Durability Design and Quality Assurance of Concrete Infrastructure

Performance-based programs boost service life

BY ODD E. GJØRV

The durability of concrete structures is related not only to design and materials but also to construction. Construction quality is highly variable, and in severe environments any deficiencies will soon be revealed. As long as prescriptive durability requirements are being specified, it's difficult to provide proper documentation of the achieved construction quality. A new strategy is needed to achieve increased, controlled durability. Enhanced durability and service life of concrete infrastructure are important from a technical and economical point of view, and can also directly affect sustainability.[1]

To a certain extent, a probability approach to durability design can take high variability into account. A numerical approach alone, however, is not sufficient to ensure durability. For concrete structures in severe environments, construction quality and variability are key to any rational approach to more controlled durability. Performance-based concrete quality assurance during construction—along with proper documentation—is essential.

Chloride-induced corrosion of embedded steel has been a major problem for concrete structures along the Norwegian coastline.[2] In 2004, however, probability-based durability design and performance-based concrete quality assurance of concrete structures were introduced in new recommendations and guidelines published by the Norwegian Association for Harbor Engineers.[3,4] Lessons learned from practical experience were incorporated into subsequent editions, the last of which was adopted by the Norwegian Chapter of PIANC, the international professional organization for maritime infrastructure.[5,6] Current experience with this durability design and quality assurance is briefly outlined and discussed; a more comprehensive review has recently been published.[7]

DURABILITY DESIGN

Probability-based durability design has been applied to a number of important concrete structures in many countries.[8-11] In Norway, such design was initially based on the DuraCrete guidelines.[12] Over the past 10 years, these guidelines and design procedures were further developed, but the basic principles essentially remained the same.

Durability analysis

The overall durability requirement is based on the specification of a given service period before a certain probability of corrosion is reached, and an upper level for this probability of 10% has been adopted. To calculate the probability for onset of corrosion, a durability analysis is carried out, which provides the basis for selecting a proper combination of concrete quality and cover thickness. The durability analysis, which is based on a simple model for the calculation of chloride penetration in combination with a Monte Carlo simulation,[13] requires the following input parameters:

- Environmental loading, including chloride load C_s and temperature T;
- Concrete quality, including chloride diffusivity D, time dependence of chloride diffusivity α, and critical chloride content C_{CR}; and
- Concrete cover X.

It should be noted that the chloride diffusivity of a given concrete is a very important parameter that reflects the general durability properties of the concrete. The procedures for determining the aforementioned parameters are described in Reference 7.

For important concrete infrastructure, it may be required to have a service life of 120 years before the probability of corrosion reaches 10%. The minimum durability requirements according to current concrete codes, however, must always be fulfilled. The following examples illustrate how the analysis works.

Effect of chloride diffusivity

Chloride diffusivity reflects the ability of concrete to resist chloride penetration. To select the chloride diffusivity for a new concrete harbor structure, for example, four concrete trial mixtures were produced and the chloride diffusivity was tested.[14] Apart from type of cementitious material, all of the concrete mixtures were identical and fulfilled the durability requirements of the existing concrete codes for a 100-year service life, including water-cementitious material ratio (*w/cm*) ≤ 0.40 and cementitious material content ≥ 360 kg/m^3 (600 lb/yd^3). The mixtures included four different types of commercial cements in combination with 10% silica fume by weight of cement (Concrete Types 1 to 4).

Based on the obtained 28-day chloride diffusivities and estimated values of the other input parameters for a severe marine environment, durability analyses were carried out for a nominal concrete cover of 70 mm (2.75 in.). Although all four concrete mixtures complied with the current code requirements, the service period before 10% probability of corrosion was reached differed significantly (Fig. 1), ranging from 25 years for the portland cement concrete to more than 120 years for the two slag cement concretes.

