THE CORROSION AND PROTECTION OF REINFORCED CONCRETE

By Corrosion Management Staff

INTRODUCTION

In the 1970's and 1980's, serious problems started to manifest themselves in many reinforced concrete buildings after a relatively short service life. Poor workmanship, cost-cutting or just plain ignorance of good concrete practice were identified as major factors in these premature failures. Costly remediation was required on many of these structures and the concrete industry received a lot of bad publicity based around the theme of 'concrete cancer'.

This led to a review of industry standards and industry codes of practice within the concrete industry, to assist in raising the quality of concrete construction to a level that would provide acceptable durability.

In 1991, the Australian Concrete Repair Association ACRA) was formed to provide an information resource for those needing to deal with the ongoing problems of concrete deterioration and repair. Membership includes consulting companies, repair material, suppliers and contractors.

In conjunction with the Australasian Corrosion Association, ACRA conducts accredited courses on concrete corrosion and repair and this review covers a number of the key issues that are covered more comprehensively in the ACA/ACRA courses.

CONCRETE BASICS

Reinforced concrete is a composite material that relies on the high compressive strength of concrete and the high tensile strength of steel for its mechanical performance. Steel has poor corrosion resistance and concrete has excellent anti-corrosion properties.

Concrete is a mineral aggregate glued together by a cement paste and consists of cement, fine aggregate (sand), coarse aggregate and water. These are mixed in the typical proportions of 1 : 2: 2 : 0.5 (cement, fine aggregate, coarse aggregate and water)

Cement itself is a complex mixture of calcium, silicon, aluminium, iron, magnesium, sodium and potassium oxides. The calcining (heating in a kiln) process drives off all water and fuses these metal oxides into more complex oxide combinations (clinker). Additions such as gypsum (calcium sulfate) control the setting time of the cement.

The setting (or hydration) of cement occurs when water is added. In perfect proportion, about 25% by weight of water is required to fully hydrate cement. This is insufficient in practice as much of the water is captive in the pores of the cement and cannot migrate to where it is needed. For that reason, complete hydration is deemed to require 42% by weight of water – a water - cement ration of 0.42.

This additional water gives rise to pores in the concrete which can provide the major pathways for corrodents to enter the concrete mass. High water – cement ratios (over 0.50) will greatly increase the permeability of the concrete and subsequently reduce its durability.

A significant outcome of the hydration reaction is the formation of hydroxides, which raise the pH level of the cement to around pH 12.5 and provide an idea passive environment for the reinforcing steel.

The characteristics of aggregates used are also important in the performance of the cement. Australian Standards covering aggregate quality nominate factor such as particle size, shape, surface texture, elastic modulus, porosity, chemical reactivity with cement paste and levels of contamination is being important in aggregate performance.

Chloride contaminated aggregates (sea sand) and soil contaminated aggregates can severely degrade the concrete's performance.

This also applies to the water used in the mix. The use of unsuitable water may result in staining of the concrete or corrosion of the reinforcing bar if chlorides are introduced to the mix in the water.

Admixtures are also included to give the concrete specific properties such as rapid-cure, improved waterproofing and a number of other special characteristics. These are listed in detail in Australian Standard AS 1478.1.

WHY CONCRETE FAILS

Reinforced concrete failure is almost always caused by the corrosion of the steel reinforcing bars. This occurs because the passivating film provided to the steel by the highly alkaline cement is destabilized by oxidation or contact with aggressive agents transported to the concrete surface by the environment to which it is in contact.

Access of corrodents to the reinforcing steel is usually a function of cracking or permability.

All concrete cracks because it shrinks on curing or is stressed beyond its design capacity. Most concrete cracks are small and the presence of the reinforcing steel restrains the concrete to minimise the formation of wide cracks. Structural cracks will occur after the concrete has hardened and may be due to overloading.

Non-structural cracks arise irrespective of the load applied to the structure and are usually the result of poor installation or design. It has been suggested that cracks less than 0.5 mm wide do not present a problem in normal exposures.

