Performance of Concrete in Aggressive Environments and the Feedback to Reliable New Performance Based Design

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ABSTRACT

We are all allowed to make a mistake. This is a human factor which we must recognise, and for which we are usually forgiven. Our limited ability to learn from the experience of others is an unfortunate weakness in the human nature and is a pity, and may be somewhat ridiculed. However, neglecting to take profit from our own experience, thus repeating our own mistakes, is not forgivable, this is merely stupid.

Such thoughts come to mind when viewing the past twenty years of experience with the performance of concrete structures in aggressive environments. The experience from the Arabian Gulf environment has provided a very valuable knowledge base for the structural and materials engineering community engaged in service life designs. Concrete is the only really important building material where the quality in the final structure is not known at the design stage but created during the first few hours and days of site execution. So inspection and testing, together with maintenance, constitute integral elements of a service life design which cost money, and the only one to pay is the Owner.

In conclusion, the Owner must specify the quality and service life he require, he must check that the quality of the materials and execution is satisfactory, and he must pay for that quality. His first difficult decision is to select the engineering support he needs.

We, meaning the Owners, the engineering profession, and society, should profit from recent years valuable experience - and not repeat our own mistakes. Realising that the Owner, through his decisions, has the dominating influence on the quality of the structure, as well as on its later performance, might be the most controversial issue in providing reliable performance based designs for the 21st Century - or for the next millennium.

KEYWORDS

Concrete deterioration; durability; environmental aggressivity; deterioration modelling; service life; performance; reliability; probability; design; experience.

INTRODUCTION

During the past few decades we have witnessed how differently various types of reinforced concrete structures can perform under the influence of various types of environment. Some structures seem to be very resistant to the environmental exposure whereas other similar structures in the same environment deteriorate at surprisingly short notice.

The experience from the Arabian Gulf environment with the at times very rapid deterioration caused by chloride induced reinforcement corrosion has provided a very valuable knowledge base for the structural and materials engineering community. The influence of the hot, humid and saline climate on the type, rate and structural effects of reinforcement corrosion has provided valuable information on which parameters govern the deterioration mechanisms. This particularly aggressive environment provides an acceleration factor for the deterioration which allows us engineers to see the effects of insufficiently designed, constructed or maintained structures just within a few years after completion.

Today we know the causes of premature deterioration, we can identify the aggressive elements in the environment, we can model the rate of deterioration thus make a prognosis of the service life of the structure, and we know which parameters we can adjust to make the structure last and serve as long as required, respecting the inherent variability of the governing parameters of concrete.

Concrete is the only really important building material where the quality in the final structure is not known at the design stage but created during the first few hours of site execution. The selection of concrete mix, the batching, the pouring, the compaction, and the curing have decisive influence on the ability of the concrete to resist the ingress of water and aggressive substance and on the type and rate of deterioration.

Therefore, quality assurance during execution, supplemented by inspection and testing of the existing structure to determine its true quality and its development with time become obvious elements of ensuring that the structure serves as required by the Owner.

This has two implications. Firstly, regular inspection and testing, together with identified needs for maintenance constitute an integral element of a service life design. Secondly, such initial actions needed to ensure long term quality together with the subsequent maintenance does cost money, and the only one to provide such money is the Owner.

Therefore, the Owner must specify the quality and service life he require, he must check that the quality of the materials and execution is satisfactory, and he must pay for that quality. The engineering profession is there to help and support the Owner in any way he requires to ensure he gets the specified quality. This includes, as an important part, to clarify and explain to the Owner the technical, the short and long term performance, and the economic consequences of the Owners alternative decisions. Only when the Owner has been made fully aware of the economic consequences can final design and execution decisions be taken.

To this end, the first decision of the Owner is to select the engineering support which possesses sufficient technical competence and experience to provide him with the quality he needs.

This is the conclusion coming out of the experience gained with the performance of concrete structures during these past decades, combined with the results of the newest research and development within concrete durability technology. We, meaning the Owners, the engineering profession, and society, should profit from this valuable experience - and not repeat our own previous mistakes.

We are all allowed to make a mistake. This is a human factor which we must recognise, and for which we usually are forgiven. Our limited ability to learn from the experience of others is an unfortunate weakness in the human nature and is a pity, and may be somewhat ridiculed. However, neglecting to take profit from our own experience, thus repeating our own mistakes, is not forgivable, this is merely stupid.

Such thoughts come to mind when viewing the past twenty years of experience with the performance of concrete structures in aggressive environments.

Realising that the Owner, through his decision, has the dominating influence on the quality of the structure he receives, as well as on its later performance, might for some be the most controversial issue in providing reliable performance based designs for the 21st Century - or for the next millennium.

DURABILITY TECHNOLOGY

To ensure long durability for concrete structures, the events which threat their durability must be identified. It must also be understood how the structures react to these events. This means that the aggressivity of the environment and the possible deterioration mechanisms should be known at the design stage.

Thus, the design of durable structures with a correct performance will have to concentrate on two parallel activities:

- Adequate resistance towards the foreseen external environmental actions.
- Satisfactory load carrying capacity and safety according to the foreseen loads.

To provide adequate resistance against aggressive environmental actions, it is necessary to understand how reinforced concrete structures deteriorate, to know how such deterioration is prevented or, at the least, to ensure sufficiently slow deterioration.