Effect of concrete cover

Additional durability analyses based on 90 and 120 mm (3.5 and 4.75 in.) concrete covers were carried out, while holding other input parameters constant. Figure 1 shows that increased concrete cover also had a significant effect on the probability of corrosion. While a nominal cover of 70 mm (2.75 in.) for portland cement concrete would give a service life of about 25 years, 90 and 120 mm (3.5 and 4.75 in.) covers would increase the service life to about 50 and 120 years, respectively.

It can be argued that increased cover thickness beyond about 90 mm (3.5 in.) would increase the risk for unacceptable crack widths. While this effect can be mitigated to some extent by incorporating synthetic fibers in the concrete, increased cover also has some secondary effects such as increasing the total dead load. An alternate solution is using stainless steel for the outer layer of reinforcement, effectively increasing the cover thickness to the remaining black steel. Durability analyses can quantify how much black steel needs to be replaced by stainless steel to meet the required safety level against corrosion.

PERFORMANCE-BASED CONCRETE QUALITY ASSURANCE

Even before concrete is placed, it can display a high variability. Depending on a number of factors during construction, the achieved quality of the placed concrete can show an even higher variability. In air-entrained concrete, large variations in air-void characteristics can also occur. This problem is exacerbated by the use of fly ash of varying carbon content, affecting both frost resistance and chloride diffusivity.

One of the most common quality problems in concrete construction is the failure to meet the specified cover thickness. Although cover thickness is normally carefully checked before placing the concrete, significant deviations can still occur. The loads imposed during concrete placement can deflect the reinforcing bars, or the chairs can be insufficiently or wrongly placed. Even for the offshore concrete platforms in the North Sea, where very high quality standards were required, most of the durability problems that developed in service can be attributed to problems that occurred during construction.[7,15] During some critical stages of the slip forming, for example, the chairs were occasionally removed, which resulted in zones with inadequate cover. To ensure performance, both the specified chloride diffusivity and the cover thickness must be properly controlled; this is achieved through ongoing verification.

Chloride diffusivity

Several methods exist to test chloride diffusivity.[7] Although all of these test methods give different values for the chloride diffusivity, they all show good correlation. The rapid chloride migration (RCM) method[11] can be used to test the chloride diffusivity independent of concrete age. In principle, the test method is based on an external electrical potential applied axially across the specimen, which forces external chloride ions to migrate into the specimen. After a certain test duration, the specimen is axially split and a silver nitrate solution is sprayed onto one of the freshly split sections. The chloride penetration depth can then be measured from the visible precipitation of white silver chloride, and this penetration depth provides the basis for calculating the chloride migration coefficient.

Although the RCM method is a rapid test method that provides data on the chloride diffusivity within a couple of days, this is not good enough for regular quality assurance during construction. Based on a calibration curve between the chloride diffusivity and the electrical resistivity of the given concrete, however, the chloride diffusivity can be indirectly controlled by a nondestructive test of the electrical resistivity. Such a calibration curve relating the two tests must be established before the construction starts (Fig. 2). Measurements of the electrical resistivity are then carried out as a quick check on the same concrete specimens as that being used for the regular control of the 28-day compressive strength. The measurements of the electrical resistivity can be carried out either by use of the two-electrode or the four-electrode method (Wenner).[16] Although the two-electrode method is a more well-defined and accurate method, both methods can be applied for simple and rapid control.[7]

Concrete cover

In severe environments, the concrete cover is normally very thick and the reinforcement is often highly congested, making it difficult to accurately measure cover thickness. The use of stainless steel reinforcement can further complicate the measurements, although cover meters based on pulse induction can be used. Manual readings of cover thickness on protruding bars in construction joints can, however, provide a sufficiently accurate basis for the quality assurance, but enough measurements must be taken to provide reliable statistical data.

ACHIEVED CONSTRUCTION QUALITY

After construction is completed, the quality assurance data are used as input parameters to new durability analyses for documenting the achieved construction quality. Because the specified chloride diffusivity is based on tests of small concrete specimens cured in the laboratory for 28 days, this chloride diffusivity may be quite different from that obtained on the construction site. Therefore, additional documentation on the achieved chloride diffusivity on the construction site must be provided. As neither the 28-day chloride diffusivity nor the achieved chloride diffusivity on the construction site reflects the potential chloride diffusivity of the given concrete, further documentation of the long-term diffusivity must also be provided.

