Considerations of the Characteristics and Use of Coated Steel Reinforcement in Concrete

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ABSTRACT

The corrosion of steel reinforcement in concrete, due in part to the inability of the concrete mass to protect the embedded steel, is a worldwide problem of massive proportions. The damage that results from corrosion, mainly cracking and delamination of the concrete, may significantly reduce the serviceability and structural integrity of reinforced concrete if early repair and rehabilitation is not carried out. These procedures are often quite expensive. While the provision of an adequate cover of a dense impermeable concrete is clearly the best means of protecting reinforcing steel, the use of additional methods of protection in concrete construction are now commonplace. One such method involves the use of coatings on the reinforcement, the two most common of which are epoxy coating and galvanizing.

A review is presented of important considerations in the manufacture, specification and performance of coated steel reinforcement. The coating itself, which can be broadly classified as metallic or non-metallic in nature, provides barrier type protection by isolating the steel from corrosive elements in the local environment. In addition, some coating metals which are more anodic than steel afford sacrificial protection in the event that the coating is damaged and the steel substrate is exposed. In the first instance, the physical integrity of the coating, as well as its low reactivity with the environment to which it is exposed, is thus vital to the success of non-metallic coatings such as paints and fusion bonded powders, as well as to noble metal coatings on steel. On the other hand, active metal coatings on steel such as zinc, provide both primary barrier protection and, where the coating is damaged and the substrate exposed, secondary cathodic protection. The long term performance of active metal coatings on steel also depends on the reactivity of the coating metal in the environment to which it is exposed.

Both hot dip galvanized and fusion bonded epoxy coated steel reinforcement have been widely used in concrete, particularly in aggressive exposure situations. Galvanizing produces a tough adherent alloy layer coating which enables it to be handled in much the same way as conventional black steel reinforcement. Galvanizing has a substantially higher chloride tolerance and resistance to the effects of carbonation than black steel, and clearly delays the onset of corrosion of the steel. When high-to-very high chloride levels accumulate in concrete, particularly poor quality concrete made with high water-to-cement ratios and shallow cover to the reinforcement, there is concern about the ability of zinc to provide continued long term protection. Epoxy coatings, on the other hand, are essentially inert and highly resistant to the penetration of chlorides, and afford excellent corrosion protection to steel provided the coating is well adhered and largely free of defects. The coating can be damaged by mechanical abrasion and impact so that, as a consequence, considerable emphasis is placed on special methods and practices during handling and fabrication. Because corrosion protection in this case depends entirely on the integrity of the coating, repair of manufacturing defects and other mechanical damage such as cut-ends of coated bars, is generally required.

While neither coating system can guarantee complete avoidance of corrosion of reinforcement in concrete over long periods of exposure, it can be expected that providing a concrete of adequate quality and durability is used, coated reinforcement offers significant advantages

over black steel reinforcement under equivalent circumstances. These include: an increased life to the initiation of corrosion; variability in the concrete cover and the presence of inferior quality concrete can be better tolerated; and corrosion protection to the reinforcement prior to it being embedded in concrete.

The results of a program of accelerated corrosion testing of black steel, galvanized steel, and epoxy coated steel in concrete are presented. Under the same conditions in equivalent concrete, galvanized reinforcement tolerated chloride levels in concrete some 2.5 times higher, and was able to delay the onset of corrosion of the steel substrate by a factor of some 4-5 times longer, compared to the initiation of corrosion of black steel. The zinc coating also provided cathodic protection to adjacent exposed steel at non-repaired cut ends of galvanized bars in concrete over a distance of some 8 mm. Epoxy coating provided overall excellent corrosion protection to steel in concrete with little evidence of failure of the coating or rust staining along the length of the embedded bars. However, at sites where the underlying steel was exposed by damage to, or removal of, the epoxy coating, such as at non-repaired cut ends, localized attack occurred to much the same extent as for uncoated black steel. Patch repairs to cut-ends of epoxy coated bars, applied strictly in accordance with manufacturer's recommendations, did not substantially delay corrosion of the steel substrate.

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1. INTRODUCTION

Concrete and related cementitious materials are the most widely used man-made building and construction products. In the United States alone, per capita use of concrete is presently about 2 tonne per year spread over all types of components and structures for commercial, industrial and residential use as well as large civil and military engineering installations including road and rail construction, pavements, port and harbour facilities, water treatment and sewerage systems, power generation plants and distribution networks, and other activities.

Reinforced concrete is a composite material comprising steel bars (reinforcement) or tendons embedded in a concrete mass: the steel carries the bulk of the tensile forces and imparts a degree of cracking resistance to the concrete which is largely compressively loaded. The performance of reinforced concrete is essentially judged on two criteria: first, its structural integrity which is its ability to safely sustain loads throughout its life; and second, its durability which is the resistance to adverse change in the concrete mass which may affect the structural behaviour or other important characteristics of the component or structure.

Concrete (and cement mortar) provides stable, long term corrosion protection to steel reinforcement due to passivation of its surface in the highly alkaline environment. As long as the passive state is preserved the reinforcement will not corrode. To maintain this condition, the concrete must be sufficiently impermeable so as to prevent, as far as possible, the rapid transport of chemical species such as chloride, carbon dioxide and oxygen to the reinforcement. The presence of chlorides may depassivate the steel even at high pH, while carbon dioxide in solution neutralizes the calcium hydroxide saturated pore water (the carbonation process) and lowers the pH of concrete below the value at which the steel can remain passivated. Oxygen is also a vital part of the corrosion process (ACI, 1991 and 1992).

To ensure adequate serviceability and durability of concrete, attention needs to be given not only to structural design considerations in reinforced concrete construction, but also to the selection of materials and proportioning of the concrete mix, placement of the reinforcement, and compaction and curing of the concrete mass. Should the steel embedded in concrete corrode, for whatever reason, the expansive forces generated by the formation of voluminous corrosion products inevitably leads to tensile cracking and rust staining of the concrete with subsequent delamination or spalling of the mass. This not only detracts from the aesthetics of the structure, an over-riding consideration in prestige construction, but may reduce the serviceability and structural integrity, and so the service life, of the structure. Once the steel depassivates and corrosion initiates, it is only a matter of time before a cumulative amount of damage occurs to the concrete structure or component and the service life is reached (Clifton, 1991).

Corrosion induced damage to concrete structures often necessitates early repair or rehabilitation and, in extreme cases, complete replacement of the structure or element well before the design life is reached. The cost, time and effort associated with such remedial work represents a significant financial commitment. The worldwide costs associated with

remedial work for corrosion induced damage to concrete are of enormous proportions: for example, in Australia, the annual cost of building repairs alone was estimated at $A50 million in 1979 escalating to $A200 million by 1990 (Beresford, 1979); in Hong Kong, the cost of early replacement of 26 public housing blocks in one estate less than 20 years old was some $HK800 million (South China Morning Post, 1986); in the UK, the Department of Transport has estimated a total repair cost of some £616 million for motorway bridges (Broomfield, 1993); while in the US, the annual cost of bridge deck repairs due to deicing salts was estimated at $US50-200 million, with substructures and other components requiring an additional $US100 million and a further $US50-100 million each year on multi-level parking garages (TRB, 1991).

There can be little question that the most cost effective way to minimize the risk of reinforcement corrosion in new concrete construction is to ensure there is an adequate depth of cover (to the reinforcement) of a dense impermeable concrete. While this appears to be a simple solution to the problem, it is an unfortunate fact that despite the well known protective characteristics of concrete, the corrosion of steel reinforcement is often observed, particularly in harsh exposure situations. The reasons for this can often be traced to insufficient cover to the steel itself and the inability of the concrete mass to adequately isolate and protect the steel, even at the design depth of cover. It is to be noted, however, that such inadequacies in concrete construction most often stem from lack of supervision and poor workmanship on site rather than deficient structural design and/or specification of materials.

When there are concerns that concrete will not be sufficiently durable for the intended purpose, or there is simply a need for superior protection to ordinary steel reinforcement, it is now commonplace to incorporate additional measures of corrosion protection in concrete construction. Many such choices are available (e.g., Babaei and Hawkins, 1988; Holland, 1992) including: membrane coatings applied to the concrete surface; impregnation of concrete with materials intended to reduce its permeability; the addition of corrosion inhibitors to the concrete; the use of corrosion resisting reinforcement such as stainless steel, nickel, titanium or non-metallic materials; the incorporation of cathodic protection systems by either the impressed current or sacrificial anode methods; or the application of protective coatings to the reinforcement itself.

Coated steel reinforcement in particular has found very wide application over many years in a multitude of types of concrete construction and exposure conditions. The two most common coating systems for steel reinforcement are fusion bond epoxy coatings, and hot dip galvanizing. Typically, coated steel reinforcement has been used in moderate-to-severe exposure conditions such as marine and coastal construction, industrial plant, water treatment and chemical processing facilities, power generation, and bridge and highway construction. Coated reinforcement is also widely employed in less severe applications in building and construction for both cast-in-place and precast concrete elements.

In the sections to follow a review is given of the nature and characteristics of both epoxy coated steel and galvanized steel for use as reinforcement in concrete. Also presented is an overview of recent experimental work on the comparative corrosion behaviour of uncoated black steel, epoxy coated steel, and galvanized steel in concrete. Of particular interest in the

experimental program was assessment of the ability of the coating system to protect the reinforcement from corrosion at variable depths of concrete cover for moderate-to-high chloride exposure, estimation of the relative chloride tolerance of black and galvanized steel, and the effect of damage to the coating on corrosion protection, such as that at cut ends of coated bars.

2. COATED STEEL REINFORCEMENT FOR CONCRETE

Coated reinforcement in this context is taken to mean conventional reinforcing steel in the form of either straight bar lengths, formed pieces or prefabricated sections to which a surface coating is applied as part of the reinforcement manufacturing or fabricating process prior to it being embedded in concrete. The coating may be metallic or mon-metallic in nature and many formulations of both types have been investigated (e.g., Bird and Strauss, 1967; Clifton et al, 1973; Muthukrishnan and Guruviah, 1988; Tomlinson et al, 1988; Treadaway et al, 1989).

At the outset, it should be noted that the use of coated reinforcement for corrosion mitigation in concrete should not be at the expense of using the best quality concrete available and appropriate to the intended application. With this in mind it can be expected that, providing due care is taken in the specification of the concrete materials and the mix design, as well as attention to good workmanship and supervision of the concreting practice, the coating of reinforcement offers at least the following advantages over conventional black steel reinforcement:

a)   an increased period to the initiation of corrosion of the reinforcement with a significantly reduced risk of cracking, rust staining and spalling of the concrete over this period;

b)   somewhat greater tolerance of inferior concrete as-placed and concreting practices and poor workmanship, such as misplaced reinforcement in the formwork, improper compaction and/or inadequate curing of the concrete;

c)   greater tolerance of adverse effects due to reduced concrete cover to the reinforcement, though intentional reduction of cover is neither a desirable nor recommended practice; and

d)   corrosion protection of the reinforcement prior to it being embedded in concrete or where the reinforcement protrudes from the concrete mass in service.

