BEST PRACTICE IN THE MANAGEMENT AND PROTECTION OF CONCRETE ASSETS

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ABSTRACT. While reinforced concrete construction has boomed over the last 60 years, critical analysis shows that along with major achievements, many civil engineering projects have failed to achieve the intended service life, due primarily to a lack of understanding about durability design, resulting in poor performance. Exposure to chloride ion continues to present industry with the greatest challenges. To the present day in Europe, industry has continued to tighten its durability performance criteria for reinforced concrete for normal exposure environments to account for chloride ion, driven by EN 206 and national durability recommendations. Yet increasingly, new infrastructure is being built in environments that are sufficiently hostile to be outside the scope and life expectation of national codes and standards. Examples include the Singapore Mass Rapid Transit System, the Bahrain-Qatar Causeway and the latest to open: the Hong Kong–Zhuhai–Macau bridge. To expedite designs, both within Europe and around the world, performance-related durability methods are being adopted, including predictive models for hostile exposure over an extended service life. But even then, a fundamental risk remains: whether what was intended, through the various cement and cover combinations, will be achieved in practice by the contractor's workforce and site practices. This paper explores the practical aspects of the durability of reinforced concrete, how the performance can be modelled and enhanced for extreme environments and how performance can be assured by effective corrosion monitoring and management strategies.

Keywords: Asset Management, Deterioration Modelling, Maintenance, Monitoring, Whole-life Costing, Cathodic Protection.

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INTRODUCTION

Over the past 60 years in Europe, reinforced concrete infrastructure has had a chequered history in terms of successful durability performance in service [1]. Early reinforced concrete structures were carefully designed, the construction was closely supervised, and mock-ups were used to prove the design concepts. The approach resulted in buildings like Weaver's flour mill surviving for 81 years, before becoming functionally obsolete [2], and civil engineering structures such as the Mulberry Harbour units, now over 70 years in seawater, not having any significant chloride ion ingress or reinforcement corrosion [3]. In those days, cement technology was in its infancy, with coarse-grained Portland cement used in much higher amounts than those considered today, which was needed just to develop high early strength.

The popularity of a material that behaves like a "liquid rock", contributed to increased reinforced concrete usage and ultimately to its premature deterioration [4]. Much of the UK's trunk road infrastructure was built between the 1950s and 1980s; this was a time when neither designers nor contractors had any real understanding of either durability design, or the risks posed by de-icing salts, or the importance of the 3-Cs of cement content, cover and curing. At this time, it was only the structural strength that governed the concrete mix design.

Concrete was used for increasingly ambitious and impressive structures, producing slender and delicate shapes and shells, with different patterns and colours. By using more finely ground cement, a higher early strength was achieved. Unfortunately, although this allowed the cement content and cost of the concrete to be reduced, industry began to realise that the new reinforced concrete buildings and bridges were susceptible to reinforcement corrosion. Absorption of carbon dioxide, which we know as carbonation, reduced the alkalinity of the concrete around the reinforcement, creating an environment that allowed steel corrosion to occur; this is prevented when the steel is in high pH media [5], as a passive film forms on the surface of the steel that prevents corrosion. Worse still, the presence of chloride ion overcame the protective qualities of the high pH and initiated pitting corrosion on the surface [6]. As well as chloride ion ingress from exposure to seawater and road de-icing salt, practice at the time was to add calcium chloride to concrete in winter to accelerate the setting process, without realising there would be an increased reinforcement corrosion risk in the set concrete.

The lesson that quickly had to be learned was that cement content, cement composition, water/cement (W/C) ratio, chloride ion content and cover all had to be considered from the perspective of reinforced concrete durability, as well as for structural strength, and that high standards of workmanship and good curing were vitally important. Annoyingly, these lessons were having to be re-learned, as many of these important properties of reinforced concrete had been known and advised upon from the early research of the 1920s [7]. In the early 1970s limits were then introduced in CP110 [8] based on environmental exposure, intended to improve durability by helping to combat the effects of carbonation and chloride ion on reinforcement corrosion risk.

Even today, industry is continuously improving its approach to durability under the known exposure environments. Recommendations for cement content and composition, W/C ratio, cover and minimum compressive strength have been tightened progressively as the severity of the prevailing exposure environments have been realised [1], as clients push for construction in ever more most hostile hot and salty exposure environments. In addition, designers must meet industry's demands for longer-lasting assets with possibly an "*indeterminate*" service life; this simply means that industry requires its assets to continue to perform until functionally obsolete, rather than having a fixed design service life of 50 or 100 years.

