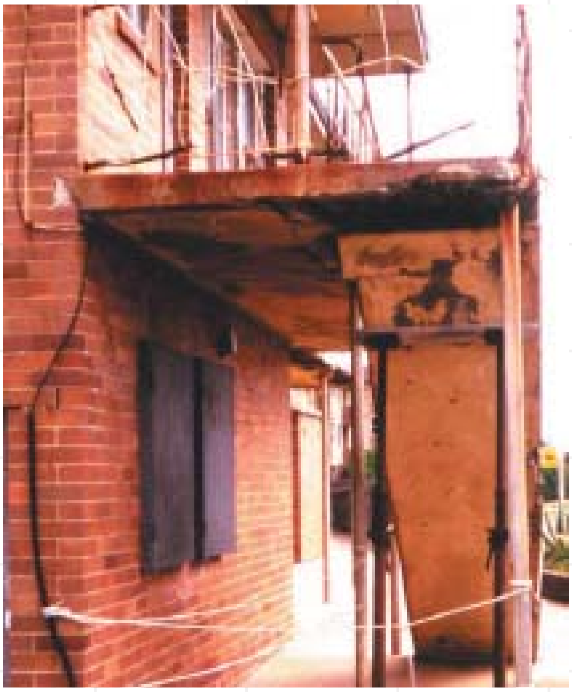
06. CONCRETE DURABILITY AND GALVANIZED REINFORCING BAR

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 identifies 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'.



Corrosing reinforcing bar has caused severe spalling of the concrete on this oceanfront dwelling.

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.

The loss of durability and serviceability of reinforced concrete caused by the corrosion of reinforcement is enormously expensive and one of the primary reasons for the need for early remediation and repair, and even demolition, of concrete structures well before their design life (usually 30-50 years) has been reached. To counter the damaging effects of reinforcement corrosion, which include corrosion-induced cracking, rust staining and spalling of the concrete mass, a number of strategies can be employed to improve the durability of concrete and afford protection to the embedded steel.

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 uses 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 as being important in aggregate performance.

The Long Bay Gaol Hospital used galvanized reinforcing bar in all the concrete wall sections because of its proximity to the ocean, in eastern Sydney, NSW.

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 permeability.

Galvanized reinforcing bar is widely used in the pre-cast concrete industry because the elements are almost always used as exposed facades and concrete cover is limited by design.

All concrete cracks because it shrinks on cooling 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.

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 de-passivated 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 subsequently 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 indicated a serious depletion of the concrete's strength.

The corrosion of the reinforcing bar in this road bridge in North America has occurred because of poor rebar placement combined with the use of de-icing salts on the road.

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 cover meters 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 salt 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 Australian Concrete Repair Association members and cover the following:

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

Reinforcing bar in routinely galvanized throughout Australia, where concrete durability is critical

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.

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 otr 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.

Coatings and penetrants can also be used 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 emulsion (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. Cementitious 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.

GALVANIZING OF REBAR

Over the years, a growing body of evidence from both laboratory experiments and ongoing field surveys of existing structures has demonstrated that the galvanizing of steel rebar extends the service life of many types of reinforced concrete structures. Though the cost of galvanizing may significantly increase the price of the reinforcing steel itself - the actual costs depending on the nature of the product to be galvanized, the location of the galvanizing plant and the extra transportation and handling required - the overall premium for the use of galvanized rebar in mass concrete is a small proportion of total concreting costs. This premium reduces considerably in buildings and large constructions where the costs of services, facilities and fixtures are major project cost components.

The corrosion of the steel reinforcement in this concrete power pole has cause it to split from end to end

Hot-dip galvanizing produces a tough and adherent coating on steel that resists abrasion and heavy handling, and which can be stored, handled and transported in much the same way as black steel. Other than following general guidelines when bending and fabricating galvanized steel, no special precautions are required to protect the coating against mechanical damage. In the design and construction of reinforced concrete utilizing galvanized rebar, the same design parameters and construction practices are used that apply to conventional black steel reinforcement is used and best practice when using galvanized reinforcement is to use appropriately designed and placed concrete such as would normally be used in conventional construction.