All coatings, whether metallic or non-metallic, provide barrier protection in that the coating is intended to isolate the substrate from the local environment thereby preventing corrosion inducing species from reaching the steel. The success of coatings in general thus depends on the integrity of the coating since, should the coating be damaged and the substrate exposed, the primary mechanism of corrosion protection will be lost unless some form of additional or

supplementary protection is available. Additional corrosion protection can be provided by the separate application of a cathodic protection system (generally impressed current), as is often the case for buried, wrapped steel pipelines for example, or if the coating itself is sacrificed in order to protect the substrate, as is the case for active metal coatings on steel.

2.1 Metallic Coatings

Metallic coatings for steel fall into two broad classifications based on their electrochemical characteristics as shown in Table 1. Those metals more anodic (i.e., active) than steel afford cathodic or sacrificial protection to the steel, while the more cathodic (i.e., noble) coating metals would be protected by dissolution of the steel itself.[1] In both cases the coating provides barrier protection to the substrate and, in the first instance at least, the longevity of the coating and thus the corrosion protection it affords depends directly on the reactivity of the coating metal in the environment to which it is exposed.

Table 1. Some Choices for Metallic Coatings on Steel

INCREASINGLY ANODIC TO IRON	INCREASINGLY CATHODIC TO IRON
Cadmium Aluminum Zinc Magnesium	Stainless Steel Lead Tin Nickel Copper

While it is theoretically possible for virtually any metal to be coated onto another metal, particularly so with the diversity of surface treatment and fabrication processes available, practical and economic considerations seriously limit the available options. In the case coatings on steel, Table 1 indicates that cadmium, aluminum, zinc and magnesium all

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1. The use of the terms anodic and cathodic in describing a corrosion process relates to the electrochemical behaviour of the two electrodes of a corrosion cell. The anode is the positive electrode at which oxidation of the metal to an ionic state occurs (e.g., $Fe = Fe^{2+} + 2e^-$); the metal thus goes into solution and ions migrate from the surface until they precipitate from solution. The free electrons so generated are conducted away from the anode to the cathode region, the negative electrode, where they are consumed by the reduction of another species which could constitute the deposition of a noble metal ion from solution (e.g., $Cu^{2+} + 2e^- = Cu$), the liberation of hydrogen in acidic solutions ($2H^+ + 2e^- = H_2$) or, as is most likely, the reduction of oxygen in the presence of water ($O_2 + 2H_2O + 4e^- = 4OH^-$). The corrosion cell thus comprises anodic and cathodic regions which are electrically connected and an electrolyte, generally an aqueous solution, to facilitate the transport of oxygen and the movement of charged ionic species (anions to the anode and cations to the cathode) to complete the circuit and balance the charge transfer.

provide sacrificial protection. While this is the case, in most normal applications magnesium is highly reactive and is too rapidly consumed; a resistant oxide coating forms on aluminum and its effectiveness in providing cathodic protection is limited; and the toxicity and cost of cadmium significantly limits its range of application. As a result, zinc is by far the most widely used active metal for iron and steel. For the noble metal coatings, many choices are available such as: stainless steel, nickel and titanium which are clad onto steel rod, sections and plate; lead sheet is used for liners in steel tanks; tin coated steel sheet is used widely in packaging and food container applications; and many metals are routinely electroplated onto steel products of all types including copper, chromium, nickel and also precious metals.

In order for cathodic metals to protect the steel substrate, the coating must remain completely intact. If it is damaged, electrolytic action between the coating and the exposed steel will accelerate dissolution of the steel: the coating behaves cathodically and is protected while the exposed steel is anodic and therefore oxidizes and corrodes.[2] This is obviously undesirable and is clearly the most serious limitation to the use of noble metal coatings in general · engineering practice where damage to the coating during storage, transportation and fabrication and during normal service conditions, is to be expected.

On the other hand, when anodic metals are coated onto steel an extra measure of corrosion protection (in addition to the barrier effect) is afforded at the steel-coating interface by the inherent sacrificial nature of the coating. In this case the coating behaves anodically while the steel is cathodic, and local damage to the coating can be tolerated and protection of the substrate obtained as long the exposed steel remains fully cathodic with respect to the coating metal.

Many metals, both active and noble, exhibit domains of passivity extending to the high pH values encountered in concrete, and such metals therefore can be expected to have improved performance compared to others having only marginal or nil passivity in the highly alkaline conditions that exist in hardened concrete. Apart from iron and traditional steels in general, metals such as zinc, cadmium, nickel, copper, zirconium, titanium and numerous precious metals, as well as a host of alloys of these metals, are known to be resistant to the high pH conditions of concrete and like products, and so find wide application in the building and construction industries.

For metal coated steel reinforcement, a number of coating systems including zinc, cadmium, nickel and stainless steel have been investigated and, in several cases, used in reinforced

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2. While the magnitude of the potential difference between two metals in contact in a particular electrolyte determines the driving force for the dissimilar metal reaction, many factors influence the rate at which that reaction occurs. For example, the relative size of the anode and cathode determines the anodic current density which will be higher, and thus the extent of corrosion greater, for small anode - large cathode situations. Also, the conductivity of the electrolyte determines the overall current flow and the extent of the electrochemical reaction, the more conductive the electrolyte the more expansive will be the region of exposed steel that will be protected, while the presence of passivating surface films or mineral deposits on either or both of the metals in contact may reduce their activity.

concrete construction. Zinc, in the form of a hot dip galvanized coating, is by far the most common coating metal for this purpose, and research and practical experience with galvanized reinforcement has been widely reported (e.g. ILZRO, 1981; Yeomans, 1987; Andrade & Macias, 1988; Swamy, 1990).

2.2 Non-Metallic Coatings

Generally in the form of organic and inorganic films, membranes, wrappings or paints, and various combinations of these, non-metallic coatings depend almost entirely on their low reactivity or inertness and the barrier they establish between the steel and its environment. In this way their behaviour is similar to that of the noble metal coatings on steel, except that galvanic effects do not accelerate corrosion of the exposed steel. It is to be noted, however, that some paints contain metallic fillers such as aluminium or zinc thereby also affording a degree of sacrificial protection. On the whole however, non-metallic coatings are considered to provide barrier type or so-called envelope protection only and, as a consequence, damage to such coatings almost always results in breakdown of the protection mechanism.

For many years, paints of many different types, formulations and methods of application have been extensively used for corrosion protection of general steelwork and consumer goods. Over the last 30-40 years, the technology of powder coating has been developed with a resultant steady increase in the market share for electrostatically applied powder coatings, a significant amount of which is used in pipe coating and concrete reinforcing bar applications (OCCA, 1984; Lambourne, 1987). Powder coating methods possess advantages over conventional paintings systems in that no polluting solvent loss occurs on application and, owing to the use of electrostatic spray, there is comparatively little over-spraying and material loss.

At present there are three major types of powder products, applied to broadly similar processes, namely:

a)   thermoplastic;
b)   thermosetting; and
c)   vitreous enamels.

Thermoplastic powders are generally identified with the plastics industry and vitreous enamels with specialty products and applicators. Thermosetting powder coating has largely developed within the paint industry because there was a common source of raw materials, especially pigments, and existing paint stoving equipment could be used for curing powders.

The first thermoset powder coatings were epoxy resin based, but other resin systems have been developed, the choice of which, for all practical purposes, can now be limited to polyester, epoxy, and hybrid epoxy-polyester types. Polyester powder coatings exhibit good exterior durability, especially for retention of gloss and color, and have good UV resistance and resistance to chalking. The epoxies offer the advantage of faster curing rates and better chemical and solvent resistance than polyester-containing powder coatings. Hybrid epoxy-polyester powders are used where the superior visual appearance of polyester, both flow and

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gloss, are required but where UV resistance is not required. Other resin systems for powder coatings include those based on acrylic and polyurethane resin but these have not been widely accepted: the acrylics have limited advantages over polyesters and only moderate performance and shelf-life problems; while the polyurethanes release volatiles on curing and cure more slowly.

For coating steel reinforcement, a host of organic compounds including epoxy and alkyd resins, phenolic, polyurethane, vinyl, polypropylene and nylons as well as bitumens, coal tars and oils, and mineral compounds such as lead oxide, aluminum silicate, zinc silicate and zinc phosphate have been variously investigated and used. Of these, the epoxy resins have proven to be the most versatile and compatible coatings to the extent that they are now virtually the only non-metallic coatings in general use for steel reinforcement. Many reviews of the development and use of epoxy coatings for reinforcement have been published (e.g. Safier, 1989; Gustafson, 1990), and there have been several recent symposia on this subject (ACI, 1988; TRB, 1993).

3. GALVANIZED STEEL REINFORCEMENT

Zinc coatings on iron and steel products have been very widely used over many years for corrosion protection, particularly so for exposed structural steelwork and consumer products, and for over a period of more than 60 years, for corrosion protection of steel reinforcement in concrete. Typical applications of galvanized reinforcement include coastal and marine structures, chemical and industrial plant, water and sewerage treatment facilities, power generation plants, road and rail bridges, and highway construction. Galvanized reinforcement has also been widely used in general building applications for both precast and cast-in-place methods of construction.

Practical experience and research over many years has clearly demonstrated the benefits of galvanizing for corrosion protection of steel reinforcement in a variety of aggressive, high chloride exposure situations (Tonini and Dean, 1976; Treadaway et al, 1980; ILZRO, 1981; Yeomans, 1987; Andrade and Macias, 1988; Stejskal, 1991). There are, however, some concerns whether the sacrificial nature of zinc can provide continued long term protection to reinforcing steel when high-to-extreme levels of chloride accumulate, especially in poor quality concrete (Griffin, 1969; Hill et al, 1976; FHWA, 1976).

As a case in point, considerable research has been done to investigate the use of galvanized steel for top and bottom mat reinforcement in bridge decks. When both top and bottom mat bars were galvanized, very low corrosion current densities resulted compared to black steel, and the extent of corrosion on the galvanized bars was significantly less with no ferrous corrosion products (i.e. red rust) apparent. When galvanized bars were used in the top mat only with black steel bottom mats, significant corrosion of the zinc occurred though with very much less red rust corrosion compared to black bars in equivalent conditions (Pfeifer et al, 1987). Other data indicates that for a 0.5 water-to-cement (w/c) ratio concrete, galvanized bars performed better than black bars, though in a 0.4 w/c ratio concrete there was similar behaviour for both black and galvanized bars after 8 years cyclic exposure, and

meaningful comparisons could not be made. It was also noted that the worst case corrosion occurred when top mat galvanized bars in high chloride concrete were coupled to black steel bars in relatively chloride free concrete at the bottom of the slab; the best case was when galvanized bars were used in both the top and bottom mats (Clear, 1981). Overall, these two comprehensive studies funded by FHWA contain data which indicate that galvanized bar, when properly used as the exclusive reinforcing material, can provide enhanced corrosion protection compared to black steel in equivalent concrete and exposure conditions.