The key to provide durable structures is the availability of scientifically sound models of the deterioration mechanisms. Thereby, the criticality and the sensitivity of different parameters can be evaluated for the selection of optimal solutions which can provide the required durability and performance at acceptable costs. Profiting from such modelling is the red thread through the modern approach to design durable concrete structures.

Environmental Aggressivity

The problems with concrete structures are few, but if they arise the consequences are very serious and costly, as the past has shown. The main, by now very well-known problem is chloride induced reinforcement corrosion.

Originally, chlorides were mixed into the concrete by using severely chloride contaminated sand and water - if not sea water - and coarse aggregates. However, for quality designed structures, this problem was realised and dealt with already long ago, first in Bahrain, but soon the experience was spreading to the other Gulf countries.

The problems re-appeared, however. This time because the quality of the concrete mix, the compaction and the curing were inadequate. In the highly chloride contaminated atmosphere of the Gulf's coastal regions, combined with high temperatures and often very high moisture levels, chlorides from the outside quickly accumulated on the concrete surface, penetrated into the outer layers and reached the reinforcement. Corrosion was initiated.

The mediocre concrete often used was also exposed to carbonation at an early stage. The carbonation front penetrated towards the reinforcement and liberated chemically bound chlorides in the cover, thus increasing the corrosion risk from the available chlorides.

Especially for marine structures or other structures exposed to a combination of chlorides and sulphates, a further mishap was the adoption of sulphate resisting cements which have a very limited binding capacity of chlorides.

To define the aggressivity, in which the structure is to be placed, becomes an essential part of service life design. Unfortunately, to classify environmental aggressivity is the weakest link in the chain of decisions needed to provide long term durable structures. In particular, the identification of the micro-environment based on macro-environmental observations is lacking, and the direct interaction between the environment closest to the surface of the structure is the most important.

Currently European activities concentrate on establishing general applicable definitions which relate directly to the individual deterioration and transport mechanisms. Previously very simplified definitions were used, mainly based on the macro-environment, and independent of the deterioration mechanisms. The new approach relates more directly to the micro-environment and is more promising.

Deterioration of Concrete Structures

In practice, the number of really significant deterioration mechanisms is limited. There are only three important basic types of mechanisms:

- Electro-chemical reactions, being reinforcement corrosion
- Chemical reactions, such as alkali-aggregate reactions and sulphate reactions
- Physical deterioration, such as salt scaling, abrasion and impact.

Corrosion destroys primarily the reinforcement, and the two others destroy primarily the concrete.

Water and salt are among the most aggressive substances threatening the durability of concrete structures. In fact, no serious deterioration takes place without sufficient availability of moisture or water. Any attempts to reduce the moisture exposure of structures in the atmosphere will have beneficial effects on the service life.

The rate at which deterioration takes place is strongly influenced by the temperature. A simple rule of thumb says that an increase of ten degrees in temperature will double the rate of chemical and electro-chemical reactions. Hence, marine structures in hot environments, and structures exposed to de-icing salts during winters followed by hot moist summers are among the most seriously exposed concrete structures.

Nearly all deterioration mechanisms develop with time through two different phases:

The initiation phase, during which no noticeable weakening of the material or of the function of the structure occur, but some protective barriers are overcome by, e.g. carbonation, chloride penetration, or sulphate accumulation.

The propagation phase, during which active deterioration normally proceeds rapidly and in a number of cases at accelerating pace. Reinforcement corrosion is one important example of propagating deterioration.

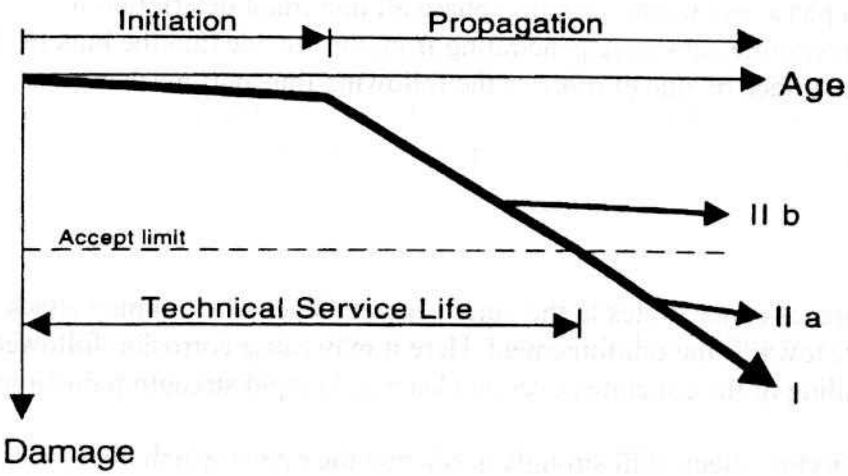

Figure 1: Technical service life is determined by the combined effect of overcoming some protective barrier during an initiation phase and an active deterioration during the following propagation phase.

Steel in concrete is effectively protected by the electro-chemical passivation caused by the alkalinity of the surrounding concrete. Reinforcement corrosion only occurs if depassivation has taken place. Carbonation of the concrete, ingress of chlorides, and leaching of lime can cause such depassivation. Hence these mechanisms may constitute an initiation phase, and the subsequent corrosion followed by cracking and spalling, etc. will constitute the propagation phase.