Compliance with specified durability

A durability requirement based on a required service life with a probability of corrosion of less than 10% is specified. To show compliance with this requirement, a new durability analysis is carried out using the average values and standard deviations of the chloride diffusivity and the concrete cover obtained from the quality control. All other previously assumed input parameters are held constant for this analysis.

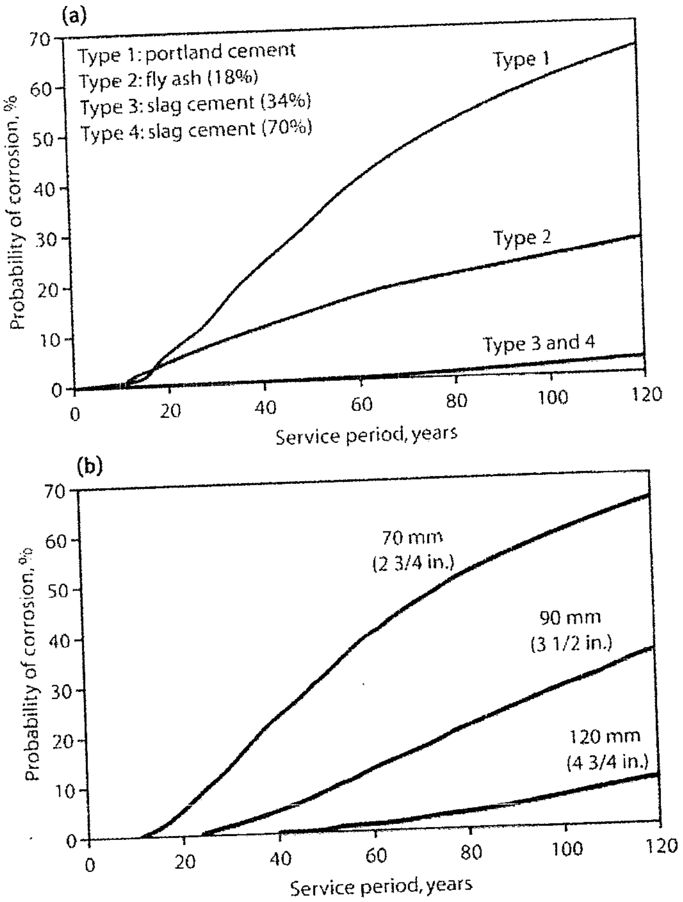


Fig. 1: Effects of cementitious material content and cover on the predicted probability of corrosion:[7] (a) mixtures evaluated with 70 mm (2.75 in.) cover; and (b) portland cement mixture (Type 1) evaluated with 70, 90, and 120 mm (2.75, 3.5, and 4.75 in.) covers

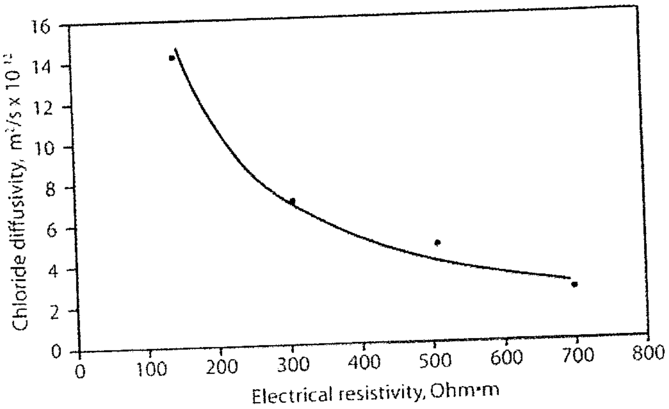


Fig. 2: Typical calibration curve for control of chloride diffusivity based on electrical resistivity measurements[7]

Durability on construction site

All measurements of the in-place chloride diffusivity should be based on tests of a number of cores taken from the real structure. To avoid weakening the structure too much, 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. Based on the achieved chloride diffusivity on the construction site after 1 year (Fig. 3), a new durability analysis is carried out, which is also based on the site data on cover thicknesses. This analysis provides the documentation of achieved durability on the construction site.

