assurance during concrete construction.

For the reference project (“Container Terminal No. 1”), where the specified 100-year service life was only based on descriptive requirements to composition of concrete mixture and execution of concrete work, it was not possible to provide any documentation of compliance with the specified durability. However, based on the applied concrete which typically showed a 28-day chloride diffusivity of $6.0 \times 10^{-12} \text{ m}^2/\text{s}$ and the achieved concrete cover of 65 mm, it was possible to estimate a service period of about 30 years before the probability of corrosion would reach 10%. Also, after a service period of 100 years, the probability of corrosion would reach about 65%, while based on the achieved chloride diffusivities on the construction site and in the laboratory during a period of six months in combination with the site-data on concrete cover, corrosion probabilities of about 80 and 60%, respectively, would be reached.

For this particular concrete harbor structure, it should further be noted that during concrete construction, heavy winds and high tides occurred. As a result, a deep chloride ingress in several of the freshly cast deck beams took place before concrete construction of the harbor structure was completed (Fig. 8). Therefore, if the risk for early-age exposure before the concrete had gained sufficient maturity and density is high, special precautions or protective measures should also be applied.

Based on general experience, the above results on achieved construction quality for “Container Terminal No. 1” indicate that a relatively high level of operation costs would be expected for maintaining a proper long-term performance and serviceability of the given structure during the specified 100-year service life.

For “Container Terminal No. 2”, a 100-year service period with a probability for corrosion of less 10% was specified. Based on obtained average data for the 28-day chloride diffusivity of $7.9 \times 10^{-12} \text{ m}^2/\text{s}$ and concrete cover of 99 mm from the quality control, a probability for corrosion of about 2% after a 100-year service period was achieved. Thus, the specified durability was obtained

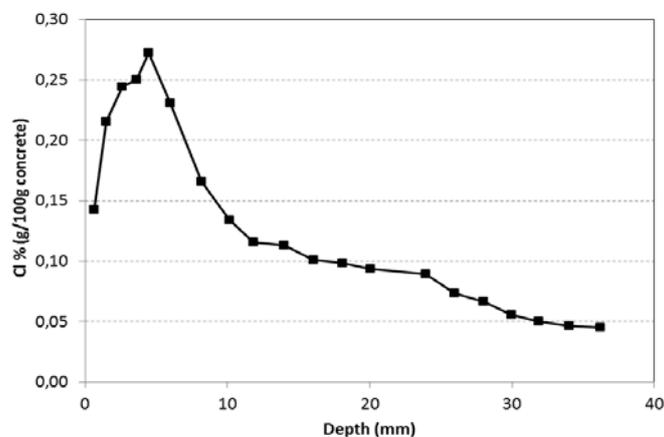


Fig. 8 Observed chloride ingress in one of the freshly cast deck beams before concrete construction of the harbor structure was completed (Gjrv 2002)

with a proper margin. Based on the obtained chloride diffusivity on the construction site and in the laboratory during one year, corrosion probabilities after a 100-year service period of about 0.05 and less than 0.001%, respectively, were achieved. These results indicate that both the achieved in situ quality during the construction period and the potential quality and durability of the structure were extremely good.

For all the concrete structures in the “Sea spaced city development” on Tjuvholmen for which the probability of corrosion should be as low as possible and not exceeding 10% during a 150-year service period, it can be seen from Table 3 that this specification was also obtained with a very good margin. Thus, for the first concrete structure which was only produced with black steel reinforcement, a probability of about 2% after a 150-year period was obtained, while for all the further concrete structures which were partly produced with stainless steel reinforcement, the corrosion probability typically varied from 0.02 to less than 0.001%. Based on both the obtained chloride diffusivities on the construction site and in the laboratory during one year, the probability for corrosion after a 150-year service period was typically less than 0.001% and hardly detectable. These results also indicate that both the achieved in situ quality during the construction period and the potential quality and durability of the structures were extremely good.

As an additional protective measure for the first concrete structure in the “Sea spaced city development” project, provisions for future installation of cathodic prevention in combination with embedded instrumentation for future chloride control were specified. For such a protective measure to be effective, however, the cathodic prevention system must be installed and activated before any chlorides have reached the embedded steel and corrosion starts. As a consequence, a very close control of the chloride ingress during operation of the structure must be carried out, which may represent a great challenge for the owner. Also for this particular structure, the achieved construction quality typically showed a high scatter and variability, while all probes for the future control of chloride ingress were only embedded in one particular location of the structure. Therefore, it soon became clear that a partial use of stainless steel would be a much simpler and more robust protective measure for all the further concrete structures in the first four parts of the project. For all these concrete structures, a partial use of stainless steel in the most exposed and vulnerable parts of the structures also proved to be an economically competitive

protective measure, even on a short-term basis. On a long-term basis, additional high expenses both for installation and operation of a cathodic prevention system are involved.

7. Conclusions

The durability of concrete structures is related not only to design and materials but also to construction. Many durability problems that develop after some time can be attributed to an absence of proper quality assurance and special problems during concrete construction. Therefore, construction quality and variability must be firmly grasped before a more controlled durability and service life of important concrete infrastructure can be reached.

For all the case structures where the above probability-based durability design and performance-based concrete quality assurance were applied, the specified durability was achieved with a proper margin. For the owners of the structures, it was very important to receive this documentation of compliance before the structures were formally handed over from the contractors. The required documentation of achieved construction quality also clarified the responsibility of the contractors for the quality of the construction process. The required documentation of achieved construction quality clearly resulted in improved workmanship.

Although the specified durability for all the above case structures was obtained with a proper margin, extensive experience demonstrates that for all concrete structures in chloride containing environments, a certain rate of chloride ingress will always take place during operation of the structures. Upon completion of each structure, therefore, it was also very important for the owner to receive a service manual for future condition assessment and preventive maintenance of the structure. It is such a service manual which helps provide the ultimate basis for achieving a more controlled durability and service life of the given concrete structure in the given environment.

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