Other data has also verified the enhanced field performance of galvanized reinforcement in both marine and bridge deck applications (for example, Stark and Perenchio, 1975; Stark, 1978, ILZRO, 1981; Stejskal, 1992). Surveys of many structures at various ages of exposure, some over 20 years, with varying concrete quality (as measured by w/c ratio and cover, for example) and very high-to-extreme chloride levels (to 10 times or more of recommended ACI levels) at the depth of the reinforcement, have consistently revealed that galvanized steel outperforms black steel where meaningful corrosion comparisons were able to be made. There was generally little or no evidence of red rust corrosion on the bars and only superficial corrosion of the zinc coating with perhaps 10-30% loss of coating thickness.

What is clear, however, is that in poor quality concrete, particularly high slump concrete with high w/c ratios which may be poorly compacted and with low cover to the reinforcement, galvanizing may delay the onset of chloride induced corrosion of the reinforcement, but this may be of limited benefit. It is interesting to note that in many of the reports where adverse findings of the benefit of galvanized reinforcement are cited (as reviewed by FHWA, 1976 and Swamy, 1990) specimens have been variously used with combinations of high w/c ratio concrete (0.65 to as high as 0.95 not being uncommon), low cover to the reinforcement (typically 12-25 mm), artificially admixed chlorides, and perhaps precracking of the specimens prior to exposure. Under these conditions it is little wonder that the corrosion delay due to the sacrificial protection afforded by zinc cannot be properly assessed.

3.1 Hot-Dip Galvanizing

Zinc can be applied to steel by many processes (e.g., electroplating, mechanical adhesion, thermal spraying and hot dipping), each process resulting in a characteristic range of coating thickness and metallurgical structure. The life of the zinc coating is directly proportional to its thickness and the nature of the environment to which it is exposed. Hot-dip galvanizing, used for the bulk of all structural steels sections including reinforcing bar, is the most important zinc coating process. The term galvanizing is generally taken to describe all zinc coating processes in which iron or steel is dipped into a bath of molten zinc (Porter, 1991).

The general layout of the hot dip galvanizing process is shown in Figure 1 (AGA, 1992). Scale, rust, oil, paint and other surface contaminants are removed by preliminary treatments, which may include abrasive blast cleaning, followed by acid cleaning or pickling in hydrochloric or sulphuric acids. The pre-cleaned steel is then fluxed with zinc ammonium chloride which removes the residual oxide film from the active steel surface, and the work is dipped into molten zinc at about 450 °C. On immersion in the galvanizing bath, the steel

GALVANIZING

Surface Preparation

Caustic Cleaning

Rinsing

Pickling

Rinsing

Flux Solution

Galvanizing

Molten Zinc Bath

Inspection

Cooling and Cleaning
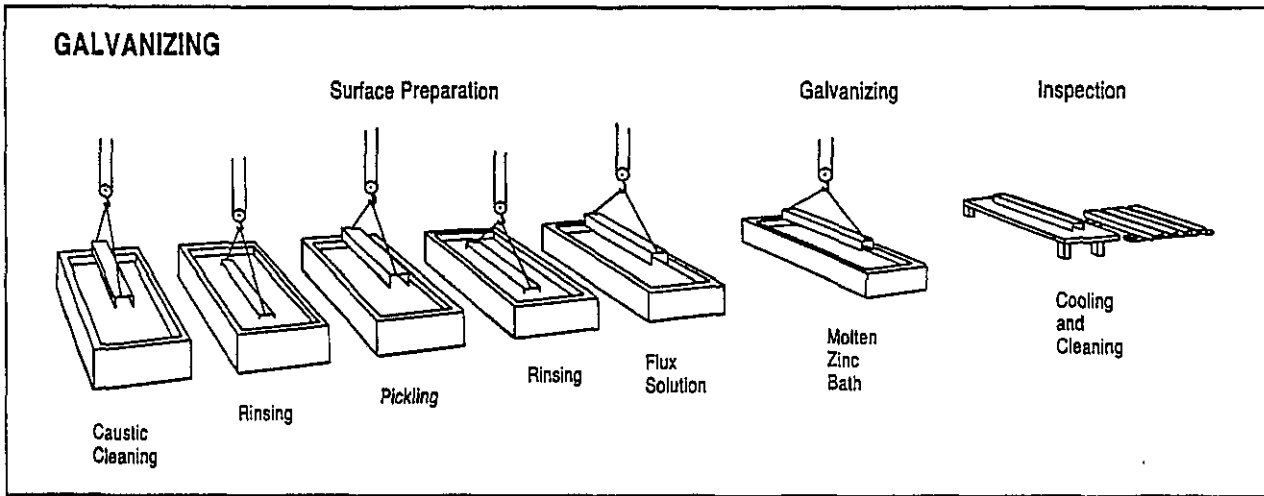
Figure 1. Schematic of Hot-Dip Galvanizing Process (AGA, 1992)
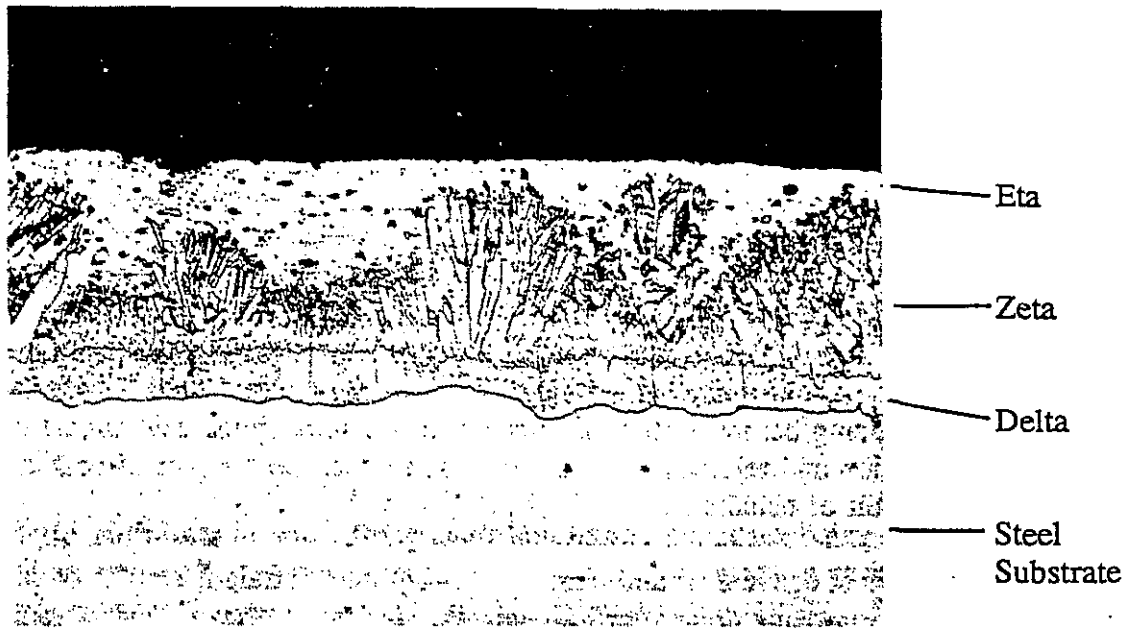

Eta

Zeta

Delta

Steel Substrate

Figure 2. Alloy Layers in Hot-Dip Galvanized Coating on Steel (x 200)

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surface is wetted by the molten zinc and reacts to form a series of metallurgically bonded zinc-iron alloy layers as shown in Figure 2. Each successive layer of the coating from the steel substrate outwards contains a higher proportion of zinc broadly identified as:

> *gamma* - a thin molecular layer containing 21-28% Fe;
> *delta* - containing 7-12% Fe,
> *zeta* - generally the thickest layer containing 5.8-6.2% Fe; and
> *eta* - a layer of relatively pure zinc at the outer surface which remains
> when the article is withdrawn from the zinc bath.

The *zeta* and *delta* alloy layers are somewhat harder than ordinary steels which, combined with the good adherence of the coating because of the metallurgical bonding, gives the coating superior abrasion and impact resistance. Of the alloy phases *delta* seems to be the most ductile and corrosion resistant.

The freshly galvanized steel is generally quenched in a water bath (which may contain chromate salts in solution) so as to halt alloy layer growth in the coating and facilitate immediate handling of the products. The purpose of the chromate treatment, for which a solution containing at least 0.2 wt% of sodium dichromate in water or a minimum of 0.2% chromic acid solution is required, is to prevent hydrogen evolution at the bar surface when in contact with fresh portland cement. However, the survival of the chromate film on galvanized rebars during storage for more than a few weeks or months cannot be guaranteed.

The thickness of the galvanized coating and the relative amounts of each alloy layer depends on many factors such as the composition of the steel (particularly the Si content) and its surface condition, the operating conditions of the bath, and the rate of withdrawal and cooling (Porter, 1991). Coating thickness is normally about 50-125 microns per surface on light steel products 1-5 mm thick, and 150-250 microns on products more than 5 mm thick.

While ASTM A 123 covers the requirements for hot-dip galvanizing of iron and steel products in general, ASTM A 767M deals specifically with zinc-coated (galvanized) steel reinforcement for concrete. The specified minimum weight of the zinc coating on the steel (10 mm nominal diameter and larger) is 1070 g/m^2 of surface for Class I coatings (equivalent to a coating thickness of 150 microns), and 610 g/m^2 for Class II coatings (86 microns thick). While a clear definition of Class I and II products is not given in A 767M, it is usual to assume that a Class I coating applies to structural, load bearing reinforcement, while Class II applies to architectural or non-load bearing bars (Wetzel, 1993). Guidance is also given on galvanizing before or after fabrication of the bars, finish and adherence of the coating, inspection and rejection criteria, and (when specified) repair of damage to the coating as a result of bending.

It is generally most convenient and economical to process straight lengths of reinforcing bar with all fabrication being done after galvanizing. During fabrication of galvanized bar, the tendency for cracking and flaking of the galvanized coating in the area of the bend increases with bar diameter and severity and rate of bend. Damage to the coating can be minimized by using large bend diameters and appropriately sized mandrels and formers, typically 5d or

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8d in size, where d is the bar diameter. On the whole, the methods used for the handling, fabrication and transportation of galvanized reinforcement are similar to those used for traditional steel reinforcement and no special requirements or techniques need be considered.

The A 767M standard indicates that some cracking and flaking of the coating in the area of the bend shall not be the cause for rejection, and that such damage is not subject to repair unless ordered in accordance with the supplementary requirements of the specification. Should repairs to the coating be required, a zinc rich formulation is used, generally an organic zinc rich paint, containing a high proportion of metallic zinc in the dry film. Though not specifically required, it is generally accepted that cut ends of galvanized bars should be repaired.

As an alternative to fabricating straight bars after galvanizing, prefabricated bars bent to special configurations or complete cage sections (e.g., spiral column reinforcement) can be galvanized. This offers the distinct advantage that little or no damage to the coating will occur as may be the case with normal fabrication practices.