Potential durability

For most cementitious materials, the chloride diffusivity tends to remain constant after about 1 year of water curing. To estimate the potential durability of the structure, chloride diffusivity is determined on separately cast specimens cured in water in the laboratory for up to 1 year (Fig. 3). This chloride diffusivity is then used to predict the potential durability of the structure based on the same model, with the other input parameters held constant.

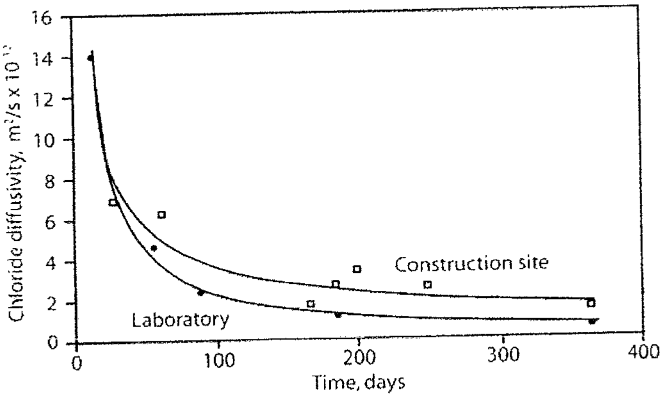


Fig. 3: Development of achieved chloride diffusivity on the construction site and in the laboratory[7]

CONDITION ASSESSMENT AND PREVENTIVE MAINTENANCE

Even if the strictest requirements have been specified and achieved, some chloride penetration will occur during the life of the structure. The owner should be provided with a service manual for regular condition assessment and preventive maintenance.[7] Based on data gathered from the observed chloride penetration of the structure, new durability analyses provide updated estimates of the probability of corrosion. Before the probability of corrosion becomes too high, appropriate protective measures should be implemented as part of the preventive maintenance scheme.

PRACTICAL APPLICATIONS

For many years, when concrete was mostly produced using pure portland cement and simple procedures, the concept of water-cement ratio (*w/c*) was the fundamental basis for both characterizing and specifying concrete quality. New cementitious materials, processed aggregate, new admixtures, and sophisticated production equipment, however, are increasingly affecting concrete properties. As a result, the simple terms *w/c* or *w/cm* have successively lost their meaning. As a consequence, performance-based specifications for concrete quality are greatly needed. In particular, this is true for characterizing and specifying concrete durability.

To obtain further information about the durability properties of the concrete typically being applied for new concrete construction in Norwegian marine environments, samples of the concrete from recent construction sites were collected to test the chloride diffusivity. In all of these cases, the basic durability requirements for a 100-year service life according to existing concrete codes included a *w/cm* ≤ 0.40 and a cementitious material content of ≥ 360 kg/m³

TABLE 1:
Chloride diffusivity of concrete in new construction in Norwegian marine environments[7]

	Chloride diffusivity (× 10⁻¹² m²/s)									
	Testing age, days									
Construction site	14	28	60	90	180	365	400	460	620	730
Container terminal 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 2, Oslo (2007)	14.0	6.9	4.6	2.4	1.2	0.7	—	—	—	0.7
New city development, Oslo (2005)	4.7	1.6	0.4	0.4	0.3	0.2	—	—	0.16	—

(607 lb/yd^3). Table 1 shows, however, that the chloride diffusivity of the various types of concrete varied widely.

For some of the structures, durability design and quality assurance were also carried out according to the recommendations of the Norwegian Association for Harbor Engineers.[4] As a reference project, a container terminal completed in 2002 is also briefly described. In this case, the specified durability was only based on existing codes and practice.