Hot dipping involves the immersion of the steel bars in molten zinc at about 450°C and holding for a sufficient period to allow the development of a metallurgically bonded coating of zinc and zinc-iron alloys on the base steel. According to AS/NZS 4680, the minimum specified coating thickness on steel products greater than 5 mm thick is 84 microns, equivalent to a coating mass of 600g/m^2 of surface. In routine processing however, hot dipping results in coatings that would generally be at least 100-120 microns thick. Each successive layer of the coating from the steel substrate outwards contains a higher proportion of zinc and the zeta and delta alloy layers in particular are somewhat harder than ordinary steels. This feature, combined with the good adherence of the coating, gives the coating its excellent abrasion and impact resistance.

It is generally most economical to process straight lengths of reinforcing bar with all fabrication being done after galvanizing. During fabrication, the tendency for cracking and flaking of the coating in the area of the bend increases with bar diameter and the severity and rate of bend. The use of large bend diameters, typically 5-8X the bar diameter, can minimize damage to the coating. Some cracking and flaking of the coating at the bend is not uncommon, and should not be the cause for rejection provided such damage is in accordance with the specification. Should repairs be required, an organic zinc rich paint containing a high proportion of metallic zinc (90% minimum) in the dry film is generally used.
As an alternative to post-galvanizing fabricating, bars bent to special shapes (ties, stirrups etc) or complete sections such as prefabricated column forms or pre-casting cages can be galvanized. This offers the distinct advantage of little or no fabrication-related damage to the coating.

ZINC IN CONCRETE
Zinc is an amphoteric metal that reacts with both strong acidic and strong basic solutions, the attack being most severe below pH 6 and above pH 13. At intermediate pH ranges, the rate of attack on zinc is very slow due to the formation of protective surface layers. When embedded in concrete, zinc is passivated for pH values between about 8 and 12.5, again due to the formation of a protective surface film of corrosion product that is relatively insoluble below pH 12.5. While zinc reacts with wet cement, this reaction effectively ceases once the concrete has hardened and the barrier layer of calcium hydroxyzincate has formed. Hydrated concrete is strongly alkaline with a pH in excess of pH 12.2 due to the presence of a saturated solution of Ca(OH)2 filling the pore space.

Corrosion of steel in concrete is usually caused by either a natural reduction in the pH of the concrete through reaction with acidic gases such as carbon dioxide – the carbonation effect, and/or the presence of chloride ions above certain threshold levels at the depth of the reinforcement. Chlorides accumulate in concrete due to salt contamination of concrete-making materials, exposure to the marine environment or saline ground waters, or the use of deicing salts as is especially common in the snow-belt states of the USA.

Black steel in concrete typically de-passivates below pH 11.5, or higher in the presence of chlorides, leading to the onset of corrosion, zinc remains passivated to about pH 9.5 thereby offering substantial protection against the effects of carbonation of the cover concrete. Zinc can also withstand exposure to chloride ion concentrations several times higher than causes corrosion of black steel.
The corrosion protection thus afforded by galvanizing is due to the combined effects of a substantially higher chloride threshold than black steel in concrete, and a complete resistance to the effects of carbonation of the concrete. The presence of the protective zinc alloy coating delays the initiation of the corrosion process, although the extent of this depends on the quality of the concrete and the

severity of the exposure.

When very high chloride levels build up in concrete, such as may occur in poor quality concrete in severe marine exposure conditions, the life of the zinc coating may be somewhat reduced. It is important to note however that the life of the galvanized rebar in these conditions would still be significantly longer than that of black steel in equivalent concrete and exposure conditions.

This issue of the chloride tolerance of galvanized steel has been widely studied. Recently, comparative accelerated corrosion studies in chloride-contaminated concrete have revealed the improved corrosion behavior of galvanized reinforcement over black steel. Under identical exposure conditions, galvanized reinforcement resisted chloride levels in concrete at least 2.5 times higher than for black steel and delayed the time to the onset of corrosion of the underlying steel by some 4-5 times. These results have been confirmed in other investigations where it has been demonstrated that galvanizing had a higher chloride threshold relative to bare steel and the delayed onset of corrosion.