3.2 Corrosion Protection to Steel

The zinc rich coating produced by galvanizing is continuous over the entire surface and so provides a tough envelope protection to the steel. On occasions, such as when the steel has not been properly pre-cleaned prior to immersion in the zinc bath, some bare areas may exist where the zinc has not reacted with the steel. This deficiency in the coating can be remedied by recycling the article through the pre-cleaning and galvanizing process.

In addition to the barrier protection afforded by the coating, zinc is anodic to steel and cathodically protects it by sacrificial dissolution should the steel substrate be exposed. The distance over which the steel is protected depends on the conductivity of the electrolyte. Typically, 5-10 mm wide gaps can be fully protected in air and a reduction of attack obtained over a wider area (Porter, 1991). For galvanized steel exposed in low conductivity (fresh) waters, protection is only afforded over a distance of 1-1.5 mm whereas in high conductivity seawater the protection distance may be up to several hundred mm (Uhlig, 1971). In addition, the relative areas of the zinc and the steel will influence the rate of dissolution of the zinc; in large anode (zinc), small cathode (steel) situations, the rate of dissolution of the zinc will be minimal whereas in the reverse situation of a large steel cathode and small zinc anode (e.g., an isolated galvanized item connected to a large steel component), the rate of zinc dissolution locally can be very high.

3.3   Zinc in Concrete

Zinc is amphoteric and reacts in both strong acids and bases, the attack being most severe below pH 6 and above pH 13. Between these values the rate of attack is very slow due to the formation of protective layers on the zinc surface (Rotheli et al, 1932). Zinc in concrete is passivated for pH values between about 8 and 12.5 due to the formation of zinc hydroxide and subsequently a complex calcium zincate compound which is relatively insoluble below

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pH 12.5. The reaction between zinc and the concrete constituents effectively ceases once the concrete has hardened.

The result of these reactions are reported to be the formation of a barrier layer of calcium hydroxyzincate accompanied by the evolution of hydrogen (Cornet and Bresler in ILZRO, 1981). Though hydrogen gas evolution may reduce the bond between galvanized plain (i.e., smooth) reinforcement and concrete and produce local porosity in the concrete, it can be prevented by either passivating the freshly galvanized bar in a dilute chromate solution, or by the addition of chromates to the concrete mixing water. In this way the zinc is not attacked by the fresh cement. Alternatively, since most cements contain small quantities of chromates, passivation will result providing at least 20 ppm of chromates are present in the final concrete mix (Porter, 1991).

While black steel in concrete typically depassivates below pH 11.5 (even higher in the presence of chlorides), zinc coated reinforcement can remain passivated to a lower pH (perhaps as low as pH 9.5) thereby offering substantial protection against the effects of carbonation of concrete. Zinc coated reinforcement can also withstand exposure to chloride ion concentrations several times higher (at least 4-5 times and perhaps much higher) than causes corrosion of black steel reinforcement (Tonini and Dean, 1976).

These two factors combined, namely carbonation resistance and chloride tolerance, are widely accepted as the basis for the superior performance of galvanized reinforcement compared to equivalent black steel reinforcement (Swamy, 1990). The total life of a galvanized coating in concrete is thus made up of the time taken for the zinc to depassivate, which is known to be longer than that for black steel because of both its carbonation resistance and higher tolerance to chloride ions, plus the time taken for the dissolution of the alloy layers in the coating. Only after the coating has fully dissolved in a region of the bar will localized corrosion of the steel commence.

During the so-called protection period when the zinc layers are dissolving, little or no disturbance of the cover concrete generally occurs, in sharp contrast to the situation when steel in concrete corrodes. The corrosion products of iron in concrete, for example Fe_2O_3, precipitate as a continuous dense layer at the bar surface and, because of the large volume change accompanying this (7.8 cc per mole of metal consumed), high localized swelling pressures are generated which soon crack the cover concrete. In contrast, when the zinc on galvanized bars in concrete corrodes, it has been postulated (Hoke et al, 1981) that the lower internal pressures so generated can be accounted for by three factors acting in unison, viz:

a)   zinc corrosion products, primarily ZnO, result in a smaller volumetric expansion (5.36 cc per mole of parent metal consumed) which is about one-third less than for equivalent iron oxides;

b)   zinc corrosion products are typically loose and powdery; and

c)   the loosely bound ZnO layer may be able to migrate away from the bar surface and fill cracks and voids in the cover concrete.

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Since it is the distress to the cover concrete which is the most destructive aspect of reinforcement corrosion, this beneficial characteristic of galvanized reinforcement needs to be thoroughly investigated. It does seem that the iron oxide layer locked in place at the interface produces large swelling pressures while the less voluminous and relatively non-adherent zinc corrosion products may be able to migrate from the interface area into the bulk concrete, thereby decreasing local stress and thus the likelihood of cracking of the concrete cover.

Another consideration when using galvanized reinforcement in concrete is the possibility of establishing a bimetallic couple between zinc and bare steel (i.e. at a break in the zinc coating or direct contact between galvanized steel and black steel bars). A bimetallic couple of this type in concrete should not be expected to exhibit corrosive reactions (which would result in the preferential dissolution of the zinc coating) as long as the two metals remain passivated. To ensure that this is the case, the depth to the zinc/steel contact should not be less than the cover required to protect black steel alone under the same conditions. However, once the metals have depassivated and are liable to corrosion, the sacrificial process will commence and the zinc will be consumed. In the context of small anode, large cathode corrosion (direct contact of galvanized steel to a large area of black steel), once corrosion has commenced it is likely that the period over which the zinc will cathodically protect the steel will be significantly reduced as previously discussed.

4. EPOXY COATED STEEL REINFORCEMENT

The coating of reinforcement with epoxies has been widely used since the mid-1970's to combat corrosion particularly in salt contaminated concrete, highway bridge decks and crash barriers, and severe exposure structures such as docks, parking garages, coastal and marine structures, and wastewater treatment plants. Epoxy coatings provide excellent corrosion protection to steel and the coating is not consumed in performing its function. The coating is essentially inert and highly resistant to both the alkaline environment of concrete and the penetration of chlorides. The barrier protection it affords to steel is due to the complete isolation of the steel from the environment (Clifton et al, 1973; Swamy and Koyama, 1987; Treadaway and Davies, 1989).

Properly applied and well adhered epoxy coatings are known to afford long term corrosion protection to embedded steel. In recent years, however, there has been a growing concern regarding the longevity of the protection afforded by epoxy coatings in aggressive environments (Clear, 1992), particularly the splash and tidal zones in marine structures (Zayed et al, 1989). The discussion has largely concentrated on three areas, viz: defects in the coating which to some extent must be allowed in the finished product (Clear and Virmani, 1983); damage to the coating during handling, fabrication and installation; and the possibility of decohesion of the coating during bending operations, particularly of large diameter bars. As a result, a great deal of emphasis is placed on the careful handling, forming and storage of epoxy coated reinforcement to minimize abrasion and mechanical damage, and touch-up of damaged areas of the coating is usually recommended.

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4.1 Fusion Bond Powder Coating

Typical fusion bond coating of steel bar (as shown in Figure 3) involves application of the epoxy powder to pre-cleaned and pre-heated bars in a production line process. Blast cleaning to near-white metal finish using steel shot or a grit shot mixture should be in accordance with Steel Structures Painting Council Specification SP10 (SSPC, 1985) with visual assessment to a standard such as National Association of Corrosion Engineers Standard TM-01-75: NACE No.2 (NACE, 1975). In addition to removing rust and mill scale, abrasive blasting greatly increases the surface area to which the coating can adhere. After cleaning, the bars are heated to approximately 230 °C and passed through the coating zone. The powder is electrostatically sprayed onto the surface[3] where it cures and hardens, then quenched by air or water to facilitate handling. In high speed production line processing, it is important that the line be run at such a speed to allow sufficient time for adequate curing prior to quenching. Most coating applicators prefer to have their equipment arranged to coat straight bars though a few have the capability to coat bent bars and pre-fabricated sections of reinforcement. Generally, shop fabrication (cropping and bending) is performed after the bars are coated (Gustafson, 1990).

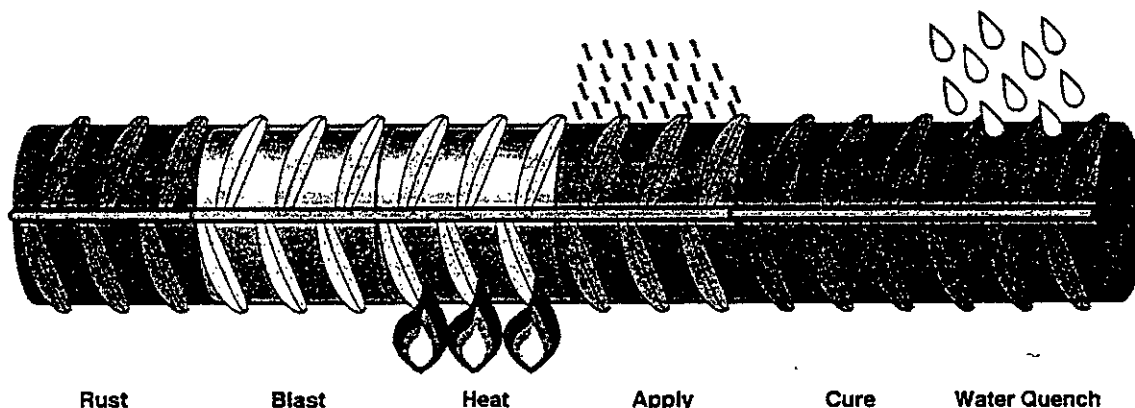| Rust | Blast | Heat | Apply | Cure | Water Quench |

Figure 3. Stages of Fusion Bond Coating Process

There are a number of standards dealing with epoxy coating of steel bar, mesh and wire for use in reinforced and prestressed concrete construction. For example, ASTM A 775 covers steel reinforcing bars with protective epoxy coating applied by the electrostatic spray method. Guidance is given on surface preparation and application of the coating, and specifies tests for thickness, continuity and adhesion of the coating. The specified film thickness after curing is 175-300 microns, based on the fact that the corrosion resistance of the bar increases

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3. Application of the powder by suspending the work in a fluidized bed is also possible.

with film thickness but the adhesion of the film to the bar is reduced. The coating shall be free of holes, voids, cracks, and deficient areas discernible to the unaided eye. Should such deficiencies occur during coating application, they are required to be patch repaired. Coated bars are tested at the manufacturer's plant with a 67.5 V, 80 000 ohm, wet-sponge type d-c holiday detector, and no more than an average of 6 holidays (pinholes not discernible to the unaided eye) per meter length of coated bar are allowed. Adhesion of the coating is evaluated by bending production coated bars at a uniform rate around a mandrel of specified size, typically 8d or 10d in diameter.