Container terminal 1, Oslo (2002)

This harbor structure was constructed in 2002, with an open concrete deck on driven steel tubes filled with concrete. At that time, the new recommendations for durability design were not available. The specifications for a 100-year service life were based on then-current codes: $w/cm \leq 0.40 \pm 0.03$; minimum cement content, 370 kg/m^3 (624 lb/yd^3); silica fume, 6 to 8% by weight of cement; air content, 5.0 ± 1.5%; and concrete cover, 75 ± 15 mm (3 ± 0.6 in.).

Although no probability-based durability design was carried out, Oslo Harbor Authority requested the best possible documentation of the achieved construction quality and durability. Quality assurance similar to that later recommended by the Norwegian Association for Harbor Engineers was carried out.

Container terminal 2, Oslo (2007)

From 2005 to 2007, a new container terminal in Oslo was constructed. This structure also consists of an open concrete deck on driven steel tubes filled with concrete. The code requirements for a 100-year service life included $w/cm \leq 0.40$, cementitious material content ≥ 330 kg/m^3 (556 lb/yd^3), and a minimum cover of 60 mm (2.4 in.). A total air content of 4 to 6% was also specified. As an overall durability requirement, specifications required a service period of at least 100 years before 10% probability of corrosion would be reached. As can be seen in Fig. 4, such a concrete structure has a lot of steel requiring proper protection.

New city development, Oslo (2005)

In 2005, a new city development project at Tjuvholmen in the harbor region of Oslo began. This project includes a number of concrete substructures in seawater with depths of up to 20 m (66 ft), on top of which a number of business and apartment buildings are being built (Fig. 5). Most of the concrete substructures include large submerged parking areas. In the shallower water, the structures include a solid concrete bottom slab on the sea bed, surrounded by concrete walls partly protected by riprap 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

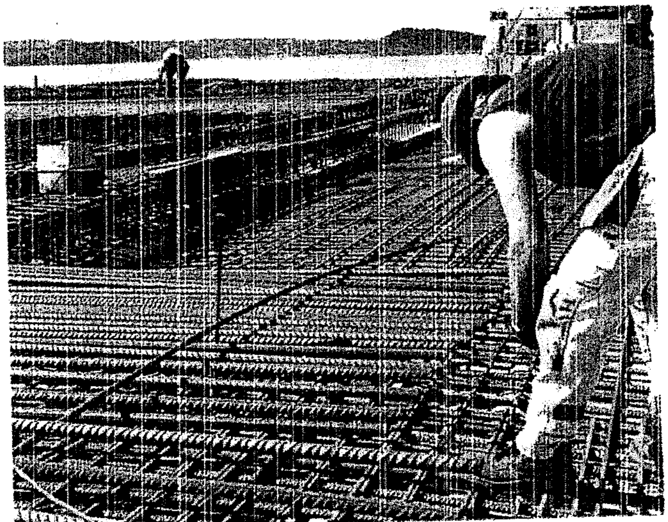


Fig. 4: Within the deck of a concrete harbor structure, there is a lot of steel that needs proper protection[7]