BUILDABILITY AND BUILD QUALITY

Today, few construction professionals will question the ability of well-built concrete buildings to perform over a normal service life when carbonation is the deterioration mechanism, provided construction is to an acceptable standard of quality, as the deterioration processes should be known. Yet failures continue to occur because of poor quality construction. As a result, the design service life or functionality is not achieved, leading to legal disputes and associated compensation claims.

Construction practice "issues" that commonly occur include: poor formwork alignment and sealing; low cover to the reinforcement; lower in-situ strength than specified; unstable mix design; and poor mixing, placing and compaction. These "issues" cause many and varied defects, affecting:

- appearance: from superficial bleed runs and blow-holes, grout loss from formwork, and unwanted colour differences affect the architectural quality;
- non-structural cracking: plastic shrinkage cracking, restraint to thermal or drying shrinkage movement, are sources of leakage and provide a path for the environment that leads directly to the reinforcement;
- durability: mix segregation with severe honeycombing and voidage, restricted flow through reinforcement, low cover, poor surface curing, result in less effective cover.

As a result, these "issues" can trigger a lack of confidence that the reinforcement will be adequately protected from corrosion over the design service life – not only affecting the parts of the structure that can be seen, but also raising concerns about those parts that are not visible.

In Europe, the "issues" have their root cause in industry design and practice [4]:

- structural designs and details, which require an impossibly difficult fit for the reinforcement within the formwork and the chosen mix (e.g. maximum aggregate size) and workability of the concrete;
- procurement by design and construct, an increasing trend where "value engineering" and cost saving compromises can impact on the durability of the design;
- lack of adequate training, where the most important people, the site operatives, are not told about the importance of their work and the attitude seems to be "*it is only concrete, so how difficult can it be to pour it?*";
- lack of experienced independent supervision, as on many projects the traditional "*Clerk of Works*" inspector and/or client's Engineer in a supervisory role is seen as an unnecessary extra expense (particularly in design and construct projects).

As an industry, it is arguable that we still do not pay adequate care and attention to the basics: concrete durability design, concrete mix formulation and training in the use of concrete. One or more of these three "basics" are usually the root cause of many building disputes, even for relatively benign exposure environments seen in building framing and warehousing, and that lead to unwanted cracking deterioration. If there is only one take-away recommendation from this paper, it is this: ultimately it is the placer of the concrete who is the most important person on the project if high quality concrete infrastructure is to be consistently produced [3].

THE CHLORIDE ION

The superposition of severe chloride exposure and buildability "issues" creates a substantial risk of premature deterioration, due to pitting corrosion on the reinforcement that leads to a rapid reduction in cross section and potential structural collapse if left unrepaired, particularly where stressed tendons are used in the design. The concrete durability specialist needs to become familiar with corrosion technologies to understand and appreciate the risks; Broomfield offers a good introduction to this important area [6].

The problems caused by one of the commonest ions on the planet, have cost the global economy countless billions of dollars for repair, unplanned maintenance and re-building of infrastructure. Yet when reinforced concrete was in its infancy, researchers knew about these risks: Loov cites two quotations from the 1920s that illustrate what we forgot in the 1950s to 1990s [7]: researchers warned "*Reinforced concrete is not a material that should be recklessly used*" and "*Do not bring reinforced concrete in contact with seawater*".

While the UK had general provisions for building construction, covered by CP110 [8], upgraded standards were provided for concrete in seawater and for concrete bridges exposed to de-icing salts. Perhaps as a result of longer experience with it, marine structures in seawater have generally performed well. As early as 1984, the recommended cover to reinforcement in the tidal/splash zone was 75mm, with a minimum cement content of 400 kg/m^3 and minimum W/C ratio of 0.45 [9]. As a result, many structures in seawater, including offshore oil platforms and piers, have lasted well; however, some have also failed prematurely. A good example of durable reinforced concrete is the Tongue Sands Fort and Mulberry Harbour units, built during 1939-1945, and made with Portland cement. The units have largely survived exposure in seawater for over 70-years, with little evidence of chloride penetration and reinforcement corrosion, due to high cover and cement content above 500kg/m^3 [10].