During handling, fabrication, transportation and storage of epoxy coated bars, damage to the coating may occur which is known to be detrimental to its corrosion performance. Accordingly, all systems for handling epoxy coated bars should have padded contact areas (e.g., nylon slings), and bundling bands should also be suitably padded. When lifting bundles of coated bars, excessive sagging should be prevented in order to minimize bar-to-bar abrasion, and bars or bundles of bars should not be dropped or dragged. Coated bars should be stored above the ground on wooden or padded supports, and appropriately protected from the elements. Repair of coating damage due to fabrication or handling is generally required if there is discernible loss of adhesion of the coating. Cut or sheared ends of coated bars should always be repaired. Loose or deleterious material should be removed from the surface, preferably by blast cleaning, and the cleaned area repaired with a patching material compatible with the coating material.

Other current standards for powder coated steel reinforcement are ASTM D 3963M and D 884, and AASHTO M 284M. ASTM D 3963M is similar in scope and intent to A 775M and specifies the same film thickness of 175-300 microns, but places considerable emphasis on prequalification of organic coatings for reinforcing bars. AASHTO M 284M is essentially identical to ASTM D 3963, though the allowable range of film thickness is 250 ± 50 microns. ASTM A 884 covers steel wire and welded wire fabric with protective epoxy coating, specified Class A coatings (180-430 microns thick) being intended for reinforcement in concrete. A further ASTM standard is being prepared for steel reinforcing bars which, prior to surface preparation, are pre-cut to length, pre-bent to final fabricated shapes and coated with pipeline type epoxies by the electrostatic spray process. In this standard, recommendations will be given regarding pretreatment of the cleaned steel prior to coating, and full cure of the coating with no forced water or air quenching of the coated steel after exiting the coating booth or post-application oven.

5. DISCUSSION OF COATING CHARACTERISTICS

It would seem that the most significant differences between the performance of epoxy coated reinforcement and galvanized reinforcement in concrete concern the method of corrosion protection afforded to the steel and the longevity of that protection. A summary of the characteristics and attributes of the two coatings is given in Table 2.

On the one hand, galvanizing produces a metallurgically alloyed coating tightly adhered to the steel. It affords sacrificial protection to exposed steel because of the anodic nature of

zinc compared to steel. When embedded in concrete, zinc is passivated (with associated hydrogen evolution) and corrosion of the coating does not commence until this passivity is destroyed. Because of both the higher chloride threshold and greater tolerance of carbonation effects of zinc compared to black steel in concrete, there will be a delay in the initiation of corrosion of the zinc alloy layers compared to uncoated black steel reinforcement. When the zinc depassivates and corrosion of the coating initiates, dissolution of the outer pure zinc layer occurs first, followed by progressive dissolution of the zinc-iron alloys in the coating. This process, which can be considered as the period during which the zinc coating is actively protecting the steel substrate, must be complete before exposure of the underlying steel and its subsequent corrosion will occur. There is thus a further delay to the initiation of corrosion of the steel substrate which, when combined with the initial period to the depassivation and initiation of corrosion of the zinc itself, equates to the effective life of the galvanized coating.

Table 2. Comparison of Coated Reinforcement Characteristics

CHARACTERISTIC	EPOXY COATED	GALVANIZED
Earliest use	1973	Early 1900's
Widely used	Yes	Yes
Cost	Comparable	Comparable
Application by	Fusion bonding	Hot dipping
- to straight bar	Yes	Yes
- to formed bar	Possible	Yes
- to fabrications	Possible	Yes
Coating thickness	200-300 microns	100-150 microns
Coating adhesion - dry	Good	Excellent
Coating adhesion - wet	Moderate	Excellent
Coating damage repair	Always	Sometimes
Coating toughness	Moderate	Excellent
Abrasion resistance	Moderate	Excellent
Special handling	Yes	No
Barrier protection	Yes	Yes
Cathodic protection	No	Yes
Chloride resistance	Excellent	Good

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Epoxy coatings, on the other hand, protect reinforcement because of the complete isolation of the steel from the environment, there being no sacrificial component. When epoxy coated steel is cast into concrete, it can be expected that any exposed steel would be passivated (and remain so) in much the same way as black steel in concrete is passivated, and so corrosive attack will not commence until depassivation occurs. Once corrosion commences, however, it can proceed freely because there is no further protection afforded to the steel. Corrosion can also spread under the adjacent coating leading to disbonding of the coating in that region. Should the epoxy coating not be properly adhered to the steel when coated bar is cast into concrete, even though the coating remains intact and apparently has no holidays, the underlying steel will not be passivated because it is not in contact with the concrete mix and underfilm corrosion can be expected.

It would appear that the main limitation to more widespread use of galvanized reinforcement is its reduced service life in conditions when very high chloride concentrations accumulate in concrete. This effect is exacerbated in poor quality concrete with shallow cover to the · reinforcement. The fact that the coating is consumed in providing corrosion protection to steel may be considered as a further limitation, though this must be judged against the extension of life to first maintenance when using galvanized reinforcement compared to that expected for black steel in equivalent concrete and exposure conditions. As for epoxy coated steel, its propensity to damage during handling, the likelihood of decohesion of the coating leading to underfilm corrosion or direct corrosion at points of damage to the coating where the steel is exposed, also place a limit on its long term performance in concrete (Sagues, 1991). Again, once this corrosion commences it can proceed unchecked.

In this regard, it is interesting to note that the FHWA has, on at least two occasions, recommended interim measures to minimize corrosion problems in fabricated epoxy-coated bar applications (FHWA, 1987). This was in response to a number of difficulties encountered with corrosion in fabricated epoxy coated bars, particularly with smaller radius bends of coated bars which pass the holiday test requirements but develop cracks later in the field, and the poor performance of field applied patch repairs. The specific FHWA recommendations were:

a)   suggest fabrication (i.e., bending) prior to applying the epoxy   coating, though noting that processing in the reverse order (coating then fabrication) was the norm;

b)   modify the bending requirements for all bends within 100 mm of the concrete surface and use large bend radii where possible;

c)   repair any evidence of failure (i.e., cracks, including hairline cracks, and debonded areas) of the coating caused by bending; and

d)   check bends for cracking or debonding just prior to installation.

These measures reflect the growing concern that the presence of holidays in the coating, poor adhesion, and fabrication damage to the coating resulting in cracking and debonding, are the

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most serious limitations to the durability of epoxy coated reinforcement in chloride contaminated concrete (Babaei and Hawkins, 1988). The present emphasis on improving coating practices and quality control, the use of more flexible coatings where fabrication after coating is undertaken, and the coating of prefabricated bars and components (as reflected in the proposed ASTM Standard) should go a long way to overcome many of the present difficulties with epoxy coated reinforcement.

It is clear that neither coating can guarantee complete avoidance of reinforcement corrosion over the life of a structure under severe exposure conditions. Their relative success can however be judged by the resultant delay to the initiation of corrosion of the underlying steel compared to the corrosion of uncoated reinforcement in equivalent circumstances. If this delay means, for example, that a 5-10 year repair cycle on a bridge deck or carpark floor can be postponed to perhaps a 10-15 year cycle, the cost savings in labor and materials alone through the life of the structure - typically 30-50 years - would likely more than compensate for the initial first cost of the coated reinforcement.

5.1 Duplex Coatings

It is well known that surface coatings, generally paints or fusion bonded powders, extend the life of galvanized steel (Gambrell, 1987). This combination of coatings on steel, often called a duplex coating, is being increasingly used in a number of areas but most widely in the automotive industry and consumer product markets, as well as the manufacture of structural steel products for outdoor exposure. The coating initially delays attack on the zinc by isolating it from the environment though, where the coating is damaged, the zinc suppresses attack on the underlying steel.

Corrosion products formed at the coating/metal interface do not undercut coatings on zinc as they do on steel and, as a result, progressive detachment of coatings on zinc may not occur to the same extent as for organically coated steels. This phenomena is reflected in ASTM D 2803 dealing with test methods for filiform corrosion between organic coatings and a substrate. The standard recommends that steel is the preferred substrate though other metals such as aluminum, copper and stainless steel may be used, but zinc and zinc-coated steel are not recommended because filiform corrosion generally does not occur on zinc.

The corrosion resistance of a properly applied duplex coating is normally greater than the sum of the lives of the two individual components. This synergic effect typically increases the life of the duplex coating by a factor of 1.8-2.0 times in severely polluted environments, 1.5-1.6 in seawater, and 2.0-2.7 in non-aggressive rural environments. Proper application of the top coat is critical and pretreatment of the zinc is required to ensure good adhesion. Compatibility of the top coat with the zinc and also to the environment where it is to be exposed must be ensured in order to optimize the benefits of duplex coating (Porter, 1991).

Powder coating of galvanized steel with polyesters, polyurethanes and epoxies, is widely used to give more durable finishes than paint. A high standard of housekeeping and monitoring of the coating process is vital to ensure good adherence and freedom from pinholing and blistering. Pinholing, which appears to be the most persistent problem, can be

controlled by preheating heavier sections prior to powder coating and, on all section sizes, ensuring that the powder is fully cured with sufficient time at the curing temperature. The introduction of additives to the powder which allow longer setting times for air and other gases to escape through the powder before it sets have been shown to decrease the risk of pinholing on thick steel (PRA, 1992). Alternatively, a heat treatment at 200-220 °C can be employed for this purpose (Porter, 1991).

As far as steel reinforcement is concerned, the above commentary suggests that duplex coating (i.e., galvanized and then powder coated) may provide an opportunity for superior corrosion protection in concrete. The barrier effect of the powder coat layer (which may not need to be an epoxy in this case) would extend the life to the initiation of corrosion of the zinc coating, while the presence of the zinc would prevent localized attack at holidays and other points of damage to the epoxy coating. In this way, each layer of a duplex coating would compensate for the likely shortcoming of the other, namely high chloride attack on zinc on the one hand, and localized corrosion at breaks in the epoxy coating on steel on the other.

There is very little technical information on the behaviour of duplex coated steel reinforcement in concrete. In one reported study, galvanized and PVC-coated reinforcing steel was investigated, but no meaningful data on the duplex effect was obtained because the chosen PVC-coating was chemically unstable in the highly alkaline environment of concrete (Nurnberger and Beul, 1991). In the US, galvanized steel spiral wire and welded wire mesh reinforcement are commercially fusion bond coated with pipeline quality epoxy powders (Ramirez, 1993).

5.2 Future Developments

A number of areas present themselves for improvement and future development of coated reinforcement with superior corrosion protection characteristics. It is clear there is a lot to be gained from improved control and refinement of manufacturing processes and fabrication methods for existing coated steel reinforcement.

In particular, the minimization of manufacturing defects and fabrication damage to epoxy coated bars, and modified handling and site practices to ensure the coating remains well adhered to the steel and is largely defect free, will likely considerably increase its already good corrosion performance. In this context, the obvious benefits of powder coating pre-fabricated reinforcement, which avoids much of the fabrication induced damage and the need for touch-up repairs, is also likely to become more widely accepted and routinely specified.