Carbonation induced corrosion on road bridge deck beam

Permeability allows carbon dioxide and other acidic agents to move through the concrete surface and reduce its alkalinity to a level at which the reinforcing steel will become depassivated and start to rust.

Permeability is almost directly related to the water-cement ratio of the original mix. At water-cement ratios of 0.70, concrete is over 10 times more permeable that concrete batched at an 0.50 water – cement ratio.

A serious, but less common cause of concrete failure is through leaching where the concrete is permeable and exposed to very soft water. The soft water leaches free calcium hydroxide out of the hardened cement gel, and subsequent results in the removal of the calcium silicates, aluminates and ferrites.

This phenomenon is manifested by the appearance of white calcium deposits on the surface of the concrete and can take the form of stalactites. Leaching at this level usually only occurs in underground car parks and tunnels, but when it is evident, it indicates a serious depletion of the concrete's strength.

CORROSION MECHANISMS

Many studies have been done on the corrosion of reinforcing bar in concrete. All corrosion is caused by electrochemical reaction. This requires an anode, a cathode and an electrolyte. All these things are present in reinforced concrete.

In most cases, reinforcing bar is used without any protective coating and relies on the passivation of its surface by the highly alkaline cement.

Unlike atmospheric corrosion of steel, which tends to be relative uniform over the surface, the corrosion of reinforcing bar can be highly localised and small areas become depassivated and become small anodic areas influenced by large cathodic areas of adjacent passivated bars.

The presence of chlorides will result in the steel surface becoming depassivated at pH levels as high as pH 11.

IDENTIFYING THE PROBLEMS

Traumatic failure of concrete structures is very rare. Failures are usually signaled well in advance with visual warnings of deterioration. These will include:

1. Spalling
2. Cracking
3. Rust staining
4. Fretting (weathering)
5. Dampness
6. Efflorescence.

Very simple testing systems such as the use of a hammer or a chain drag can be used to detect delamination in horizontal structures such as bridge decks. A device called a Schmidt Hammer has been developed by the concrete inspection industry that works on a rebound system to determine the soundness of the concrete.

Instruments are available that can measure the depth of cover over the reinforcing bar. These covermeters can highlight potential problem areas.

Electrochemical methods (half-cell potential surveys) are one method of determining if corrosion currents exist in the embedded reinforcing bar. There is some reservations about the validity of this method in some types of concrete structures, although it is used in the USA to determine the condition of bridge decks subject to de-icing salts application in winter.

Other techniques such as linear polarisation resistance and resistivity of the concrete can be used, along with the measurement of depth of carbonation, in environments where other factors do not need to be considered.

REPAIR METHODS

While this review is not intended to deal with repair methods, the techniques used are well established by ACRA members and cover the following:

1. Crack repair
2. Patching and patching materials
3. Use of inhibitors
4. Recasting with new concrete
5. Shotcreting

For major structures, cathodic protection systems offer a high level of long-term protection. Cathodic protection is simply the application of a current to the reinforcing steel to override the corrosion currents.

This can be done using anodes or impressed current from a power source. Cathodic protection systems are best designed into the structure and their design and installation is a specialised area that requires a high level of technical expertise.

Cathodic protection technology can be used to desalinate chloride-contaminated concrete and re-alkalise concrete that has been affected by carbonation that has reduced the pH.

Major high-risk structures such as underwater tunnels and oil platform structures use cathodic protection systems to ensure their durability.

PREVENTING PROBLEMS IN THE FIRST PLACE

The best place to deal with concrete durability is at the design and construction stage where new concrete is being placed.

Concrete mix design will specify the relative amounts of cement, coarse aggregate, sand (fine aggregate), water and admixtures. The resultant concrete mix must have the following properties:

1. The wet concrete must be sufficiently workable to allow it to fill the forms and penetrate gaps between reinforcing steel and make 100% contact with the reinforcing steel.
2. The cured concrete must have the required design strength.
3. The cured concrete must be as free of cracks as possible.
4. The cured concrete must be impermeable to the environment to which it is exposed.