In Europe, heavily-loaded bridges are regularly exposed to de-icing salts and, as many papers testify, the post-WW2 roads programme led to considerable numbers of trunk road bridges being built between 1950 and 1990, including for the UK the Midlands' famous "Spaghetti Junction". However, many bridges failed to achieve the intended 120-year design service life set out in the standards of the time; in some cases, a life of only 20-years was achieved before major maintenance was required to address corrosion of reinforcement caused by the severity of de-icing salt exposure. This was despite precautions being taken, including construction being maintained to a high standard through on-site supervision, meaning buildability "issues" were minimised; most trunk road schemes had their own Resident Engineer and testing laboratory, reporting to the Highways Authority. Unfortunately, the designs had inadequate durability provisions against de-icing salts, as judged by today's standards, although they were based on the codes and standards of the time [11]; for the most severe exposure, Parts 4 & 8 of BS 5400 permitted C32/40 concrete at 50mm cover, and 330kg/m^3 cement content at 0.45 W/C ratio – significantly less stringent than the above recommendations for seawater exposure.

That is not to say that all bridges required major maintenance, as some bridge assets have performed well under chloride ion exposure, particularly post-tensioned bridges where higher strengths and cement contents were needed for structural purposes. However, the warning signs were appearing for reinforced concrete bridges and based on the findings, UK's Department for Transport changed its recommendations for concrete durability provisions: previously it had been thought that reinforced concrete needed no additional protection; by 1990, all highway bridge surfaces were being sealed with a waterproof bridge deck membrane, to prevent downwards penetration of saline water into the concrete deck, and concrete parapets and abutments were treated by hydrophobic impregnation to reduce the risk of chloride spray entering the surface. Despite these precautions, movement joints remained weak points that were prone to failure, particularly those above half-joints and support crossbeams, leading to corrosion in the reinforced concrete substructures [12], as illustrated in Figure 1.

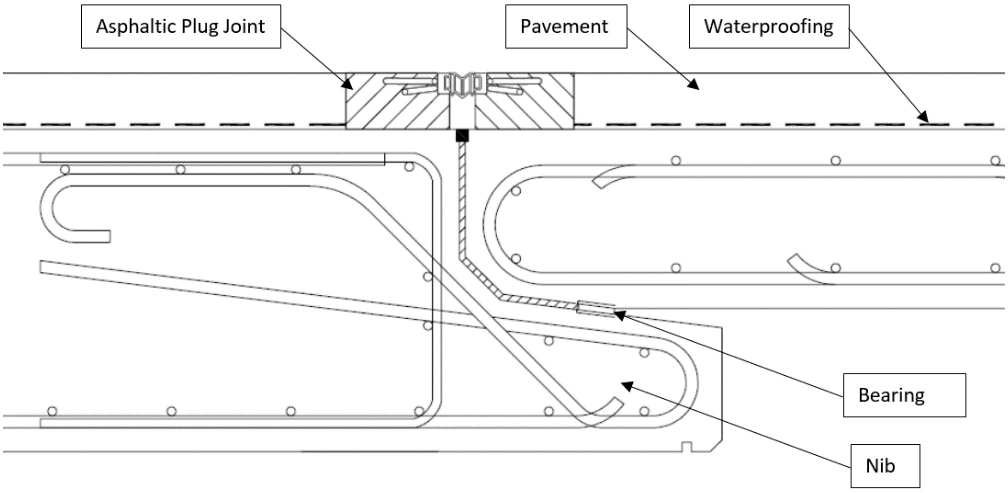

Figure 1 Section through Trent Valley Floodplain Viaduct Half-joint, built 1966 [12]

With the benefit of hindsight, the internal surfaces of the half-joint could have been protected with an impervious coating from construction, which would have counteracted any leakage of de-icing salts should the asphaltic plug joint fail. Now it has been built, the internal surfaces are be completely inaccessible, requiring very specialised measures to combat corrosion. Also, as was found on the Midland Links viaducts, the consequences of leakage through joints could be minimised by retrofitting gutters below the joint in the deck slab to catch escaping water that contained de-icing salt and so prevent it soaking into the support sub-structures.

Macro-environmental factors exacerbated the chloride ion problem, such as the "hollow leg" effect found in reinforced concrete tunnels and hollow offshore concrete structures such as oil and gas platforms. This occurs where water moves through concrete by capillary action or hydrostatic pressure, until the movement of dry air on the inside face causes evaporation of the water. At the point of evaporation, any salts contained in the water will be left behind, concentrating the salts at that inside face, as illustrated in Figure 2 below.