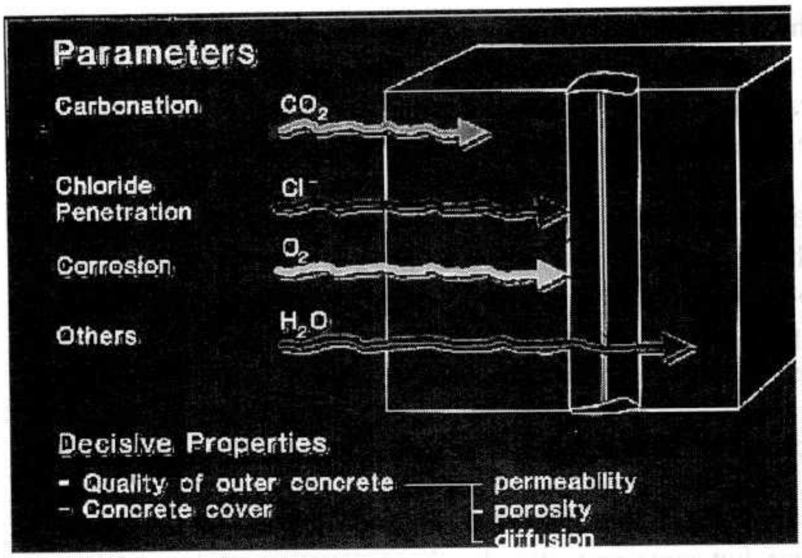

Figure 2: Transport mechanisms for aggressive substances govern the processes during both initiation and propagation phases. The most important quality parameters are therefore penetrability of the outer concrete and thickness of cover to reinforcement.

Transport Phenomena

In both the initiation phase and the propagation phase all important deterioration mechanisms depend on some substance penetrating from the outside into the bulk of the concrete through the surface by one or more of the following transport mechanisms:

- Capillary suction
- Permeation
- Diffusion

The aggressive substance concentrates in the outer concrete layer where it may attack the concrete or move towards the reinforcement. Here it may cause corrosion followed by cracking and spalling of the concrete cover and leading to rapid strength reductions.

Cyclic wetting and drying effects will strongly accelerate the rate at which dissolved aggressive substance enters the concrete and concentrates near the surface of evaporation. Similarly, with one wet surface and the opposite surface subjected to drying, a one way transport of water with dissolved substance from the wet to the drying surface will be created. This will result in an increase in the concentration of the dissolved substance, such as chlorides or sulphates, at the drying surface, due to evaporative effects.

All the transport mechanisms are non-linear by nature, except permeation when a steady state transport has been reached. This must be considered when the consequences of a given aggressive environment acting on a structure are evaluated. For example, the penetration depth of a carbonation front into concrete is nearly proportional to the square-root of the exposure time. Chloride and sulphate diffusion will have a similar non-linear rate of penetration. The consequences of this observation are important when the optimal concrete cover is selected.

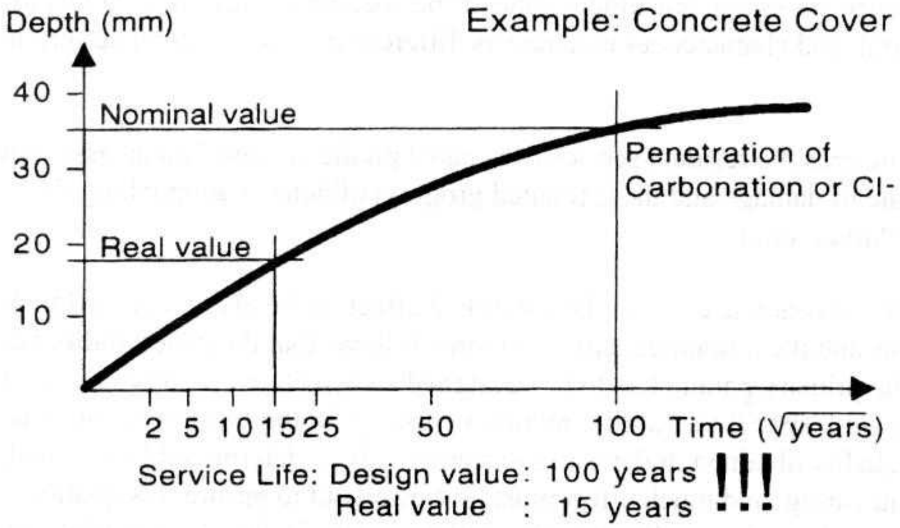

Figure 3: Nearly all transport mechanisms are non-linear related to time. The dominating influence of concrete cover is illustrated: halving the cover reduces the initiation period by 86 percent.

Cracks

Most modelling of transport mechanisms assumes the concrete to be homogeneous. Unfortunately, this is not the case due to local variations in compacting and curing, and in particular due to cracking.

Cracking is an often occurring feature, and load induced cracking is a natural feature in concrete sections loaded to tension. The reinforcement is introduced to compensate for this. Expansive forces due to ongoing deterioration may also lead to cracking of the concrete. This cracking may be internal or may reach the surface, and it may be oriented as single cracks or be formed as random map cracking. In all cases this will have considerable influence on the transport of substance into and within the concrete.

Cracking will open up the surface to early ingress of aggressive substance, which includes water, and the initiation period may be considerably reduced.

An example is when chloride contaminated water enters the concrete and causes early depassivation of the reinforcement. This must be considered when initiation periods in environments containing chloride are evaluated. The rate of corrosion will then be determined by the moisture level and the availability of oxygen, parameters which in practice can only be roughly estimated beforehand.