For galvanized reinforcement, detailed investigation of the mechanisms whereby zinc passivates and then corrodes in concrete, and knowledge of the precise chloride thresholds for these processes, is vital to an improved understanding of the beneficial attributes of zinc coating. More widespread galvanizing of pre-fabricated reinforcement will also eliminate some potential problem areas regarding fabrication damage to the coating and touch-up of cracked and flaked regions, and cut-ends of coated bars.

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As discussed, duplex coatings for reinforcement, particularly powder applied epoxy over a zinc base, appear to offer considerable potential corrosion advantage and is clearly a technology which needs to be thoroughly investigated. Areas requiring detailed investigation will likely include:

a)   the choice of metal for the active metal layer, though zinc appears to be best suited for this purpose;

b)   the method of application of the active metal layer to the steel, for example by hot dipping, thermal spraying, or other coating processes;

c)   the use of pretreatments to the active metal surface (in particular zinc) to ensure proper adhesion and curing of the organic top coat;

d)   the choice of powder for the top coat, which could be either epoxy or polyester based, and may not need to be of the same type in use for existing powder coated reinforcement; and

e)   the method of application of the powder, which could be by electrostatic spraying, fluidized bed immersion, or other coating processes.

6. CORROSION TESTING OF COATED REINFORCEMENT

Over the period 1988-1991, a series of accelerated corrosion investigations were undertaken in which the performance of coated steel reinforcement in concrete was studied (Yeomans, 1989; Yeomans and Novak, 1990). The work was supported by the International Lead Zinc Research Organization under ILZRO Project ZE-341. Hot dip galvanized steel, fusion bonded epoxy coated steel, and uncoated (so-called) black steel reinforcement were embedded in identical cylindrical concrete specimens and exposed to cyclic wetting and drying in 3.5% salt solution and continuous salt fog. Of particular concern was the ability of the coating system to protect the reinforcement at variable depth of concrete cover in moderate-to-high chloride situations, and the effects of damage to the coatings such as at cut ends which may or may not be repaired.

6.1 Materials and Specimen Geometry

All reinforcement was 16 mm diameter deformed (i.e.,, ribbed), quenched and auto-tempered steel with a minimum yield stress of 410 MPa. The zinc coated steel was hot dip galvanized resulting in a typical coating thickness of 110-150 microns, such as would be required for a Class II coating to ASTM A 767M (minimum specified coating thickness of 86 microns). Repairs to the cut ends of galvanized bars used a zinc rich priming paint applied to a dry, wire brushed surface. The epoxy coating was electrostatically applied to straight lengths of bar by the fusion bond process resulting in an average film thickness after curing of about 175 microns. This value was at the lower end of the range of film thickness as required, for example, in ASTM A 775M (180-300 microns), but individual measurements were generally

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Table 3. Mix Proportions and Properties of Concrete

Coarse aggregate size	10 mm
Mixing water content	225 kg/m^3
Cement content (Type A cement)	281 kg/m^3
Coarse aggregate content	828 kg/m^3
Fine aggregate content (sand)	986 kg/m^3
Water-to-cement ratio	0.80
Slump	80 mm
28 day strength	29 MPa

above the 130 micron lower limit. Cut ends of epoxy coated bars were repaired with a proprietary patching compound supplied by the powder manufacturer and applied in accordance with their recommendations.

Reinforced concrete cylinders 150x300 mm were cast with either Type A or Type B reinforcement geometry as shown in Figures 4 and 5. Type A specimens with 150 mm lengths of reinforcement embedded vertically with 10-15 mm concrete cover were used for half-cell potential surveys, corrosion assessments and metal loss determinations; and Type B specimens, used for the majority of the corrosion assessments, contained a "tree" of reinforcement, the vertical piece of which had no concrete cover at its ends while the lateral pieces had cover to their ends in the range 10-40 mm. One type of reinforcement only (i.e., black or coated steel) was used in each specimen. Additional plain concrete cylinders were cast for compressive strength testing and chloride ion determination.

Prior to casting, the black steel reinforcement was lightly sand blasted to remove all surface scale and rust. The epoxy coated and galvanized reinforcement were washed and rinsed clean. For the Type A specimens, both cut ends of the coated reinforcement pieces were repaired as indicated above, while for the Type B specimens one cut end only of each piece of reinforcement was repaired.

The details of the mix design and properties of the concrete are given in Table 3. The concrete was lightly rodded and vibrated to ensure adequate compaction. All corrosion specimens were fog room cured for 7 days immediately after demoulding while the compression cylinders were fog room cured for 28 days.

6.2 Exposure Environments and Assessment Methods

Two accelerated corrosion environments were used; cyclic salt water wetting and drying and continuous salt fog. The wetting and drying cycle comprised three days wetting fully
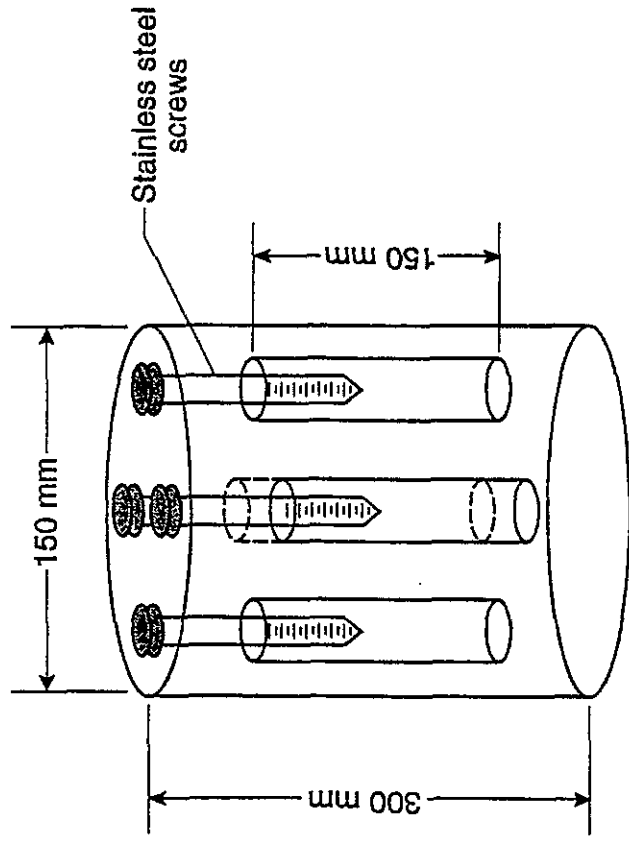
Figure 5. Type B Corrosion Specimens Showing Approximate Concrete Cover to Bar Ends

Figure 4. Type A Corrosion Specimens for Half-Cell Potential Surveys and Weight Loss Determinations

immersed in 3.5% sodium chloride solution at 40 °C followed by oven drying for four days at 60 °C. The continuous salt fog exposure was at 40 °C and 100% relative humidity and also used a 3.5% sodium chloride solution.

Half-cell potential surveys of all Type A specimens were done at regular intervals during the exposure testing using a copper-copper sulfate (CSE) reference electrode according to ASTM C 876. The permanent connection to the fully embedded reinforcement was via a heat shrink plastic clad stainless steel screw which was shown to have no influence on the potentials determined. All readings were taken on the specimens immediately after their removal either from the salt water bath or the salt fog cabinet.

Samples for chloride analysis were drilled from the plain concrete cylinders using a 12 mm carbide tip bit in an impact drill. Initially, four equi-spaced 10 mm deep holes were drilled on the long axis of the cylinder, and the powder from each hole was collected and mixed. Two chloride determinations were made using this averaged sample of concrete. Drilling and sampling from each hole was continued in increments of 10 mm to a maximum depth of 50 mm. Prior to returning the cylinders to the exposure chambers, the holes were sealed with an organic two-component filling material. The second and third samplings were equi-spaced around the circumference of the cylinder. The acid soluble chloride content was obtained by dissolving the sample in nitric acid followed by potentiometric titration with silver nitrate according to ASTM C 114. All chloride ion concentrations are reported as percent by weight of cement.

At intervals during the exposure period, specimens were split open and the reinforcement removed for examination and assessment of the extent of corrosion activity. The weight loss of the black steel bars was determined by the method recommended in ASTM G1 using Clarke's solution. Estimation of the zinc coating thickness loss was by metallographic sectioning, polishing and etching.

7. EXPERIMENTAL RESULTS AND DISCUSSION

7.1 Corrosion Assessment

A summary of the extent of corrosion observed on the reinforcement in both accelerated environments is given in Figures 6 and 7. The corrosion depth indicated refers to the depth below the cylindrical surface of the Type B specimens at which either well progressed corrosion was observed (hatched bars) or where corrosion was not actively progressing but was likely to have initiated (non-hatched). Chloride penetration profiles for the concrete in each environment are given in Figures 8 and 9, and data for the weight loss of black steel reinforcement is given in Table 4 and Figure 10.

Of the three types of reinforcement, uncoated black steel was the most susceptible to corrosion even at relatively low chloride levels, with early cracking and disruption of the cylinders due to the expansive forces generated by the corrosion products. Over the 132 day test period, corrosion was well progressed on the reinforcement some 30-40 mm below the
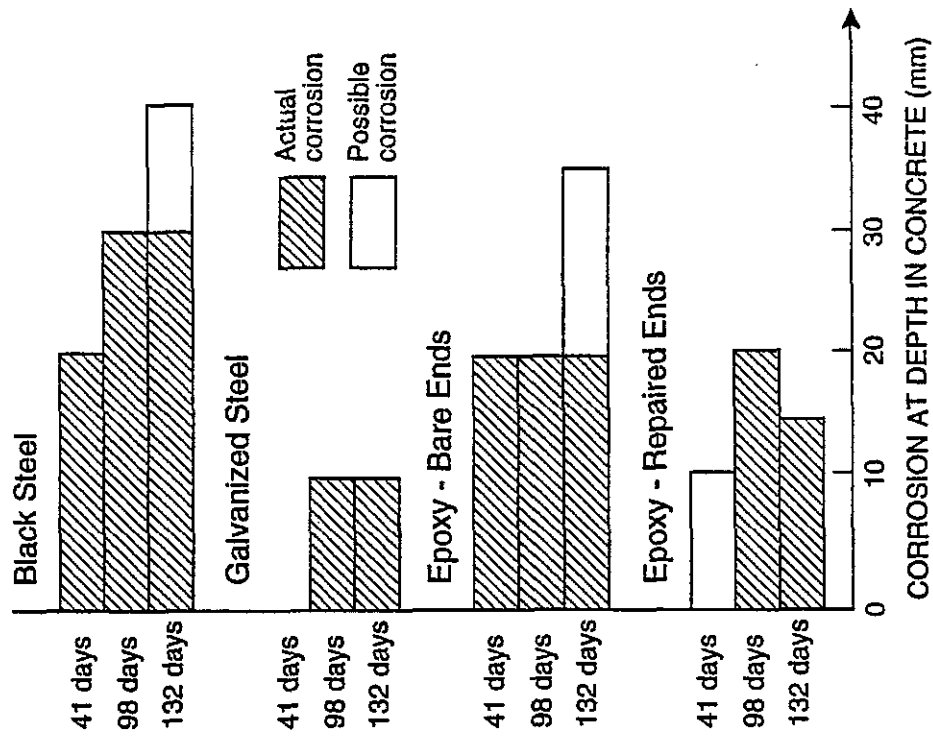
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SALT FOG EXPOSURE