An example of the hollow leg effect causing accelerated chloride ion build-up at the evaporation point, is in a mass rapid transit system, such as the Hong Kong MTR that first opened in 1979. The concrete tunnel segments were found to have developed high levels of chloride ion build-up at the depth of the internal reinforcement after only 15 years. Learning from this evidence, it has been shown that even mildly brackish groundwater can be pulled through the reinforced concrete tunnel section. This mechanism drove one of the design approaches for the Copenhagen Metro, where various measures were considered to address ingress into the tunnel segments, including provision for cathodic protection, as discussed later in this paper. For other schemes in Singapore, where the local soils had high chloride ion contents, waterproofing additives in the concrete, waterproof surface coatings to the outside face, and other measures have been used [13, 14].

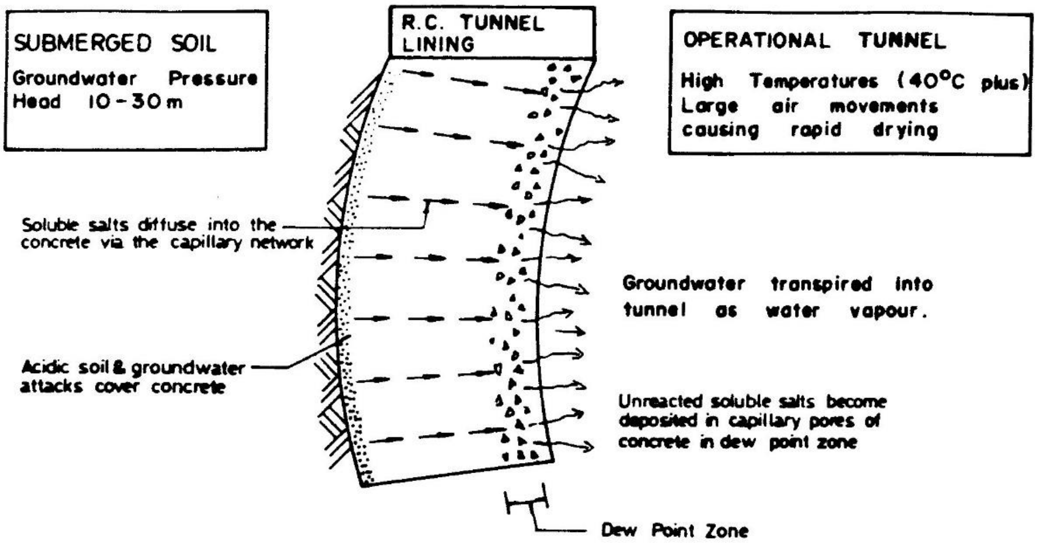

Figure 2 Penetration process for chloride ion through hollow structures [13]

THE CODE CATCH-UP

Table 1 Exposure Classes to BS 8500-1 [17]

CLASS	DESCRIPTION
X0	No risk of corrosion or attack
XC	Corrosion induced by carbonation
XD	Corrosion induced by chlorides other than from sea water
XS	Corrosion induced by chlorides from sea water
XF	Freeze-thaw attack
ACEC	Chemical attack from aggressive ground
XAS	Chemical attack from seawater

For new structures in Europe, the chloride ion attack risk has been managed by progressive tightening of European and national standards, particularly for concrete in bridges and in seawater. With advances in our understanding of reinforced concrete corrosion, the European cement standard BS EN 197-1 [15] now includes a wide range of cement compositions incorporating fly ash (FA), ground granulated blastfurnace slag (GGBS), silica fume and limestone fines (LF). Durability provisions require the designer to consider not only the structural load cases, but also the environmental exposure cases, based on six attack classifications, sub-divided into 18 exposure classes as found in BS EN 206 [16]. With CEN members being a diverse mix of northern nations such as Iceland and Finland, and warmer climes of Spain and Malta, BS EN 206 allows national standards bodies to establish requirements based on experience from where the concrete is to be used.

BS 8500-1 [17] gives recommendations for UK climatic conditions, including minimum cement content and cement type, minimum and nominal cover, maximum W/C ratio and minimum characteristic strength, including design measures to address attack from sulfate-bearing clays that can cause the thaumasite-form of sulfate attack [18], as summarised in Table 1.

BS 8500-2 also allows combination cements to be produced in the concrete mixer from blending Portland cement with FA, GGBS or LS [19], rather than just using pre-blended cements manufactured to BS EN 197 [15], as is the requirement to BS EN 206 [16].