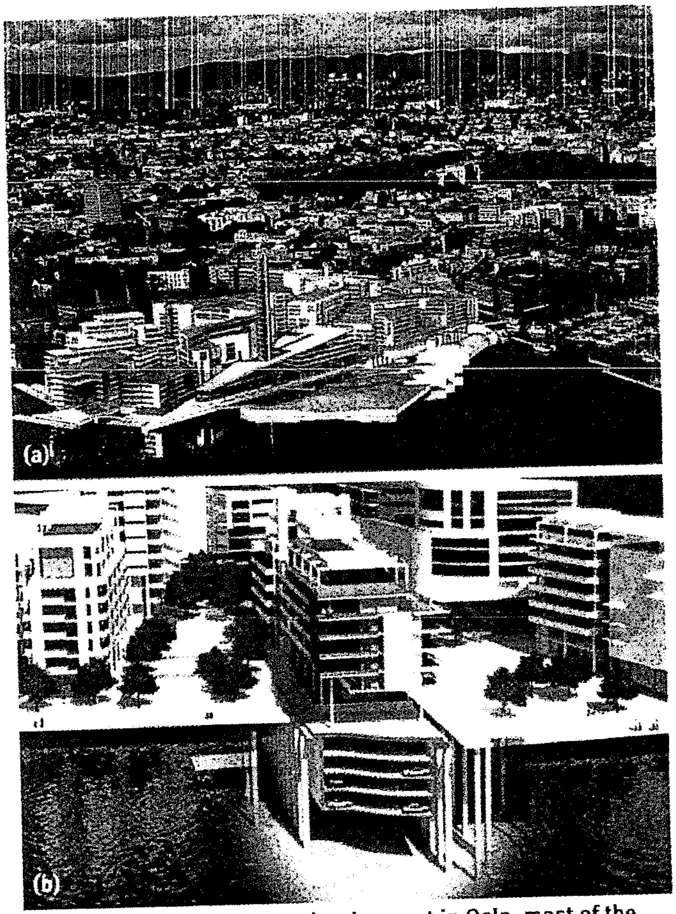


Fig. 5: In Tjuvholmen, a new development in Oslo, most of the concrete substructures were subjected to probability-based durability design and performance-based concrete quality assurance: (a) rendering of development (*rendering courtesy of Tjuvholmen KS*); and (b) detail and section showing how the prefabricated concrete caissons at Tjuvholmen provide four levels of submerged parking (*rendering courtesy of Skanska*)

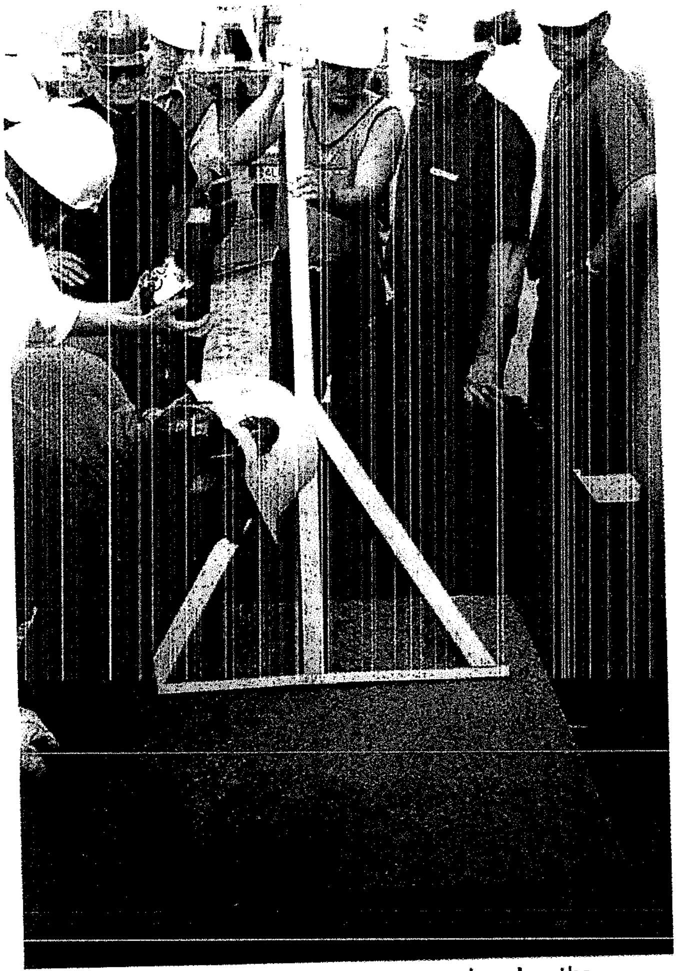


Fig. 6: Numerous dummy elements were produced on the construction site to provide an additional basis for documentation of achieved construction quality. The dummy elements were either slab- or wall-type elements[7]

the deepest water, four large concrete caissons were constructed in a dry dock, moved into position, and submerged in water up to 20 m (66 ft) deep. These structures provide four levels of submerged parking (Fig. 5).

