SUMMARY

Durability Plans are now a common requirement for many Australian infrastructure projects. An asset owner’s focus is not only on capital costs but on minimising maintenance and avoiding operational disruptions.

For the construction of major transport, civil and water facilities many asset owners have recognised that dependence on construction Standards alone are unlikely to produce structures that will meet the anticipated service lives.

The design life of the major assets and asset components constructed of concrete is normally 100 years. In many cases carrying out durability assessment, design and planning is now an integral part of the project delivery.

INTRODUCTION

Durability Plans provide a framework for the design of assets and components so their service lives are realised. In formulating an effective plan the impact of micro and macro environmental loadings and the effects of certain destructive external agents on building materials are assessed.

Not surprisingly Durability Plans written specifically for Australian transport projects and major civil engineering works projects tend to focus on the performance of reinforced concrete. Predicting service lives through an understanding of the destructive deterioration mechanisms and the ability to use predictive modelling techniques is an essential competency in what is a “real life” commercial environment dominated by construction and engineering cynics.

DURABILITY PLAN FUNDAMENTALS

A Durability Plan provides a framework and guidelines so that the asset designers can select materials that will ensure that the required service lives are achieved. In many cases early-age acceptance criteria is used to predict service lives of the materials and components. These acceptance criteria are subsequently incorporated in the relevant contract specifications.
Nominated Design Life

Obviously this is critical in establishing durability performance. A commonly used definition of design life is “the period over which an asset must perform its intended function without replacement, refurbishment or significant maintenance”.

For reinforced concrete degradation resulting from carbonation or chloride induced corrosion of the reinforcement, the limit state design has been assumed to be cracking and spalling.

The Durability Assessment Process

The durability assessment process culminating in the selection of suitable materials and the protective surface treatment of asset components is shown in Figure 1.

![Figure 1. Steps in the Durability Assessment Process](image)

Although the steps are self-explanatory what is less obvious is what can be classified as a “potential destructive external agent”. Such agents include stray electrical currents, movement of aggressive substances along the concrete surface by a train’s airstream and physical abrasion. These are discussed in detail later on in this paper.

ENVIRONMENTAL LOADINGS

The aggressivity of the surrounding environment directly impacts on the durability of a structure and/or its components. There is nothing unique or special about the environmental loadings that are used to determine the service lives of Australian infrastructure. The environmental loadings result from exposure to rainfall, temperature, humidity and polluted atmospheres or contact with acid sulphate soils, contaminated soils and aggressive groundwater.

Soil and ground water testing requirements are shown in Table 1.
Table 1. Soil and Ground Water Testing Regimes

<table>
<thead>
<tr>
<th>Ground water testing regime:</th>
<th>Soil testing regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>pH</td>
</tr>
<tr>
<td>Sulphate content (mg/l)</td>
<td>Sulphate content (mg/l)</td>
</tr>
<tr>
<td>Chloride content (mg/l)</td>
<td>Chloride content (mg/l)</td>
</tr>
<tr>
<td>Magnesium content (mg/l)</td>
<td>Magnesium content (mg/l)</td>
</tr>
<tr>
<td>Calcium content (mg/l)</td>
<td>Calcium content (mg/l)</td>
</tr>
<tr>
<td>Carbonate and Bicarbonate content (mg/l)</td>
<td>Carbonate and Bicarbonate content (mg/l)</td>
</tr>
<tr>
<td>Total alkalinity as CaCO₃ (mg/L)</td>
<td>Total alkalinity as CaCO₃ (mg/L)</td>
</tr>
<tr>
<td>Dissolved Iron (mg/l)</td>
<td>Dissolved Iron (mg/l)</td>
</tr>
<tr>
<td>SRB Count (MPN/ml)</td>
<td>SRB Count (MPN/ml)</td>
</tr>
<tr>
<td>Water conductivity (μS/cm)</td>
<td>Water conductivity (μS/cm)</td>
</tr>
</tbody>
</table>

Revised Ambient Air Quality legislation has now become very effective in controlling the level of pollutants in the atmosphere. It is only in built up industrial areas that air testing would be undertaken and this occurs very infrequently. The presence of carbon dioxide in the air has the potential to cause concrete damage, more so in road tunnels, where the CO² concentration is likely to be higher.