There are a number of Australian Standards that define requirements for concrete quality, including the Slump Test (AS 1012.3.1:1998) that indicates the shape of the aggregate use and more importantly, the amount of water in the mix.

The compressive strength of the cured concrete is the most commonly measured property of a concrete mix. Testing procedures for this property are defined in AS 1012.9:1990.

Chloride induced rebar corrosion on bridge column.

Two of the major factors affecting concrete strength and durability are the water-cement ratio of the mix and the level of compaction during installation. Poor compaction can reduce concrete performance by the same degree as a high water-cement ration. If both are combined in the same mix, the durability of the concrete will be severely compromised.

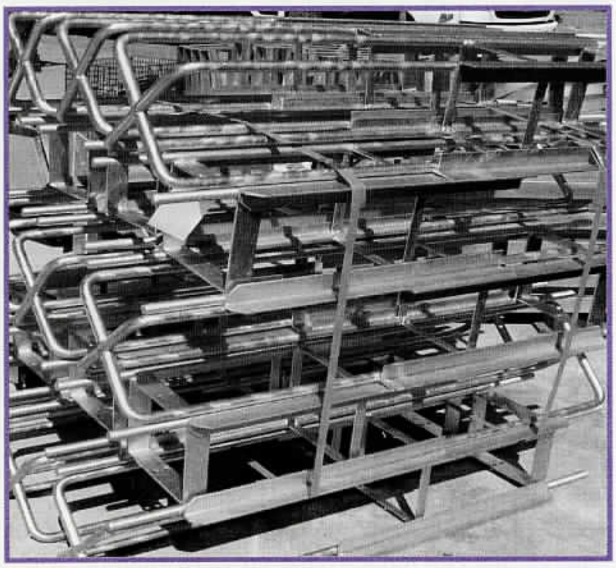
Admixtures are incorporated in the concrete mix to modify its performance for specific construction purposes. The use of admixtures can improve durability but others may impact negatively.

Examples of admixtures include:

1. **Air entraining admixtures**: These compounds form very small bubbles in the concrete, which improves its resistance to frost attack and improves workability. Concrete strength is reduced by the use of these additives.
2. **Set retarding admixtures**: These are used when the curing speed needs to be delayed (e.g. in hot weather).
3. **Set accelerating admixtures**: These 'rapid cure' additives are used to speed-up the concreting operations or may be used during cold weather were normal curing times may be prolonged. The high level of chloride ions in these admixtures (based on calcium chloride)

has a detrimental effect on concrete durability through accelerated risk of reinforcing steel corrosion.

4. **Water reducing and set modifying admixtures**: These compounds maintain the workability of concrete at low water-cement ratios and can either advance or retard the set, depending in the construction requirements.
5. **Waterproofing additives**: These additives reduce the water absorbing characteristics of concrete. They consist of pore filling materials and/or water repellent compounds.



These large bolt cages are a good example of the effectiveness of hot dip galvanizing in steel embedded in concrete.

Coatings and penetrants can also be use on the concrete surface the prevent of minimise access of corrodents to the concrete. There are five common forms of these materials used to improve concrete durability. These are:

1. Penetrants. These are usually solvent-borne hydrophobic compounds that restrict movement of water through the concrete surface.
2. Water-borne coatings. These are polymer emulsions (e.g. acrylic) that key to the surface and provide barrier protection to the concrete, from the environment.
3. Solvent-borne coatings. These are organic coatings, predominantly two-pack systems, that polymerize on the concrete surface to produce heavy-duty, more abrasion resistant coatings.
4. Cemintitious overlays. These are specially formulated renders applied to the concrete to reduce permeability, particularly to carbon dioxide.
5. Sheet membranes. These are used when the concrete needs to be isolated from aggressive chemicals and thermoplastic polymers that can be welded in-situ to provide a high integrity barrier are most commonly use.

COATING REINFORCING STEEL

While its proponents state that reinforcing bar needs no protection in good quality concrete, the plethora of failures due to rebar corrosion indicates that the added assurance of applying a protective coating to the rebar may be a good investment in long-term concrete durability.