The developer requested a service life of 300 years. A service life of more than 150 years is not valid, however, so durability analyses were carried out to minimize the probability of corrosion at 150 years. Further protective measures were also specified for the various structures, including embedded instrumentation for chloride monitoring in combination with provisions for future cathodic prevention and replacement of the black steel reinforcement with stainless steel in the outer layer of the most exposed parts of the structures. During construction, concrete cores taken from numerous dummy elements produced on the construction site provided an additional basis for documentation of achieved construction quality (Fig. 6).

Results and discussion

It should be noted that the current procedures for durability design do not provide a basis for the prediction of any service life. Beyond the onset of corrosion, a very complex deterioration process starts with many further critical stages before the final service life is reached. As soon as depassivation has taken place and corrosion starts, however, the owner has a problem, which in the beginning only represents a cost problem but later on also develops into more of a safety problem. Both from a technical and economical point of view, it's much easier to control the initiation period before the very complex electrochemical corrosion process starts.

A summary of the data from the structures is shown in Table 2. Clearly, the predicted service lives with a probability of corrosion of less than 10% should be considered as estimates only.[7] The durability analyses

TABLE 2:

SPECIFIED DURABILITY AND DATA ON ACHIEVED CONSTRUCTION QUALITY

Project	Specified durability	Probability of corrosion, based on 28-day control	Achieved durability, based on in-place data	Potential durability, based on laboratory-produced and cured specimens
Container terminal 1, Oslo (2002)	Current codes (100 years)	—	After 100 years: Approx. 80%	After 100 years: Approx. 60%
Container terminal 2, Oslo (2007)	After 100 years: Probability of steel corrosion ≤10%	Approx. 5%	After 100 years: Approx. 0.6%	After 100 years: Approx. 0.01%
New city development, Oslo (2005)	After 150 years: Probability of steel corrosion ≤10%	Approx. 0.1%[*] (Approx. 1 to 4%)[†]	After 150 years: Approx. 0.001%[*] (Approx. 0.7%)[†]	After 150 years: < 0.001%[*] (Approx. 0.1%)[†]

[*] Stainless steel

[†] Black steel

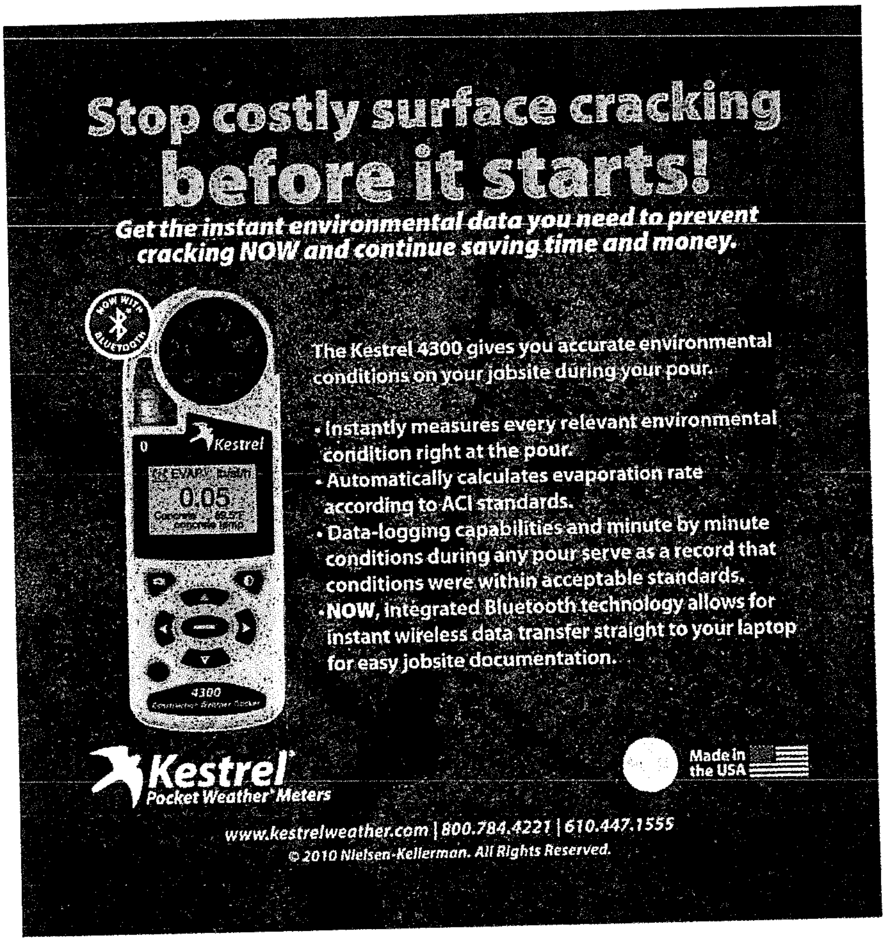
supported an engineering judgment of the most important characteristics related to the durability of the structures, however, including their variability. Hence, a proper basis for comparing and selecting one of several technical solutions to obtain a best possible durability of the various structures was obtained. It can be argued that the specified durability was only based on the 28-day chloride diffusivity of the concrete, while the chloride diffusivity of different types of cementitious material may develop very differently. Additional durability analyses based on values of the chloride diffusivity at later ages were also carried out, but none significantly changed the basis for comparison of the various types of concrete.