**POTENTIAL DESTRUCTIVE EXTERNAL AGENTS**

**Stray electrical currents**

In the design of concrete structures for rail projects, corrosion of metals due to stray electrical currents is an important consideration. Methods to mitigate corrosion include the use of concrete with high resistivity or the use of electrical current drainage techniques. For many tunnels, the predominate structural element is made of reinforced steel fibre concrete and therefore special precautions are unnecessary.

**Movement of Aggressive Substances by the Train’s Airstream**

This is an issue for rail tunnels. Chloride ions are sucked through porous concrete in solution by wick action or carried by contaminated water that seeps through cracks, construction joints etc. The water is then moved along the surface of the tunnel lining by the air movement generated by trains. Once a sufficient concentration has accumulated, chlorides can back diffuse through the cover zone to initiate corrosion of the inner face reinforcement.

**Physical Abrasion**

Generally surface wearing and abrasion of building elements is unlikely to be a major concern for the structures made of grade 40 concrete (or higher grades). However it is still critical that all concrete elements are adequately cured as curing has a major impact on abrasion resistance.

**DETERIORATION MECHANISMS**

Deterioration mechanisms for concrete elements are summarised in Table 2.

These were the deterioration mechanisms used to identify potential durability issues that were addressed in Durability Reports. Not all of the mechanisms are discussed in this paper.
### Table 2. Concrete Deterioration Mechanisms

<table>
<thead>
<tr>
<th>Construction Material</th>
<th>Deterioration Mechanism</th>
<th>Factors Influencing the Rate of Deterioration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement</td>
<td>Chloride induced Corrosion</td>
<td>Environmental exposure – chlorides, CO2, RH etc</td>
</tr>
<tr>
<td></td>
<td>Carbonation induced corrosion</td>
<td>As placed concrete quality, particularly cover, compaction and curing</td>
</tr>
<tr>
<td></td>
<td>Localized corrosion at cracks and joints</td>
<td>Crack control</td>
</tr>
<tr>
<td></td>
<td>Thermal/Restraint and Shrinkage Cracking</td>
<td>Joint preparation</td>
</tr>
<tr>
<td></td>
<td>Stray Current Corrosion</td>
<td>Surface treatments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Orientation to the rail direction</td>
</tr>
<tr>
<td>Concrete matrix</td>
<td>Acid Sulphate Soils</td>
<td>Environmental characteristics – pH level, SO4 and magnesium concentration</td>
</tr>
<tr>
<td></td>
<td>Alkali-Aggregate Reactivity</td>
<td>Aggregate properties</td>
</tr>
<tr>
<td></td>
<td>Sulphate attack</td>
<td>Crack control</td>
</tr>
<tr>
<td></td>
<td>Acid attack from contaminated groundwater and soil</td>
<td>Concrete quality</td>
</tr>
<tr>
<td></td>
<td>Soft Water Attack (leaching)</td>
<td>Surface preparation</td>
</tr>
<tr>
<td></td>
<td>Delayed Ettringite Formation</td>
<td>Construction methods</td>
</tr>
<tr>
<td></td>
<td>Thermal/Restraint and Shrinkage Cracking</td>
<td>Concrete peak temperature</td>
</tr>
<tr>
<td></td>
<td>Microbiological Influenced Corrosion</td>
<td></td>
</tr>
<tr>
<td>Fiber reinforced</td>
<td>Most of the issues identified for “Concrete”. Generally corrosion of the fibres is not seen as a major problem.</td>
<td>As above</td>
</tr>
<tr>
<td>concrete</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### AUSTRALIAN CONCRETE DESIGN STANDARDS

Meeting the requirements set down in Australian Standards and in documents such as the NSW Road Maritime Services (RMS) Specifications and the Australian RailCorp Engineering Standards should result in the life expectations of a concrete asset being achieved. However in practice this is not always the case as the Standards are many in number, lack technical harmony and have conflicting specifications.