For carbonation, local depassivation of steel will occur earlier at cracks, and corrosion may begin. However, experience shows that such purely carbonation initiated corrosion at narrow cracks, say less than 0.3 mm at the súrface, will usually die out after some time due to self healing and re-passivation of the steel caused by clocking of the cracks with dust, rust and lime.

The inhomogeneity, including cracking, is one of the specific features of concrete as a structural material, and characterises concrete as different from many other structural materials.

For existing structures the residual service life can be predicted based on an assessment of the actual state of damage and the estimated progress of deterioration taking the above features into account.

The penetrability of concrete cover is the combined effect of the above outlined transport mechanisms and the inhomogeneity. From this follows that the penetrability becomes one of the primary parameters to be "designed" when concrete structures are tailored to comply with specific durability requirements, e.g. in the form of service life demands. The quality obtained in the actual structure will be determined by the quality of execution and curing, and much effort must be carried out to ensure this quality throughout the structure if durability must be achieved. This is also the part of the execution which is most in need of supervision.

Influence of Structural Form

The geometric form of exposed structures has considerable influence on the interaction between the concrete and the environment. Complexity in the structural form will usually increase the sensitivity of the structure to deterioration, shorten service life or require increased efforts in future maintenance. Configurations which lead to difficult execution, such as congested reinforcement, small dimensions and difficult access, increase the risks of inferior in situ quality. Such situations may eliminate all good intentions to specify high quality concrete, adequate covers, etc. at the design stage.

Close to out-going edges and corners aggressive substance can penetrate into the concrete from more than one side and lead to local concentrations. If the concrete or the reinforcement is prone to deterioration under the prevailing environment, corners and edges will lead to an early development of damage at the out-going corners and along the edges.

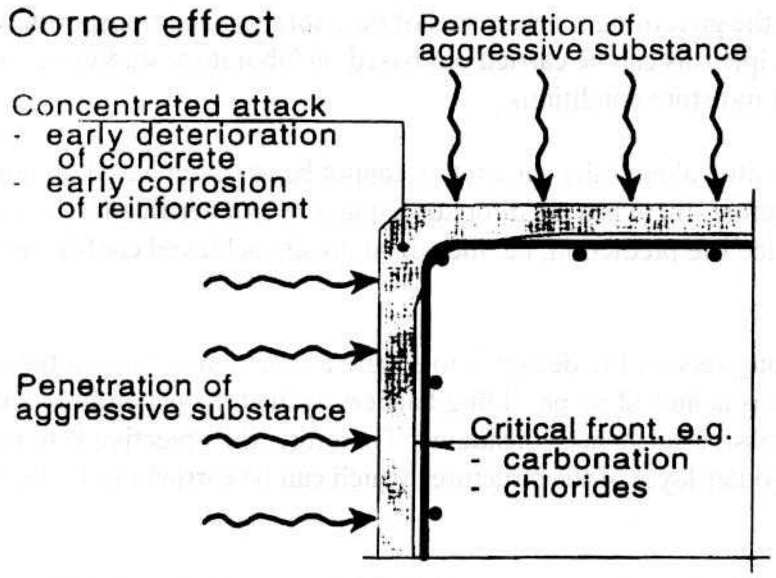

Figure 4: Aggressive substances tend to concentrate in the concrete at sharp outgoing edges and corners the so-called corner effect.

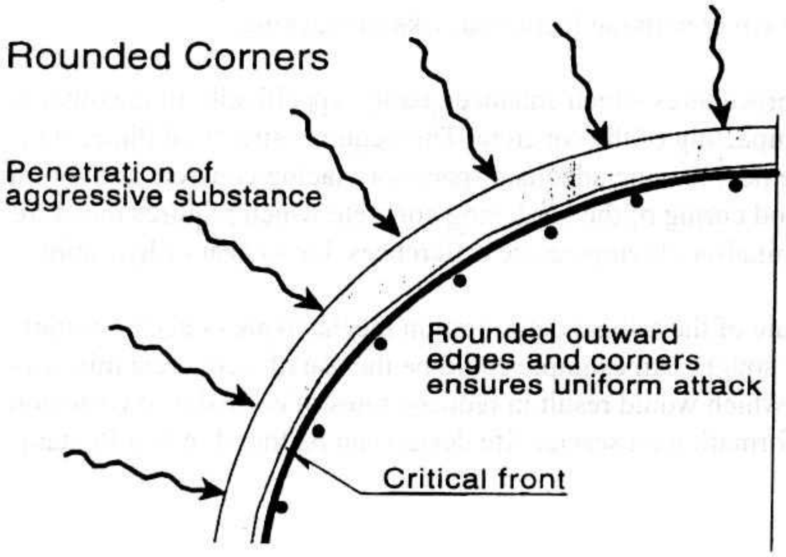

Figure 5: Rounded or polygonal out-going edges and corners distribute and reduce the attacks by aggressive substances in the corner areas.

PREDICTION OF SERVICE LIFE

Knowing the mechanisms of deterioration, their governing parameters, and the kinetics of the deterioration mechanisms, the parameters necessary to quantify the prediction of service life can be listed.

For existing structures the governing mechanisms of deterioration and transport have to be determined. In principle this can be carried out based on laboratory studies of similar materials under similar moisture conditions.

However, the actual in situ value of the parameters cannot be assessed based on laboratory studies only. Therefore, there is a need for subsequent in situ verification of the values used in the service life prediction, i.e. the actual on site achieved coefficients of transport.