For the reference project Container terminal 1, which was based on the then-current codes and practice, a service life of about 30 years was obtained before the 10% probability of corrosion would be reached. This structure was produced with a concrete showing a 28-day chloride diffusivity of 6.0×10^{-12} m^2/s (Table 1) in combination with a nominal cover of 75 mm (3 in.). Based on the chloride diffusivity both from the construction site and the laboratory after about 6 months of water curing, probabilities of about 80% and 60%, respectively, for corrosion to occur after a 100-year service life were obtained.

For Container terminal 2, a 100-year service life was specified before 10% probability of corrosion would be reached. Accordingly, the design was based on a 28-day chloride diffusivity of 6.9×10^{-12} m^2/s (Table 1) in combination with a nominal cover of 90 mm (3.5 in.). Upon completion of this structure, a probability of corrosion of approximately 5% after a service period of 100 years was obtained, showing that the specified durability was achieved with a proper margin. Based on the chloride diffusivity from the construction site and the laboratory after 1 year of curing, probabilities of 0.6% and 0.01%, respectively, for corrosion after 100 years were obtained. These results indicate that both the achieved durability on the construction site and the potential durability of the structure were very good.

For most of the concrete structures in the new city development project that were produced with stainless steel reinforcement, a probability of corrosion of 0.1% after a service life of 150 years was typically obtained, showing that the specified durability was achieved with a very good margin. This result was obtained with a concrete typically showing a 28-day chloride diffusivity of 1.6×10^{-12} m^2/s (Table 1) and a nominal cover of 85 mm (3.3 in.). Based on typical chloride diffusivities from the construction site and the laboratory after 1 year, probabilities of less than 0.001% for corrosion to occur after a 150-year service period were obtained. These results indicate that both the achieved durability on the construction site and the potential durability of the structures were extremely good.

Table 2 shows that the use of ordinary steel bars in the first structure in the new city development project gave a probability of corrosion of 1 to 4% after 150 years. Upon completion of this first structure, it was concluded that a partial use of stainless steel would have given a much simpler and more robust protective measure compared to that of the embedded instrumentation for chloride monitoring in combination with preparation for future cathodic



prevention. The following concrete structures were constructed with some stainless steel, and this solution proved to be economically competitive, even on a short-term basis.

DOCUMENTED DURABILITY

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 can be reached.

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

Upon completion of the new concrete structures, it was also very important for the owners to receive a service manual for the future condition assessment and preventive maintenance of the structures. This service manual helps provide the ultimate basis for achieving a more controlled durability and service life of the structures.

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