There are numerous Australian Standards which can be used as reference documents when preparing a Durability Plan. The most relevant ones being:

- AS 2159 Piling - Design and Installation
- AS 3600 Concrete Structures
- AS 4678 Earth - Retaining Structures
- AS 4997 Guidelines for the Design of Maritime Structures
- AS 5100.5, Bridge Design, part 5 - Concrete
- AS 3735 Concrete Structures for Retaining Liquids.

The Concrete Standards enigma is one of the restraints that make durability planning extremely difficult.

The Concrete Institute of Australia recognises current Standard’s short comings and is in the process of developing a “Durability Series” providing recommended practices for the achievement of concrete durability performance.
The durability requirements in Australian Standard are fragmented through different Standards and their Commentaries dealing with concrete durability requirements for different structures (e.g. AS 2159, AS 3735, AS 4997, AS 5100.5 and AS 3600). Perceived conflicts between these documents (e.g. higher covers in AS 3735 than in AS3600 for the same life and exposure) might sometimes be explained by different owner requirements (e.g. reliability required) but reasons for the difference are not given and the associated assessment methods not clearly stated. To some extent the concrete industries energy for continuing to development of durability codes is squandered through maintenance of the multitude of codes that cover the same topic in variable ways. (Frank Papworth, CIA Durability Committee Chairman).

What is even more amazing is not one of the Australian Concrete Standards differentiates between the performance of concretes made with different binder compositions. The very much “out of date”, AS 4997- Guidelines for the Design of Maritime Structures, provides Tables for minimum reinforcement cover where it is “expected” that a design life of 25 years will be achieved. The AS 4997 Standard, does concede, that the use of blended cements “may” improve the resistance to chloride penetration.

DURABILITY DESIGN OF CONCRETE ELEMENTS

Although all of the previously identified deterioration mechanisms need to be considered when preparing a Durability Report this paper only reports on the mechanisms that could cause major damage to concrete.

Chloride Ion Induced Reinforcement Corrosion

Chloride ingress into concrete is a major corrosion risk for the reinforcing steel in structures. Sources of chloride ions are sea water, brackish water, saline soils, and airborne particles. The majority of NSW Infrastructure projects experienced exposure to chlorides at one level or another.

The corrosion process is well documented. The time to corrosion initiation depending on the surface concentration of chlorides, pore water pH, depth of cover, chloride diffusion properties of the concrete and chloride binding characteristics of the cement or any supplementary cementing materials. Once initiated, the rate of corrosion will be controlled primarily by the moisture and oxygen permeability and concrete resistivity characteristics. The time to failure, as manifested by cracking or spalling of the cover concrete, depends on the physical properties of the reinforced concrete.

A very simplistic approach to predicting the time to corrosion was used assuming that the transport of chloride occurs is entirely by ionic diffusion. This is clearly not the case but has been accepted by many authors and durability modellers. In all cases diffusion was modelled using a solution to Fick’s Second Law of Diffusion (Equation 1).

It is recognised that the diffusion coefficient is “time dependent” (Equation 2) and this variation was based on modified data provided by ACI Life 365 and in DuraCrete – Final Technical Report, BE95 – 1347.