The primary task for long service life design is to ensure a sufficiently long initiation period. In practice, this is achieved by providing barriers against the penetration and accumulation of the aggressive substance considered. Therefore, the objective is to provide a good protective outer layer of the structures which can be carried out by the following means:

- Selecting concrete quality, i.e. concrete mix, which provides low penetrability for the aggressive substance characterising the environment in question, e.g. low water-cement ratio, and high chemical resistance towards these substances, e.g pozzolanic additions.

- Selecting large concrete cover to the reinforcement, finding an optimum between the advantage of a larger cover with the increased risks of cracking.

- Ensuring execution procedures which enhance quality, specifically in the outer layers, such as good compacting of the concrete. This requires structural dimensions and detailing of reinforcement leaving adequate space for placing concrete and for introducing vibrators. Good curing of the hardening concrete which requires moisture control as well as limitation of temperature differences due to heat of hydration.

In addition, a reduced rate of the critical deterioration mechanisms - once they start propagating - should be sought. An example could be the use of a concrete mix with high electric resistivity which would result in reduced rates of corrosion if corrosion is initiated. Additional information on service life design can be found in and Rostam (1996).

DESIGN STRATEGY FOR THE NEXT CENTURY

For the service life design of new structures a pragmatic strategy has to be found based on the selection of measures to protect the structure against premature deterioration. A set of appropriate measures can be combined to ensure that the required service life is obtained with a sufficiently high probability.

The strategy is called "multi-stage protection", and leaves the selection of the individual protective measures to the designer. The different measures may act simultaneously in contributing to the protection, or one measure may be substituted by the next, once the former has been overcome, eliminated or surpassed by the aggressive substance.

Protective measures may be established by:

- the selected structural form;
- the concrete composition, including special additions or admixtures;
- the reinforcement detailing including concrete cover;
- a special skin concrete quality, including skin reinforcement;
- limiting or avoiding crack development and limiting crack widths, e.g. by prestressing;
- additional protective measures such as tanking, membranes or coatings, including coating of reinforcement and alternative reinforcement materials;
- specified inspection and maintenance procedures during in-service operation of the structure, including monitoring procedures;
- special active protective measures such as cathodic protection or monitoring by way of sensors.

A different level of reliability is associated with the protective effect of each type of measure. This level depends much upon the quality assurance scheme associated with establishing and maintaining each protective measure.

The required service life should in general be obtained without relying on special or additional protective measures such as coatings. However, in especially aggressive environments such additional measures may be foreseen, e.g. under cyclic wetting and drying of concrete exposed to saline waters in hot and humid environments, concrete decks exposed to regular de-icing salts, columns also exposed to salt water splash in marine environments or due to de-icing salts.

The choice of protective measures must be carefully considered in relation to the particular aggressive environment encountered. Possible secondary effects must also be considered such as the selection of epoxy coated reinforcement with individually coated bars, which will rule out the later use of cathodic protection. Another unfavourable secondary effect could be the increased rate of carbonation following treatment with water repellent impregnation.

Accessories such as drainage, joints bearings, railings, connections, installations, fixings etc. usually have a shorter service life than the structure itself, and adequate provisions for maintenance and replacement should be provided in the design.

It must be emphasised that design for a specific service life does not mean that the structure will perform satisfactorily during the whole service life without maintenance and repair. On the contrary, it is considered as an integral part of the service life design that some degree of inspection and maintenance has to be carried out.

In the following sections a number of the methods which a multi-barrier protection may consist of are described in more detail.

Non-corroding reinforcement

Among the different approaches to improve durability is the use of non-corroding reinforcement or the use of protective coating on the reinforcement.

There are two common types of non-corroding reinforcement:

- Fibres (carbon or glass)
- Stainless steel

The use of such alternative materials may add substantially to the cost of construction. When comparing the material cost of the alternative reinforcement with the material cost of black reinforcing steel this often results in the conclusion that the alternative material is several times more expensive than black reinforcement. However, a calculation of the life cycle costs may prove that the alternative reinforcement material is less expensive due to the absence of repair cost.

Use of alternative materials may e.g. be cost effective for the owner in severe aggressive areas as i.e. splash zones. This would imply that a replacement of the black steel with alternative material is made in a relatively small area only.

Fibres

Fibre Reinforced Plastic (FRP) materials used as reinforcing bars or tendons are composed of unidirectional fibres enclosed in a matrix material. The fibres are the main element for strength and stiffness, whereas the matrix material serves as a protection agent and distributes stresses between the individual fibres. The prevailing matrix materials are epoxy and polyester resins. At present three main fibre types are used for FRP products: glass, aramide and carbon fibres. Depending on the fibre type, the FRP products are labelled GFRP, AFRP or CFRP.

Rods of Fibre Reinforced Plastic, FRP, are made by pultruding the fibres through a resin such as epoxy, then through a special tool to give the rod the right cross-section and finally through an oven to harden the resin. A rod of carbon fibre can be stronger than the strongest steels known in construction, and weighs less than a fourth.

Carbon fibre, which for years have been used where their strength and low weight are required, are gradually finding their way into civil engineering construction. However, the fact that this material is very resistant to corrosion may very well prove to be an even stronger term than its phenomenal weight/ strength ratio.

Composite materials from carbon fibres embedded in a plastic matrix hold promise for the future, particularly if mass production can lead to a reduction of the prices.