Considerable work has also been done to identify the nature of zinc corrosion products and the effect of these on the integrity of the concrete. A number of minerals have been identified in the corrosion products including zinc oxide and zinc hydroxide. A unique feature of these corrosion products is that they are friable (loose, rather than blocky) minerals and they migrate well away from the bar and into the adjacent concrete matrix where they fill voids and micro cracks. As a result, these products cause very little disruption to the surrounding matrix and this helps maintain the integrity of the concrete itself. This behavior should be contrasted to the situation encountered when black steel in concrete corrodes. Iron corrosion products are extremely bulky and precipitate at the steel-concrete interface causing the build up of tensile stresses sufficient to crack the cover concrete.

APPLICATIONS OF GALVANIZED REINFORCEMENT

The rationale for the use of galvanized steel in concrete centers on the concept that the coating provides a safeguard against early or unexpected corrosion of the reinforcement. The coating itself should not be used as the primary or sole means of corrosion protection, rather it should be used in conjunction with an adequate cover of a dense impermeable concrete suited to the type of structure and the exposure conditions. There is a premium to be paid for this additional protection, above that provided by the concrete mass, but the advantage to accrue is that premature, and possibly whole-of-life, avoidance of costly cycles of repair and remediation of the structure can be avoided.

Particular circumstances where the galvanizing of reinforcement is likely to be a cost-effective and sound engineering decision include:

- light-weight pre-cast cladding elements and architectural building features;
- surface exposed beams and columns and exposed slabs;
- prefabricated building units such as kitchen and bathroom modules and tilt-up construction;
- immersed or buried elements subject to ground water effects and tidal fluctuations;
- coastal and marine structures;
- transport infrastructure including bridge decks, roads and crash barriers; and
- high risk structures in aggressive environments.

Throughout the world, galvanized reinforcement has been successfully used in a variety of types of reinforced concrete buildings and construction applications. Some examples include:

- bridge decks, pavements and crash barriers;
- coastal bridges and highway structures;
- cooling towers and chimneys;
- tunnels, water storage tanks and treatment facilities;
- docks, jetties and offshore platforms;

- sea walls and coastal balustrades;
- paper mills, water and sewerage treatment works; and also
- processing facilities and chemical plants.

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, ashave 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.

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.

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. Paints and related materials – Methods of test – Exposed to weathering – Degree of blistering

INGAL

SPECIFIERS MANUAL

01 - SPECIFIERS MANUAL — THIRD EDITION

Industrial Galvanizers Australian Galvanizing Division (IGAG) operates nine galvanizing plants around Australia, ranging in size from large structural galvanizing facilities to specialised small plants designed to process small parts.

The Australian Galvanizing Division has galvanized in excess of 2 million tonnes of steel products in Australia since its first plant was commissioned in 1965 and is recognized for its ability to handle complex and difficult projects, as well as routine contracts.

This experience has been collated in the Specifiers Design Manual, to assist those involved in the design of steel products and projects to better understanding the galvanizing process and allow the most durable and cost-effective solutions to be delivered to these products and projects. All sections of this Third Edition have been completely updated and additional sections have been included to provide additional technical information related to the use of hot dip galvanized steel.

In addition to its Australian Galvanizing operations, Industrial Galvanizers Corporation has a network of manufacturing operations in Australia, as well as galvanizing and manufacturing businesses throughout Asia and in the USA.

The company's staff in all these locations will be pleased to assist with advice on design and performance of hot dip galvanized coatings and products. Contact details for each of these locations are located elsewhere in this manual.

This edition of the Industrial Galvanizers Specifiers Manual has been produced in both html and .pdf formats for ease of access and distribution and all documents in the Manual are in .pdf format and can be printed if paper documents are required.

The Specifiers Manual is also accessible in its entirety on the company's web site at www.ingal.com.au.

Additional copies of the Specifiers Manual are available on CD on request.

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