Figure 7. Corrosion Activity in Continuous Salt Fog Exposure
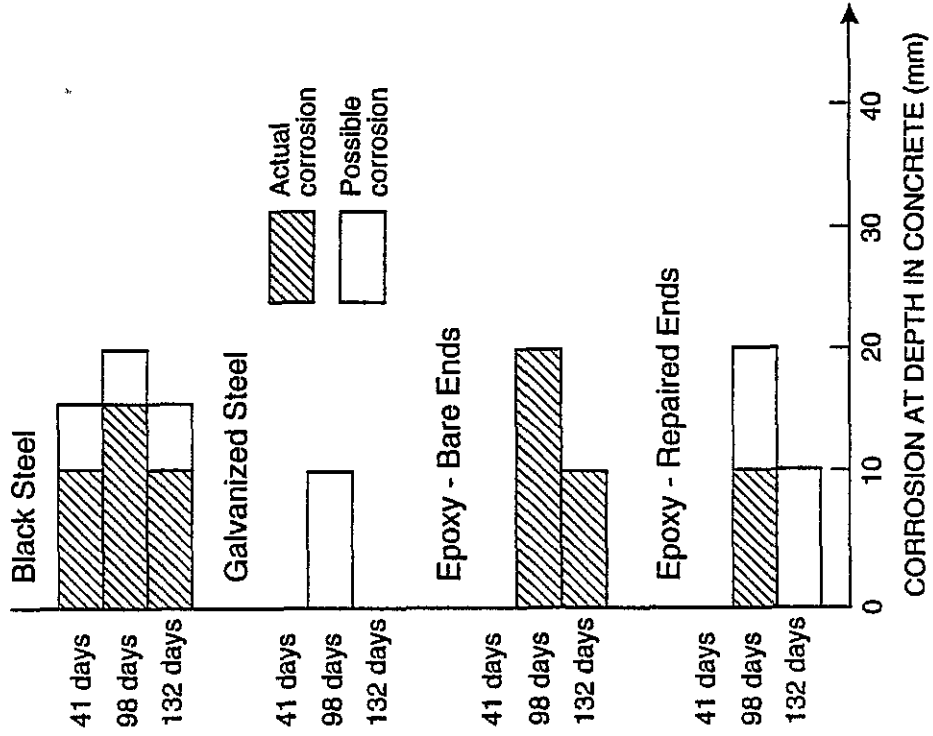
WET AND DRY EXPOSURE

Figure 6. Corrosion Activity in Cyclic Wet and Dry Exposure

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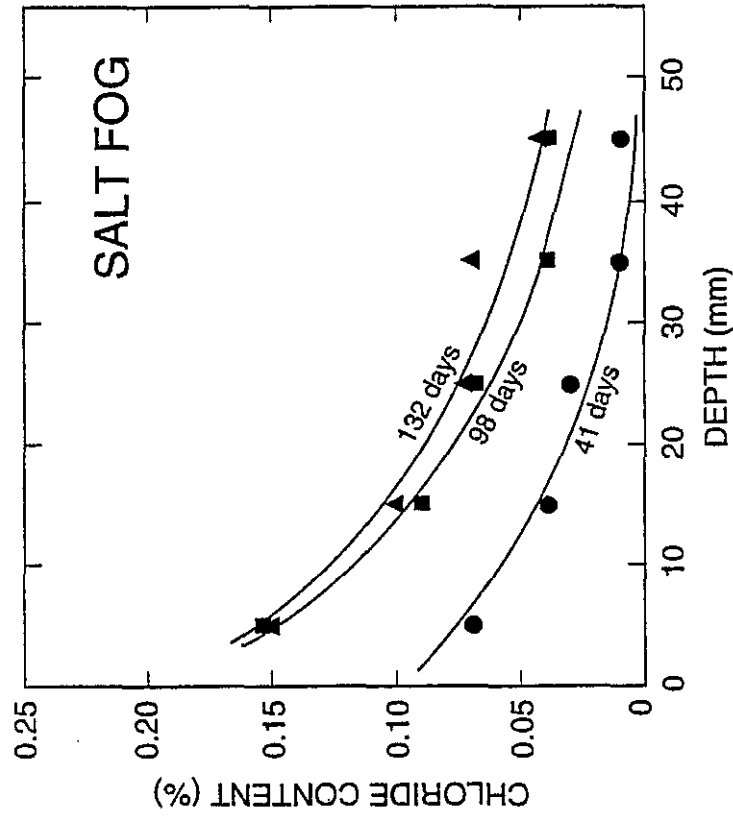
Figure 9. Chloride Profiles in
Continuous Salt Fog Exposure
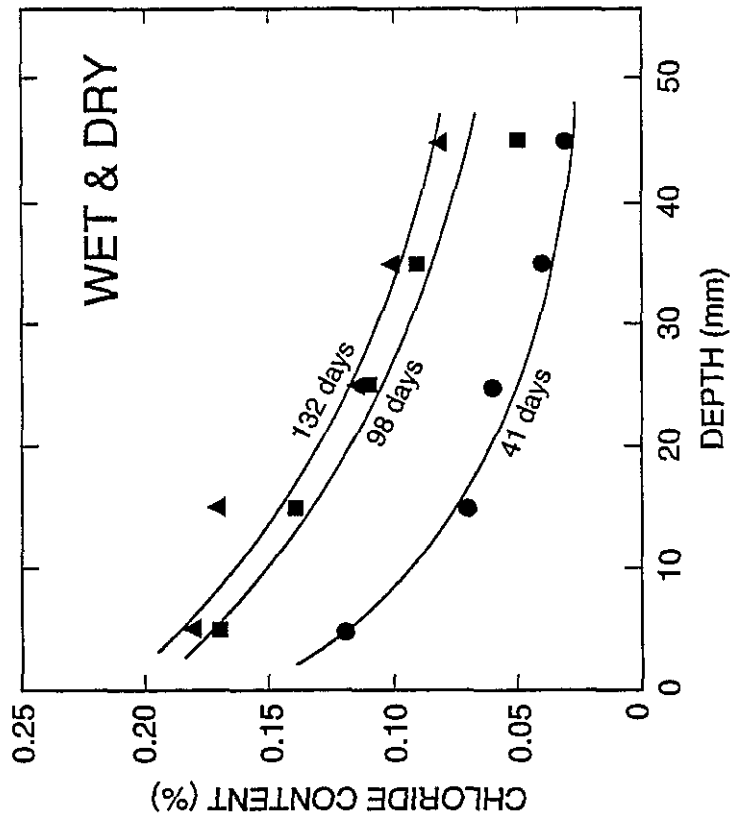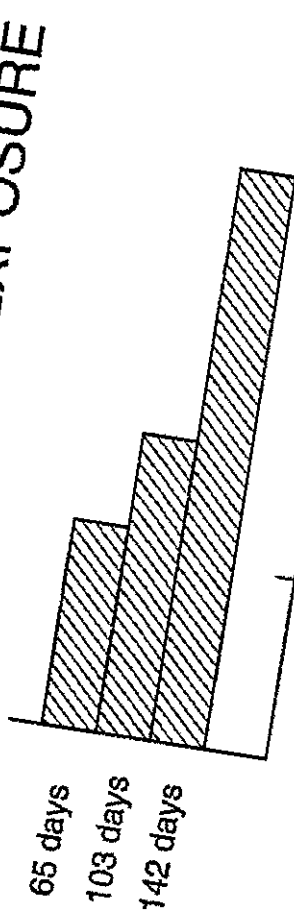

Figure 8. Chloride Profiles in
Cyclic Wet and Dry Exposure

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Figure 10. Weight Loss of Black Steel with 10-15 mm Depth of Cover

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concrete surface in the wet and dry exposure, and 10-20 mm in the salt fog. In some cases the bars were deeply pitted and in areas where adjacent pits had possibly coalesced, there were broad depressions where considerable metal loss and reduction in area had occurred.

The data in Table 4 (and as shown in Figure 10) indicates an increasing weight loss from the black steel in both exposure conditions. While weight loss data is a useful indicator of corrosion activity, it is more common to convert such data to a corrosion rate such as the mass or depth of metal loss per year (Treadaway et al, 1989). By assuming that metal loss is uniform over the whole surface and that the corrosion rate is constant during the period of exposure, an average rate of corrosion of 272 microns/year in the cyclic wet and dry exposure and 14 microns/year in the continuous salt fog resulted. An average value for both exposure conditions is given since the individual values determined for each exposure period were not significantly different, indicating that the respective corrosion rates remain essentially constant with time.

It is important to note that these values probably underestimate the actual rate of corrosion since, on the one hand, metal loss is not uniform due to the pitting observed and, on the other, the corrosion rate is not constant because of the existence of an initiation period for corrosion during which little or no metal loss occurs. Despite this, it is clear that the cyclic wet and dry regime resulted in a corrosion rate some 20 times higher than the continuous salt fog exposure.

The bar graph data in Figures 6 and 7 indicate that galvanizing significantly reduced the incidence of corrosion compared to black steel in both exposure conditions. The extent of this reduction however was much more noticeable in the salt fog (Figure 7) where virtually no corrosion of the galvanized steel occurred in the concrete over the test period.

Table 4. Weight Loss Data and Corrosion Rate for Black Steel
in Concrete with 10-15 mm Depth of Cover

EXPOSURE CONDITION	DAYS	WEIGHT LOSS		CORROSION RATE (microns/year)	
		Total (g)	Yearly (g/yr)	Individual	Average
Cyclic Salt Water Wet and Dry	65 103 142	2.52 3.88 7.88	14.15 13.75 20.08	241 233 341	272
Continuous Salt Fog	67 116 142	0.14 0.07 0.59	0.76 0.22 1.52	13 4 26	14

During the inspection periods when the concrete cylinders were split open, it was observed that a grey/white precipitate initially formed at the zinc/concrete interface[4], the presence of which was taken to indicate that the zinc and iron-zinc alloys in the coating were dissolving and thereby sacrificially protecting the steel. Over this period, no corrosion of the steel substrate occurred and there was no visible disruption to the concrete mass. Once the zinc coating was lost from the reinforcement surface however, corrosion of the steel substrate followed with consequent rust staining and cracking of the concrete.

In the cyclic wet and dry environment, corrosion of the exposed ends of galvanized bars with no concrete cover occurred within 41 days with some corrosion to about 10 mm depth after 98 days and beyond. In the continuous salt fog, a similar amount of corrosion was observed at the exposed end after 41 days though very little or no corrosion occurred at depth in the concrete over the remainder of the test period to 132 days. The repairs to cut ends of the galvanized bars performed well and there was essentially no difference in the performance of the repair to that of the galvanized bar itself. It was also evident that steel exposed at non-repaired cut ends was being protected from localized corrosion due to the presence of the zinc on the adjacent bar surface for it was noted that the bare steel ends of galvanized bars embedded in the concrete were not corroding. This gives an indication of the distance over which zinc will protect steel in concrete, in this case to at least the radius of the bars themselves (i.e., 8 mm).