In Christoffersen et al. (1998) an example of the use of reinforcement bars made of carbon fibres can be found.

Stainless steel reinforcement

Stainless steel is an iron based alloy. The main alloying element is chromium, and in addition to this nickel and molybdenum are added (other elements may also be used). By increasing the level of alloying element the corrosion resistance of the steel is increased.

The classification of the stainless steel is based on the crystal structure which is developed within the steel, due to the chemical composition and the thermal treatment. Within the area of concrete reinforcement only three types of stainless steels are available, these are classified as austenitic, ferritic and duplex (austenitic-ferritic) stainless steels.

The most commonly used stainless steel for reinforced concrete are austenitic stainless steels: AISI (The American Iron and Steel Institute) type 304 and 316. AISI 304 offers less corrosion resistance than AISI 316, and is not recommended to be used in aggressive environments.

The ferritic stainless steels are less corrosion resistant than the austinitic steels, and should therefore not be used in an aggressive environment.

Duplex stainless steel is the most corrosion resistant material, and as such can be used under the most extreme environments. But as increasing alloy content results in increasing cost of materials, it is important to select a steel type which is adequate for the application at the lowest cost.

Stainless steel and black steel can be used together, without problems related to galvanic corrosion, provided that the stainless steel reinforcement is in metallic contact with the black reinforcement. Information on the use of stainless steel as reinforcement can be found in Stainless Steel Reinforcement (1997) and Pedefferi (1998)

Cathodic Protection

Cathodic protection can be installed on new structures. The installation may be energised initially (cathodic prevention system) or the installation might just be there in anticipation of a future need for cathodic protection.

The aim a cathodic prevention system is either to stop chlorides from reaching the reinforcement, or if the chlorides have reached the reinforcement to stop the corrosion process.

Cathodic protection is a technique to protect the reinforcement from corrosion, obtained by passing an electric current from an anode through the surrounding electrolyte into the reinforcement, which then becomes the cathode.

The technique includes the following steps:

- Installation of anodes in the structure
- Installation of reinforcement connections
- Ensuring reinforcement continuity

The anode system is connected to the positive pole of a power source while the reinforcement is connected to the negative pole of the power source, see the principle in the figure below.

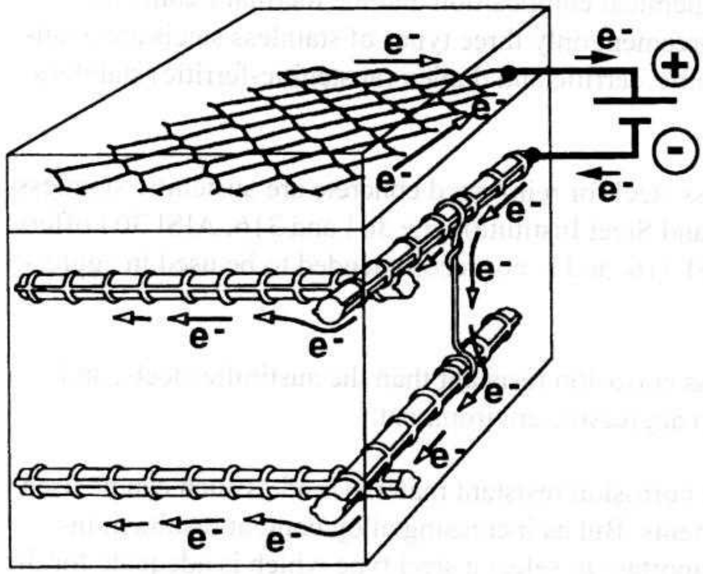

Figure 7: Principle of cathodic protection.

The direct current is supplied either from the local power supply through a transformer/rectifier (impressed current cathodic protection) or from a less noble metal (sacrificial anode cathodic protection).

The difference between the cathodic protection and prevention is the magnitude of the current density. In the case of cathodic protection the current is in the range 5-20 mA/m^2 steel surface, while in the case of cathodic prevention the current is below 5 mA/m^2 steel surface, see e.g. Berkeley and Panthmanaban (1990).

The current applied by cathodic prevention will polarise the steel reinforcement and the chloride ions are repelled. If the cathodic prevention installation is maintained properly, a long service life of the system is foreseen, extending the service life of the structure similarly.

Preparation of the structure for the future need of cathodic protection might be inappropriate, because the anode design and types may change over the next decade so that improved systems may be available by the time protection is required. Furthermore, if the corrosion is localised a local protection may be more cost effective. It is, however, always important that the continuity of the reinforcement is established at the construction stage.

Durability monitoring

The purpose of durability monitoring is to predict where or when there is a risk of reinforcement corrosion and to serve as basis for choosing the optimum time for maintenance and repair.

Durability monitoring can not replace the periodically inspection of the structures, but is a valuable supplement to this, especially at places which are not easy accessible, or where the consequences of corrosion might be substantial regarding safety and cost.

Reinforcement corrosion is one of the major causes of deterioration of our concrete structures. By supplementing the periodically inspections with durability monitoring, corrosion may be discovered or predicted before initiation, and the safety of the structures is therefore heightened and the maintenance and repair costs can be held at a reasonable low level.

By the durability monitoring a range of sensors such as corrosion cells are cast into the concrete structure in critical sections i.e. in construction joints, and where cracks are expected in the structure and where the exposure conditions are severe.

Current measurements are carried out using the corrosion cells which enables the prediction of the corrosion rate.