Industry's incremental approach to the better management of chloride ion risk in extreme exposure conditions can best be illustrated by comparing the provisions in the UK's national standards over time. Table 2 is adapted from TR 70 [2] and shows the changes for seawater exposure for Class XS3, defined as *upper tidal, splash and spray zone*.

Table 2 Summary of reinforced concrete durability requirements for exposure class XS3 (seawater upper tidal, splash and spray zones) based on TR 70 [2]

CODE OF PRACTICE / BRITISH STANDARD	PORTLAND CEMENT / CEM I				BLASTFURNACE CEMENT/CEM III/A*			
	mcc (kg/m^3)	mwc	$f_{ck,cube}$ (MPa)	c_{nom} (mm)	mcc (kg/m^3)	mwc	$f_{ck,cube}$ (MPa)	c_{nom} (mm)
CP 110-1:1972	330	0.45	50	50	330	0.45	40	50
BS 6349-1:1984	400	0.42	40	50	400	0.42	40	50
BS 8110-1:1985	400	0.45	50	50	400	0.45	50	50
BS 8110-1:1997 [20]	400	0.45	50	50	400	0.45	50	50
BS 6349-1:2000	400	0.40	50	60	360	0.50	37	50
BS 8500-1:2002	360	0.40	50	60	360	0.40	45	50
BS 8500-1:2006 [21]	380	0.40	50	60	380	0.40	45	50
BS 6349-1-4:2013	360	0.35	50	90	380	0.35	50	55
BS 8500-1:2015	380	0.35	55	90	380	0.35	50	55

Assumes maximum aggregate size 20mm
XS3 is equivalent to exposure classes previously described as severe, very severe or extreme
* Assumes CEM III/A has GGBS content of at least 40%, representative of UK Portland blast-furnace cements 1925-1990
mcc = Minimum cement and ACM by mass equivalent to the definitions of EN 197-1 [15]
mwc = Maximum free W/C ratio
$f_{ck,cube}$ = Characteristic cube compressive strength
c_{nom} = Nominal cover, assuming required minimum cover plus an allowance of 10mm.

Table 2 shows that over the past 40 years, the recommendations in the latest versions of BS 6349-1-4 [22] and BS 8500-1 [17] have significantly tightened, even within the last 9 years:

- in 2006, BS 8500-1 [21] recommended 60mm nominal cover with a characteristic strength of C40/50 and W/C ratio 0.40.
- in 2015, BS 8500-1 [17] recommends 90mm nominal cover, with a characteristic strength of C45/55 and W/C ratio of 0.35.

If CEM IIIA is used, the current recommendations of BS 8500-1 are 55mm nominal cover with C40/50 concrete made with provided the GGBS content is at least 46%.

NON-CEMENTITIOUS ENHANCEMENTS

Various durability design enhancements have been proposed for reinforced concrete, including powder-epoxy resin coating of reinforcement, waterproofing admixtures, corrosion inhibitors and surface coatings, each having their own benefits and drawbacks.

- powder-epoxy coatings have proven performance under laboratory conditions, but when used with less care and attention on site, the coating can be chipped and rendered vulnerable. Also, when bent at site, the coated bars can split, as the Florida Keys failures demonstrated [23];
- hydrophobic admixtures have proven performance and are commonly specified for basements below the water table. The economics of treating all concrete (e.g. a base or caisson) when only the cover zone needs protection, can make the admixture expensive for large pours. Resistance to water under high hydrostatic pressure is limited, as indicated in Figure 3 using a 100m pressure head on a 50mm thick core sample.
- corrosion inhibitor calcium nitrite has been used in the USA since at least 1970 [24] and is recommended as a '*proven corrosion-inhibiting admixture*' for chloride conditions; research has shown that under-dosing can increase the severity of pitting corrosion [25]. Combination hydrophobic and inhibiting admixtures can be an effective strategy [14];
- surface coatings are the protection of last resort, as applying a coating means an enduring maintenance commitment at intervals of between 10 and 20 years, depending on the type of coating and the exposure environment [26, 27].

No single solution above provides the panacea for durable reinforced concrete, so a strategy is needed for hostile exposure, both at new build, and following deterioration in service.