The predominant coating options for reinforcing bar are hot dip galvanizing and epoxy coating. There has been much debate, particularly in the USA, regarding the merits of each coating system.

The major end-use for coated reinforcing bar in the Northern Hemisphere is in bridge decks where de-icing salt is used on the roads during winter.

A number of significant structures such as the Sydney Opera House and Parliament House in Canberra have made extensive use of galvanized reinforcing bar in Australia, as have the sewerage outfall tunnels in Sydney.

The use of galvanized reinforcing bar has been more prevalent in Australia, as the epoxy coated rebar industry here is insignificant compared to that in the USA.

A great deal of research has been undertaken by the Federal Highways Administration in the USA in assessing coated reinforcing bar performance. Dr.Stephen Yeomans, from the University of NSW Australian Defence Academy spent a period on secondment to the USA for the Commerce Technology Administration National Institute of Standards and Technology.

A complete copy of his report on this research project (funded by the International Lead Zinc Research organization – Project ZE 341) was published in two parts in Corrosion Management in November 1993 and February 1994.

The conclusions in this report condense the galvanizing versus epoxy issues as follows:

1. Epoxy coating provides excellent corrosion protection to reinforcing steel provided the coating remains intact. If the coating is severely damaged, such as at cut ends, corrosion occurs to a similar extent to that for black steel in

equivalent circumstances and corrosion progresses along the bar under the adjacent coating.

2. Patch repairs to cut ends of epoxy coated bar did not substantially delay corrosion of the steel substrate compared to the corrosion of un-coated black steel in equivalent concrete and exposure conditions.

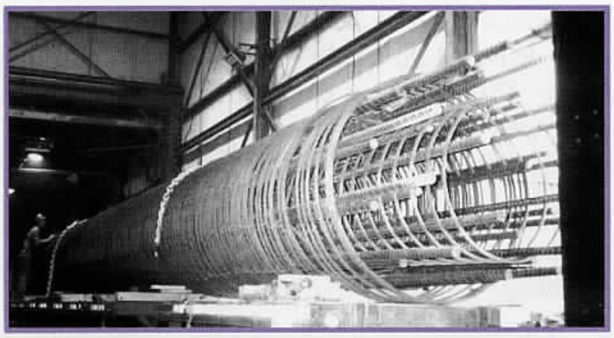
3. Results indicate that holidays and points of minor damage in a fusion bonded (epoxy) coating are responsible for the large negative half-cell potentials measured for epoxy coated reinforcement. General corrosion of the uncoated steel would be expected at such potentials, though there was little evidence of corrosion of the epoxy coated reinforcement. This suggests that the half-cell measurements to assess the corrosion of the epoxy coated bar in concrete are unreliable.

4. Galvanized reinforcement can tolerate chloride levels in concrete at least 2.5 times higher than those causing corrosion in black steel under equivalent concrete and exposure conditions.

5. Galvanizing provides sacrificial protection to steel in concrete, the period over which the zinc layers dissolve effectively delaying the onset of corrosion of the steel substrate. The distance over which the exposed steel is protected at the cut ends is in the order of 8 mm.

6. Results indicate that the total period over which the galvanizing delays the onset of corrosion of reinforcing steel in concrete is in the order of 4-5 times that for corrosion of black steel in equivalent concrete and exposure conditions.

7. Half-cell potential measurements of galvanized steel in concrete may provide an opportunity to continuously assess the performance of the reinforcement and predict remaining life of the zinc coating in service, but further study is needed.



Large fabricated reinforcing cage for an over-water bridge column in preparation for hot dip galvanizing.

SUMMARY

Well-designed and constructed concrete structures have a well-established reputation for durability. However, the fact that failures have occurred reflects that the variables occur in the construction process. The nature of concrete renders it a very costly proposition to repair.

The Australian Concrete Repair Association represents the industry and ensures that its members are suitable qualified to undertake the specialised processes involved in the remediation of concrete failure.

At the specification end, options exist to ensure that the durability of concrete structures can be best assured by the use of protective coating systems on the concrete surface, and more importantly, on the reinforcing bar.

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Editor.