The number and location of monitoring sensors require an evaluation of the structure with respect to areas exposed to aggressive environment, areas where the consequences of corrosion are largest, and areas which are not easy accessible.

Design of a durability monitoring installation require specialist skills, as an incorrect location of the monitoring makes the monitoring worthless or could even give a false sense of security. The experience using corrosion monitoring dates back to the early 90'es, where the first sensors were installed, however a closer evaluation of results is still to be seen.

Example of multi-stage protection

A multi-stage protection strategy has been used on the Great Belt Link East Railway Tunnel. This example is also described in detail in COWI (1994).

The required design life of the tunnel is 100 years, and the durability of the lining in the submarine environment is an important consideration. The external environmental conditions along the tunnel with fairly permeable ground, high water pressures and a potentially aggressive environment as well as the internal environmental conditions with warm, humid, polluted air of varying pressure and velocity and possible spills, necessitated special measures against deterioration of the lining.

A multi-stage protection strategy was applied for the precast concrete lining segments, including the following elements:

- An annular grout with high binding capacity for chlorides and sulphates;
- Segments of very dense, high strength concrete with fully gasketted joint seals, ensuring a water tight lining;
- Epoxy coating of welded reinforcement cages;
- Possibility of future cathodic protection of welded reinforcement cages.

The annular grout is required to be of low permeability and capable of autogenous healing. The mix has a very low water/cement ratio of max. 0.35, and includes both flyash, micro silica and additives, aiming at an early strength and giving a high density and low permeability material.

A number of protective measures for the steel were considered. The concrete cover to the steel is a compromise between structural requirements and durability objectives, and 35 mm was eventually adopted. The bid documents provided for either external coatings to the segments or use of fusion-bonded epoxy coating to the reinforcement.

In the event, the reinforcement has been coated with epoxy which required the welded cages to be blast cleaned, heated to 260°C, dipped in the fluidized bed for 4 seconds, and then cured and stored. The cages emerged from the fluidized bed with a very even coating. So far as we know, the fluidized bed technique for epoxy coating has not been used before for three dimensional reinforcement cages.

The tunnel segments were monitored as well. Corrosion cells are placed in the segments.

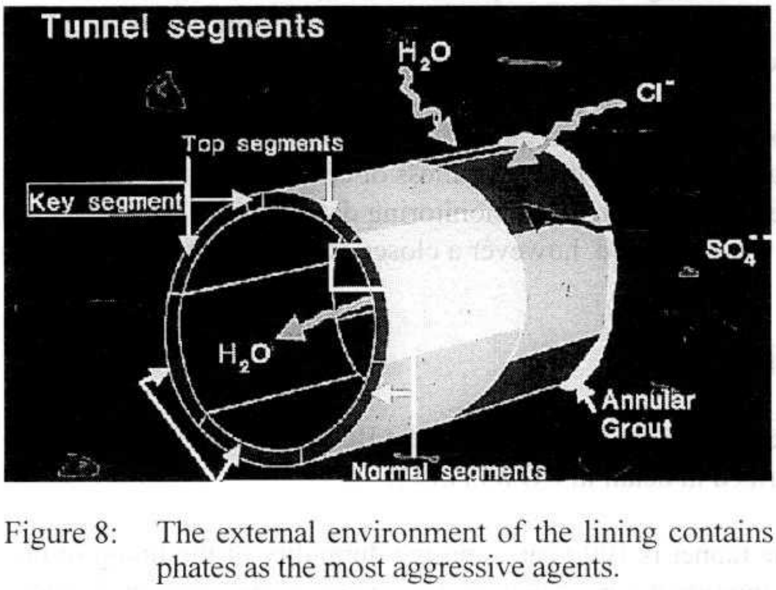

Figure 8: The external environment of the lining contains dissolved chlorides and sulphates as the most aggressive agents.

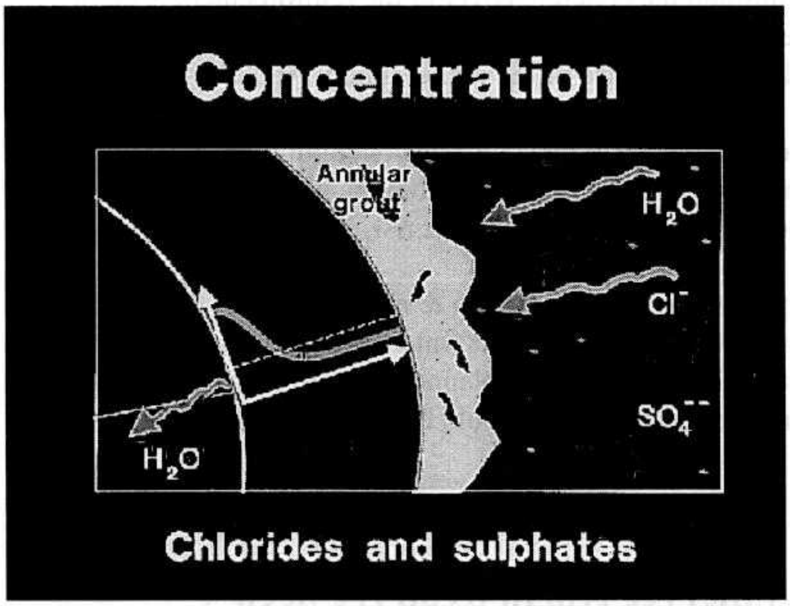

Figure 9: Details of the soil-lining interaction. The aggressive agents will accumulate near the inside of the lining due to evaporative effects.