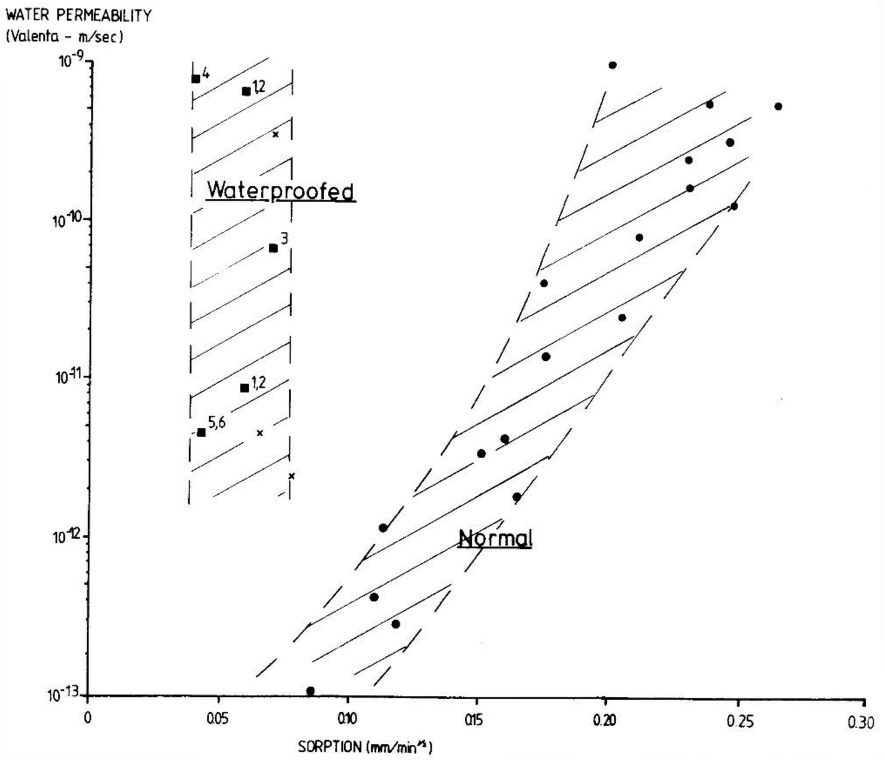

Figure 3 Relationship between Water Permeability and Sorption for 100mm diameter x 50mm thick core specimens subjected to 100m hydrostatic head [28]

STRATEGY FOR HOSTILE EXPOSURE AND INDEFINITE LIFE

By the mid-1990s, on new construction projects such as the Copenhagen Metro [29] and Singapore Metro extension [14], deterioration modelling for chloride ion exposure was being used routinely to predict corrosion risk for a service life of well over 100 years. Multi-barrier protection strategies have emerged that incorporate additional corrosion detection measures, supported by provision for impressed current cathodic protection (ICCP) should this be needed later in service. The latest landmark crossing to open is the record-breaking 35.6 km Hong Kong-Zhuhai-Macao Bridge (HZMB), a bridge and tunnel link across the Pearl River Estuary, which is the latest example of enhanced asset durability prediction in the prevailing hostile exposure conditions [30].

Durable construction in hostile environments and at new site locations (i.e. outside the scope and/or life estimates of national codes) requires performance-related methods that consider the locally-available materials and the effects of the local macro-environment. This has driven a four-step approach to durability assessment:

- pre-construction durability assessments and testing, using the locally available concreting materials and knowledge of what has worked;
- modelling the design service life based on accelerated testing, based on recognised durability models;
- installing monitoring probes within the cover zone to validate the durability modelling in service;

- preparing a quality assurance plan to ensure the reinforcement has the correct cover, and the concrete is mixed, placed, compacted and cured as intended by the durability design.

Several software packages are available for modelling durability, including Life-365 [31] and DuraCrete [32], based on electrically-accelerated chloride migration testing of trial mixes made using the local materials, using methods such as NT Build 492 [33]. A recent review of the different modelling approaches is given by Pillai [34].

The past 40 years of experience has taught industry not to build and forget assets, particularly where they are in extreme/hostile exposure environments. Assets must be actively monitored over the design service life. To do this effectively, a durability management plan is required for the assets that will allow changes in performance to be monitored and compared with the design service life modelling. Where the actual performance deviates from the predicted performance, such as where higher levels of chloride ion ingress are found in the cover zone, then proactive steps can be taken to address deficiencies, thereby helping owners to make informed finance-led decisions as to the best times and ways to intervene.