A time weighted average diffusion coefficient \( (D_{TWA}) \) was used, calculated assuming reduction of the diffusion coefficient over the first 30 years followed by a constant value thereafter. The time weighted diffusion coefficient was calculated according to Equation 3.
\begin{align}
    c_{x,t} &= c_s \left[ 1 - \text{erf} \left( \frac{x}{2 \sqrt{D_t}} \right) \right] \quad (1) \\
    D_t &= D_t \left( \frac{t_1}{t} \right)^m \quad (2) \\
    D_{TWA} &= \frac{\sum D_n I_i}{\sum I_i} \quad (3)
\end{align}

Where:
\begin{align*}
D &= \text{apparent diffusion coefficient of chloride (m}^2\text{/s)} \\
D_t &= \text{apparent diffusion coefficient at time t (m}^2\text{/s)} \\
D_{t1} &= \text{apparent diffusion coefficient at time of testing t1 (m}^2\text{/s)} \\
D_{TWA} &= \text{time weighted average diffusion coefficient (m}^2\text{/s)} \\
x &= \text{depth of chloride ion penetration} \\
c_x,t &= \text{chloride concentration at depth x and time t (%)} \\
c_s &= \text{surface chloride concentration (%)} \\
\text{erf} &= \text{numerical error function} \\
t &= \text{time (s)} \\
t_1 &= \text{time at test (s)} \\
t &= \text{time (s)} \\
m &= \text{age factor depending on mix proportions}
\end{align*}

The structural design typically called for 40MPa or 50MPa concrete grades with the required durability performance dictating binder composition and content. The durability modelling parameters of the concrete mixes are shown in Table 3.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
SCM & Aging Factor & Diffusion Coefficient & Diffusion Coefficient & TWA \\
    &               & Coefficient       &   56                       &      \\
    &               & Coefficient days &   m                         & TWA  \\
\hline
50MPa Fly ash & 25\% & 0.4 & $6.0 \times 10^{-12}$ m$^2$/sec & $2.5 \times 10^{-13}$ m$^2$/sec \\
50MPa Slag & 65\% & 0.57 & $2.0 \times 10^{-12}$ m$^2$/sec & $1.0 \times 10^{-13}$ m$^2$/sec \\
40MPa Fly ash & 25\% & 0.4 & $6.0 \times 10^{-12}$ m$^2$/sec & $6.0 \times 10^{-13}$ m$^2$/sec \\
40MPa Fly ash & 30\% & 0.44 & $6.0 \times 10^{-12}$ m$^2$/sec & $6.0 \times 10^{-13}$ m$^2$/sec \\
40MPa Slag & 65\% & 0.57 & $2.0 \times 10^{-12}$ m$^2$/sec & $3.1 \times 10^{-13}$ m$^2$/sec \\
\hline
\end{tabular}
\caption{Concrete Mix Durability Parameters Used in Durability Design}
\end{table}

In Australia, the commonly used chloride threshold level that initiates the breakdown of the passive film protecting reinforcement bars and signifying the end of the corrosion initiation phase is 0.06\% (for carbon steel). In predicting the total service life of the structure, the propagation phase (the time from initiation to unacceptable level of concrete cracking or delamination) is included. This is justified by accepting that high strength slag and fly ash concrete mixes have very high resistivity. An overall risk assessment determined the length of the propagation phase. The maximum period used was 20 years. In live prediction modelling the chloride concentration at the concrete surface influences the ultimate life of the structure. Typical values used are shown in Table 3.
When these values are imputed into the equations 1, 2 and 3 with the other parameters from Table 2, minimum reinforcement covers are determined as shown in Figure 2. These covers are increased by 5mm to 15mm to cater for steel fixing tolerances and ground conditions.

![Chloride Penetration - Slag and Fly Ash Concretes](image)

Figure 2. Minimum Reinforcement Cover for Various Chloride Exposures

It is also noted that the above predictions are deterministic and do not account for the inherent variability in concrete properties, depth of cover, etc. that occur in reality. A reliability approach (statistical probability) to chloride ingress prediction is really more appropriate but is seldom used.

Chloride ion induced corrosion of reinforcement can occur either by direct diffusion or through back “back diffusion”. The “back diffusion” of chlorides from saline groundwater or sea water is a major potential deterioration mechanism in tunnels and caverns where corrosion of the inner layer of reinforcement is acerbated ventilation systems or by drying air streams generated by train movement.
Like tunnels, desalination plants also have their own special problems. These include the impact of extended wetting and drying cycles. Each time the concrete pores dry out and then are re-filled with sea water (or brine) the chloride concentration front moves further towards the reinforcement. This movement is driven by sorption and/or hydrostatic pressure. During the drying out period, oxygen is readily available and once the protective passive layer at the reinforcement has been destroyed, corrosion will quickly occur. This situation is mostly likely to occur when the concrete filters, holding tanks, pump stations, tunnels etc. are emptied for prolong periods to carry out maintenance and at times when the plant is not fully operational or even mothballed.