Figure 10: Bored railway tunnel lined with precast concrete segments.

For the tunnel structure to meet a 100 year service life requirement, maintenance and repair must be expected to be an integral part of operation of the tunnel. In-tunnel maintenance and repair can be very costly as it will, in some cases, involve disruption of traffic operation. For this reason the planning of operation & maintenance efforts will to a large extent be based on the data collected from a corrosion monitoring system built into the segments at the construction time.

The buildt in corrosion cells will provide information on the durability performance of different sections of the tunnel and allow estimates to be produced on the remaining service life of the structures.

The rate of chloride ingress through the concrete cover to the reinforcement is monitored at outer as well as inner surfaces as both the external and internal environment potentially affect the durability performance of the tunnel lining. At depths between 0 and 30 m below the sea bed the outer surfaces are exposed to chloride concentrations equivalent to direct exposure to sea water.When chloride containing ground water with time has penetrated the segment and water evaporates from the inner surface back wards diffusion of chlorides will put the inner reinforcement at risk of corrosion.

The integration of monitoring in the general operation & maintenance of the structures ensures cost optimal planning of maintenance efforts. Interventions, possibly in the form of implementation of preventive measures, can be planned prior to active deterioration has occurred and before premature deterioration would even be possible to detect through traditional visual inspection.

DEVELOPMENT OF A GUIDELINE FOR DURABILITY DESIGN

Within recent years several models have been developed to predict the progress of various destructive mechanisms in concrete structures. Such models can be used to formulate a guideline for durability-based design of concrete structures. Such a guideline will be a major step forward in the design of concrete structures because it gives specific rules for design in contrast to current design methods which to a large extent are based on "deem-to-satisfy" rules.

A guideline for durability-based design can be developed within the so-called LRFD (Load and Resistance Factor Design) format. The same format as existing well-known codes like the Eurocodes. In the guideline the following will be given

- Design equations
- Representative values of material, geometry and environment factors
- Partial safety factors

Design equations can de developed/selected for durability-based design on the basis of experience gained from measurements on existing structures. The representative values of material and environment parameters can be determined on the basis of reported test results, results from existing structures and on the basis of compliance tests. Finally, the partial safety factors can be determined by code calibration. For more detailed information on the development of a design basis see e.g. Joint Committee on Structural Safety (1991).

The partial safety factors must be determined such that the structures designed according to the guideline has the same safety with respect to a number of events as structures which in the past have proved to behave satisfactory. The considered events can e.g. be initiation of corrosion, spalling, the width of corrosion induced cracks. etc. Naturally, the safety of a given structure with respect to these events can only be predicted if models of the occurrence of these events exist. More information on probabilistic analysis can e.g. be found in Madsen, Krenk and Lind (1986).

The guideline should also be developed such that partial safety factors can be selected depending on the planned quality assurance, inspection strategy and maintenance and repair. This, can be done on the basis of a detailed investigation of the most common methods and models of the accuracy and efficiency of these methods.

Consider for example chloride-induced corrosion. Corrosion is initiated if the chloride concentration around the reinforcement exceeds a critical threshold value. In this case the design equation can be written

$$g = c_{cr,d} - c_d\left(x_d, t\right)$$

where $c_{cr,d}$ is the design value of the critical chloride concentration and $c_d\left(x_d, t\right)$ is the design value of the chloride concentration as a function of time, *t*, and the design value of the cover thickness, x_d. If the value of the design equation at a given time is less than zero the design is not acceptable.

The chloride ingress will depend on a material parameter such as the chloride diffusion coefficient, *D*, the surface chloride concentration, c_s, as well as a number of additional factors describing the material, the environment and the execution. For all these variables a characteristic value and a partial safety factor must be determined.

For a given characteristic value and a given partial safety factor the design value is then given by for example

$$x_d = \frac{x_c}{\gamma_x}$$

where x_d and x_c are the design value and representative value of the cover thickness, respectively, and where γ_x is the partial safety factor associated with the cover thickness.

Using a methodology as outlined above a more homogenous level of safety with respect to events such as initiation of corrosion, cracking and spalling can be obtained. However, using such a guideline does not imply that less effort should be given to other factors connected with the design and construction process such as e.g. detailing, curing, etc. On the contrary, such a guideline can only be used if sufficient quality assurance is implemented in order to assure that the effect of factors connected to the design and construction process is minimised.

SUMMARY AND CONCLUSION

Within the last few decades experience from observations of degradation of concrete structures, especially in the aggressive environment in the Arabian Gulf environment, has lead to a better understanding and an increased awareness of the effects of destructive mechanisms. This experience has also provided a basis for the development of models describing the deterioration and the effect of an aggressive environment.

On the basis of an understanding of the deterioration mechanisms a number of different methods for design of new reliable structures in an aggressive environment have been developed.

Such methods can be combined into a strategy called "multi-stage protection". The multi-stage protection may involve a number of methods ranging from the selected structural form to advanced inspection and maintenance methods such as corrosion cells and cathodic protection.

Using economic models of the effect of the various methods, the designer of a given structure may determine the optimal design and maintenance scheme which minimises the costs of the owner. To provide a rational basis for such decision making and thus for a more reliable and cost-effective design and maintenance is the challenge facing the engineers in the coming decades.

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