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COVER:

This acid tank is a prime example of a very difficult surface for recoating. Severe steel corrosion, 24-hour operating environment, high levels of humidity and a chloride contaminated surface at low pH is a challenge for any industrial coating.

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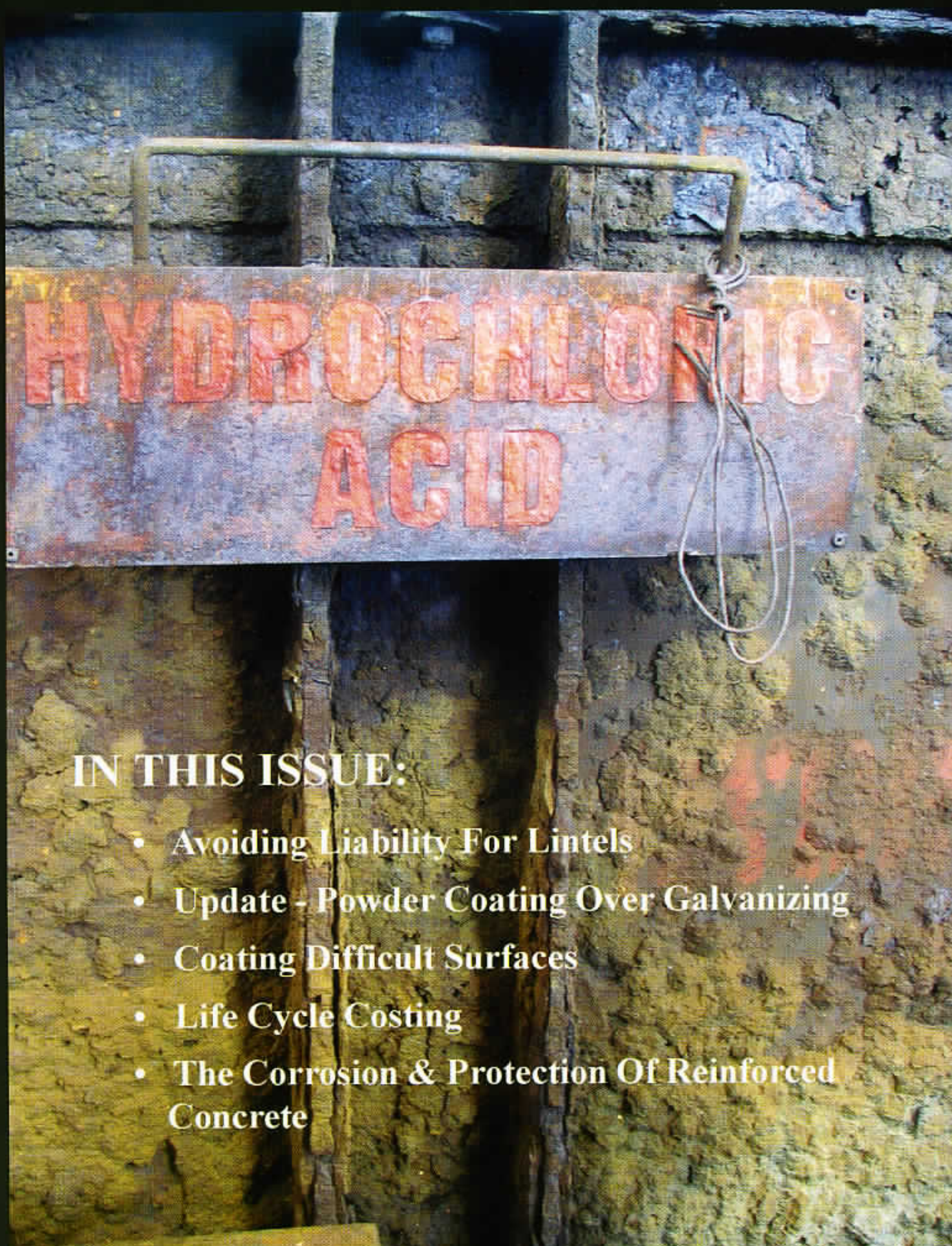

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