**Acid Sulphate Soils (ASS)**

Acid sulphate soils exist on a number of the Pacific Highway reconstructions sites.

Acid sulphate soils are soils containing iron sulphides. In Australia, the acid sulphate soils of most concern are those which formed within the past 10,000 years, after the last major sea level rise. The sea water's chemical reaction with land sediments produced large quantities of iron sulphides in waterlogged ground. When exposed to air, these sulphides oxidise to produce sulphuric acid, hence the name acid sulphate soils. Acid Sulphate Soils are either classified as “actual acid sulphate soils” (AASS) or “potential acid sulphate soils” (PASS).

The presence of acid sulphate soils was found at relatively shadow depths on both the Ballina Bypass and the Kempsey Bypass construction sites. Various options were considered to determine the most efficient way of handling the potential acid attack. These included the use of special concrete mixes, applying protective coatings, sacrificial concrete layers or isolating the structures from the acidic ground waters.

For “high permeability soils” (ground water seepage greater than $10^{-5}$ m/sec) with pHs in the range of 3.5 to 4.5, concrete mixes containing large proportions of SCMs (30% fly ash or 65% slag) were used. In other areas where high permeability soils had a pH less than 3.5, isolations methods were used.

Relying on standard concrete pipes in an acid sulphate environment cause special problems if a 100 year service life was to be achieved. The major concern was acid attack to the exterior surface rather than the interior. Although epoxy coatings and PVC/polypropylene membranes were considered in the end we settled on the use of secondary drainage system (aggi pipes and increased bedding) to divert the any acidic water away from the concrete surfaces.

**Carbonation Induced Reinforcement Corrosion**

The corrosion of reinforcement bars due to carbonation of the surrounding concrete is a bigger issue in Australian than New Zealand. This is because of the regular use in concrete of Supplementary Cementitious Materials (SCM), primarily fly ash.

Carbonation of the concrete occurs gradually over the service life of structures when exposed to carbon dioxide. Carbon dioxide in the atmosphere or dissolved in water reacts with the calcium hydroxide in the concrete's matrix. When concrete becomes carbonated the pH is reduced to approximately 8.3. A carbonation front with a reduced pH will progress from the surface and ultimately break down the passive alkaline film that protects reinforcement, providing that there is sufficient water and oxygen present.

The rate of carbonation of concrete is dependent on many factors including CO$_2$ concentration, moisture content of the concrete and diffusivity of the hardened concrete matrix. The diffusivity in turn depends on the concrete mix, cementitious content, type and
content of SCMs used, water/cementitious binder ratio, extent of curing, pore size and pore distribution within the concrete, and connectivity of pores. The presence of cracks will permit local ingress of CO\(_2\) and could result in carbonation and subsequent corrosion ahead of the main carbonation front in sound concrete.

A commonly used relationship between carbonation depth and time is equation 4. This was the relationship used when carrying out the durability design for the sections of NSW motorways reconstruction.

\[
x = k \sqrt{t}
\]  

(4)

Where:
\(x\) = depth of carbonation
\(k\) = carbonation coefficient (mm/year\(^{0.5}\))
\(t\) = time (years)

Typical “\(k\)" values are shown in Table 5. These were based on an atmospheric CO\(_2\) concentration of 0.04% and a curing period of 7 days.