HZMB already incorporates sensors into the cover concrete to provide computer-aided structural health monitoring, an approach that has been used increasingly over the last 20 years. There is now an almost endless array of systems to assist, inform and assure asset operators about the continued fitness for purpose of their assets, as explained by Brownjohn [35]. Sensors can detect: load behaviour, such as defections, dynamic response, strain and inclination; environmental exposure, including wind speed, seismic effects, precipitation and temperature; and deterioration, such as the effect of sea salt, causing resistivity, half-cell and linear polarisation changes. Sensors built into the structure from the start offer much more certainty in terms of life prediction than here sensors are retrofitted afterwards in response to unexpected problems developing.

Where problems do develop, then a variety of measures can be taken to retard chloride ion migration, with the most common being surface protection systems (SPS) or ICCP.

Considerable advances have been made in the formulation and protective qualities of SPS for concrete structures. The three common generic types include:

- hydrophobic impregnation to produce a water-repellent surface, where the pores and capillaries are internally coated, but not filled, so no visible film is left on the surface of the concrete and there is little or no change in its appearance;
- impregnation with resin to reduce the surface porosity and to strengthen the surface, by partially or fully filling the pores and capillaries;
- coating with resin to produce a continuous protective film on the surface of concrete.

Coatings can be "designed" by the specifier to have a specific resistance to carbonation and chloride ion penetration. Tests are also available for in-service durability and crack-bridging performance, with a selection of criteria available through the certification route of BS EN 1504-2 [36]. However, as noted earlier, the chosen SPS will have a finite life and to maintain the intended protection, the SPS will need to be applied periodically.

For ICCP, provided it has been considered from the outset, then a simple system could be installed at construction that is energised to counteract chloride ion ingress, if this is expected. More commonly ICCP it is retrofitted: provided the reinforcing cage is continuous, then either a surface anode can be provided or, for structures buried in the ground or standing in seawater, external anodes can be installed that use the conductivity of the medium (i.e. the soil or water). ICCP design to BS EN 12,696 [37] allows a system to be configured either to prevent corrosion in new structures before it starts, commonly called *Cathodic Prevention*, or to stop corrosion when it has started doe to high levels of chloride ion ingress. ICCP works by the following three principles:

- developing a negative charge on the steel surface, which occurs as a direct result of the applied cathodic protection voltage, and which repels the negatively charged chloride ions away from the steel and attracts them to the positively-charged anode, typically located at the surface of the element receiving ICCP;
- the excess of energy at the steel surface establishes the cathodic reaction, and forms hydroxide ions;
- hydroxide is produced within pits at anode sites on the steel surface and neutralises the acid generated by the pitting corrosion reaction and as a result the pH around the bar increases, promoting restoration of a new passive film and stabilisation within the base of the pits.

Embedded reference electrodes are also installed at strategic locations to evaluate the performance of the anode systems and enable system adjustment to obtain optimum protection levels at the reinforcing bar surface, linked to a communication system that should include [3]:

- automated monitoring at scheduled intervals;
- remote adjustment of the system, based on the monitoring data;
- automatic reporting;
- alarm condition monitoring for the system and AC supply.

CONCLUDING REMARKS

This paper sets out some recent history about reinforced concrete usage in Europe and globally. It explores how codes have changed over the last 60 years, moving away from designing concrete structures based on strength alone, assuming the concrete cover would protect the steel indefinitely. Since the early 1980s, researchers, designers and standards bodies have been playing catch-up to offer an effective design for durability for the known climates, as well as offering performance assessment guidance for new site locations around the world.

Designers can now confidently design durable concrete buildings in normal environments, with adjustments to minimum cement contents, minimum cover, W/C ratio, as well as meeting the required structural strength. This is because globally the codes have been regularly updated to improve durability and provide robust design solutions that allow reinforced concrete to perform reliably in standard environments.

Preventing chloride-induced corrosion in hostile exposure conditions still poses a challenge, especially as most landmark structures have exposure conditions and life expectancies that are outside normal code provisions. Standard approaches include durability modelling, based on pre-construction assessments, using tools such as DuraCrete to provide assurance that the intended service life will be achieved. As necessary, increased assurance can be provided by electrochemical measures such as ICCP and SPS. Also, the construction must follow a quality assurance plan, to ensure the reinforcement has the correct cover, and the concrete is mixed, placed, compacted and cured as intended by trained operatives – arguably the most important people influencing the success of the project.

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