<table>
<thead>
<tr>
<th>Concrete Grade &amp; SCM</th>
<th>Carbonation Coefficient (mm/yr(^{0.5}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>S40, OPC</td>
<td>2.0</td>
</tr>
<tr>
<td>S40, 25% FA</td>
<td>5.0</td>
</tr>
<tr>
<td>S40, 65% BFS</td>
<td>7.0</td>
</tr>
<tr>
<td>S50, OPC</td>
<td>1.0</td>
</tr>
<tr>
<td>S50, 25% FA</td>
<td>3.0</td>
</tr>
<tr>
<td>S50, 65% BFS</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The ‘\(k\)’ values do not apply to tunnels where CO\(_2\) levels can be as high as 0.1%.

For the road bridges and other motorway structures the traditional concrete mix is a 40Mpa grade with a 25% fly ash binder content. As shown in Figure 3, the minimum cover to the reinforcement is 50mm (for a 100year life) to which a further 5mm to 15mm was added to cater for steel fixing tolerances and ground conditions. The total required cover exceed that specified in the Australian Bridge Standard AS5001.5 for a class B1 exposure zone.

For later projects, the fairly lengthy propagation phase was taken into account which meant that the Bridge Standard reinforcement covers were adequate.
Sulphate attack

Excluding soils classified as acid sulphate, the measured sulphate concentration in the soils and ground water was found to be relatively low (less than 4000 ppm). In this situation special concretes or protective coatings were considered unnecessary. In the occasions where the chemistry of the ground water indicated the presence of high magnesium ions, the exposure classification was upgraded and reinforcement cover increased accordingly. The one advantage of blended cements containing SCMs is that they are a sulphate resistant cement.

Leaching Due to Soft Water Contact

The softening of concrete surfaces due to soft water attack is a degradation mechanism that is not always fully understood and frequently overlooked.

Soft water has a low concentration of calcium ions and can leach free calcium hydroxide from the hardened cement paste and decalcification of the CSA in the cement. Generally this is only a problem when the water is mobile. Pozzolans (fly ash or amorphous silica) or slag will react with the calcium hydroxide in the concrete and in most situations reduce leaching attack. Two approaches were used to determine the possibility of leaching occurring and the severity of the attack.

These were:

- Determining the Langelier Saturation Index (LSI) - the difference between the pH of the groundwater and the pH of a solution, which has the same concentration of calcium ions as the groundwater.
- Using one of the numerous soft water/hard water programs that are found on the internet. These are provided by chemical suppliers attempting to sell products to swimming pool owners.

Table 6 provides a summary of LSI values and the relationship to risk of attack and treatment.
Table 6. Risk Assessment of Concrete Attack due to Mobile Soft Water

<table>
<thead>
<tr>
<th>LIS value</th>
<th>Description</th>
<th>Treatment Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 5</td>
<td>Severe corrosion likely</td>
<td>Protection or mitigation action recommended</td>
</tr>
<tr>
<td>- 2 to -3</td>
<td>Moderate corrosion</td>
<td>Protection or mitigation action may be required</td>
</tr>
<tr>
<td>- 1</td>
<td>Mild corrosion</td>
<td>Limited protection or mitigation action may be required</td>
</tr>
<tr>
<td>- 0.5</td>
<td>Corrosion unlikely</td>
<td>No treatment needed</td>
</tr>
<tr>
<td>&gt;0</td>
<td>Near Balanced</td>
<td>No action</td>
</tr>
</tbody>
</table>

One of the challenges in protecting rock bolts in tunnelling where soft water existed was overcome by using a 50Mpa grout with a high SCM content (30% fly ash and 5% silica fume).

**CONCLUSION**

In Australia, durability plans are becoming an integral part of the design and construction of civil engineering projects. They provide the framework for the design of assets and components so that their service lives, normally a 100 years, are realised. Purely meeting the requirements set down in Australian Standards will not necessarily ensure that service life of an asset's will be achieved.

Australian Concrete Standards specifying requirements for concrete structures are many in number, lack technical harmony and have conflicting specifications. The Concrete Institute of Australia recognises current Standard’s short comings and is in the process of developing a “Durability Series” that will provide recommended practices for the achievement of concrete durability performance.