The epoxy coating generally provided excellent corrosion protection to the steel and was largely unaffected throughout the period of exposure, even in high chloride situations. However, at cut ends and isolated points of damage to the body of the coating, the performance of the epoxy coated reinforcement was similar to that of black steel in equivalent circumstances. At cut ends which were not repaired, localized severe corrosion occurred at about the same time and depth in the concrete as was the case for black steel, and in several instances corrosion penetrated along the bar under the adjacent coating with subsequent detachment of the coating. Over the 132 day test period, corrosion of non-repaired cut ends of epoxy coated bars was observed 20-35 mm within the concrete for the wet and dry exposure and 10-20 mm in the salt fog. Where repairs to the coating had been done, it was apparent that the steel substrate was still susceptible to corrosion by localized failure of the repair patch, corrosion being observed (over the same period) at depths of 10-20 mm in the wet and dry exposure and to about 10 mm in the salt fog exposure.

7.2 Chloride Penetration

The cyclic wet and dry exposure clearly resulted in more severe attack on the reinforcement than the continuous salt fog and this can largely be attributed to the higher levels of chloride penetrating the concrete. From Figure 8 it is clear that a very rapid build up of chlorides

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4. The reaction product was not analyzed but, in light of other evidence (Pfeifer et al, 1987), is likely to be either zinc oxide or zinc hydroxychloride, both of which have extremely low solubility products in the range 10^{-15} to 10^{-17} (reported in Porter, 1991).

occurred at depth in the wet and dry exposure with chloride concentrations in excess of 0.1% only to a depth of 30-35 mm after 98 days. In the salt fog (Figure 9), the chloride levels were much lower, with concentrations above 0.1% to about 15 mm depth only after 132 days.

A chloride limit of 0.1% by weight of cement has been recommended for conventional reinforced concrete in a moist environment and exposed to chloride (ACI, 1992). For chloride concentrations above this limit, corrosion is likely if moisture and oxygen are readily available; if below this limit, the risk of corrosion is low. On this basis, it is apparent that all reinforcement to a depth of about 35 mm in the wet and dry was exposed to an unacceptable level of chlorides within the test period. At lesser concrete covers, the reinforcement was exposed to chloride levels up to twice the limiting value (about 0.2% near the concrete surface) and thus liable to rapid attack. For the salt fog exposure, reinforcement within the top 15 mm of cover only was likely to be adversely affected by the chlorides, the surface concentrations being around 0.15%.

The effect of these chloride levels is most clearly seen in the comparative weight loss data discussed above. There is about an order of magnitude greater weight loss at each exposure interval in the wet and dry compared to the salt fog and, as previously indicated, an overall difference in corrosion rate of about 20 times. In the wet and dry, expected chloride concentrations at the 10-15 mm position were 0.11-0.15% over the 65-142 day test interval, though lower chloride levels of 0.05-0.11% were likely in the salt fog.

By comparing the corrosion assessments in Figures 6 and 7 and the chloride concentration profiles in Figures 8 and 9, it is possible to estimate threshold chloride concentrations at which corrosion was observed for the black steel and galvanized steel reinforcement in each environment (see Table 5). From this it can be shown that the ratio of the chloride concentration required to cause corrosion of galvanized steel (at any depth of cover) is always more than 1.5 times that for corrosion of black steel and, realistically, may be 2.5 times or more greater.

Table 5. Chloride Thresholds for Corrosion of Black and Galvanized Steel in Concrete

EXPOSURE	BAR TYPE	41 DAYS		98 DAYS		132 DAYS	
		Depth	% Cl⁻	Depth	% Cl⁻	Depth	% Cl⁻
Cyclic Wet & Dry	Black	20 mm	0.06	30 mm	0.10	40 mm	0.10
	Galvanized	0 mm	>0.15	10 mm	>0.15	10 mm	>0.17
Continuous Salt Fog	Black	15 mm	0.04	20 mm	0.08	15 mm	0.10
	Galvanized	0 mm	0.10	10 mm	>0.15	0 mm	>0.15

The factor of 1.5 is given because in several cases a lower bound only, not an absolute chloride concentration, can be inferred from the data available for the galvanized steel and, at these concentrations, corrosion had not necessarily commenced at depth in the concrete. These results are in general agreement with published data which gives a chloride threshold for corrosion of galvanized reinforcement typically several times that which can be tolerated by black steel in equivalent circumstances (ILZRO, 1981; Tonini and Dean, 1976).

7.3 Half-Cell Potential Surveys

Copper-copper sulphate half-cell potential surveys were done throughout the exposure period on each type of reinforced concrete cylinders. Though potential mapping is a commonly used method for assessing the condition of steel reinforcement in concrete, the measured potential is only an indicator of corrosion activity and does not predict the rate or extent of corrosion (ASTM C 876).

Comparisons of the half-cell potentials for the black steel and epoxy coated steel reinforcement are given in Figures 11 and 12. It appears that both steel types behave similarly though it is important to note that while the black steel exhibited considerable corrosion activity once its potential reached about -550 mV, the epoxy coated steel was not showing any noticeable corrosion (at about the same potential) over the test period. The results suggest that the presence of holidays in the epoxy coating, whereby the underlying steel was locally exposed, was responsible for the observed potential shift even though the steel was not noticeably corroding. This is an example of a situation where large negative potentials do not necessarily indicate corrosion activity of steel in concrete, and also suggests that half-cell measurements cannot be reliably used to assess corrosion of epoxy coated reinforcement.

Of greater interest was the variation in half-cell potential with time for black compared to galvanized steel in concrete as shown in Figures 13 and 14. This comparison revealed the delay period over which the galvanizing actively protected the steel against corrosion. At the beginning of the exposure period, both steels were passivated and their half-cell potentials were approximately -150 mV for black steel and -650 mV for galvanized steel. The difference between these values (about 500 mV) is of the order of the difference in electrode potential expected between iron and zinc in various electrolytes (e.g., 420 mV in sea water). At a later time, presumably once depassivation had occurred, the potential of the black steel changed to about -550 mV, while that of the galvanized steel initially changed to a potential around -1050 mV which is the potential zinc should give against $Cu/CuSO_4$ (Shrier, 1978).

Once the potential of the black steel reached -550 mV, active corrosion was observed as would be expected and little further change in the potential occurred while corrosion continued. For the galvanized steel however, the potential gradually increased from -1050 mV to about -600 mV over a period of time, the duration of which depended on the severity of the exposure conditions. It was during this period of increasing potential that the reaction products previously noted were observed on the zinc surface; at the end of this period the zinc and zinc alloys were essentially lost from the galvanized steel surface, corrosion of the steel substrate commenced and the potential remained essentially constant thereafter.
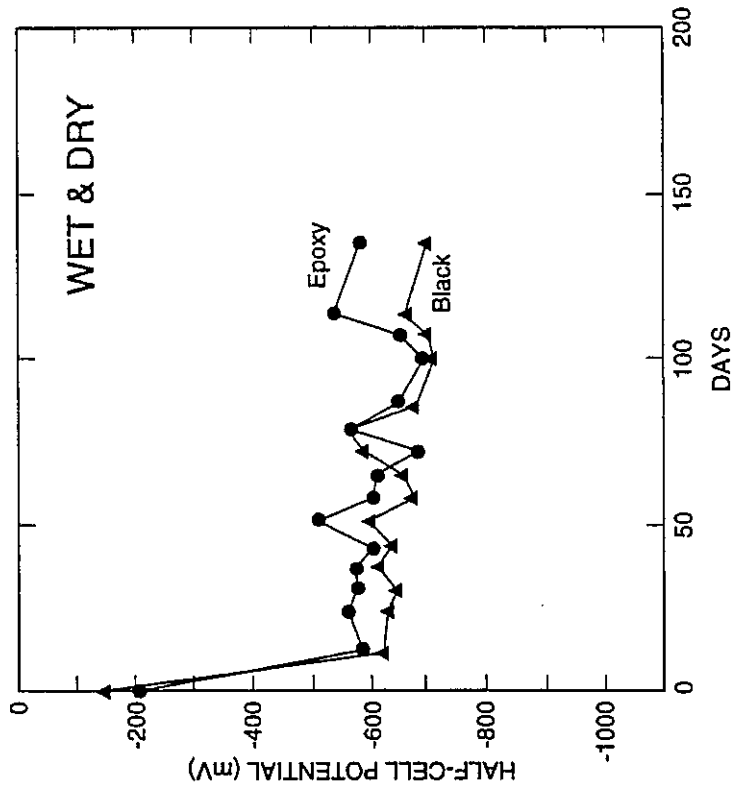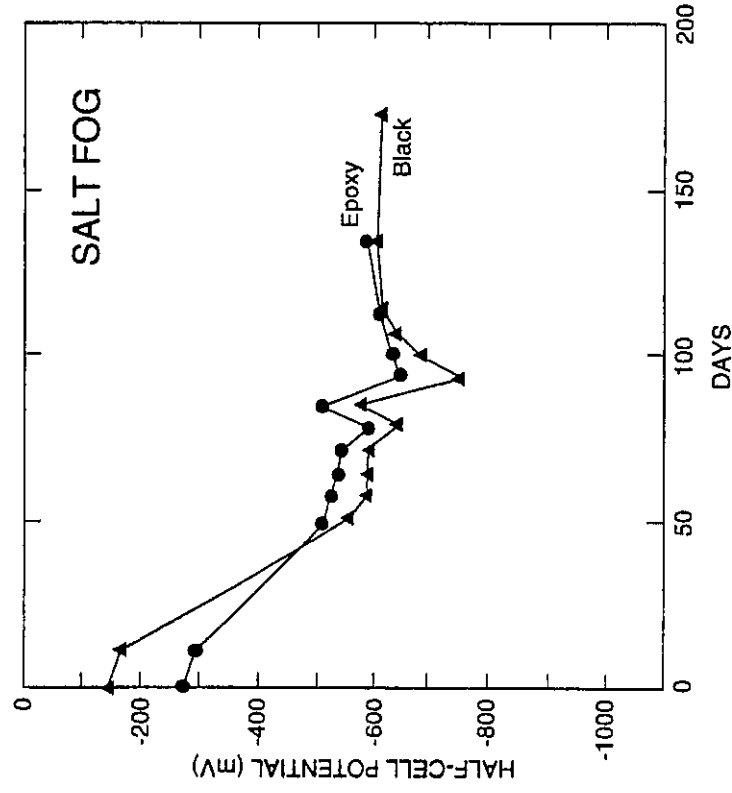
Figure 12. Half-Cell Potentials for Black Steel and Epoxy Coated Steel in Continuous Salt Fog Exposure

Figure 11. Half-Cell Potentials for Black Steel and Epoxy Coated Steel in Cyclic Wet and Dry Exposure
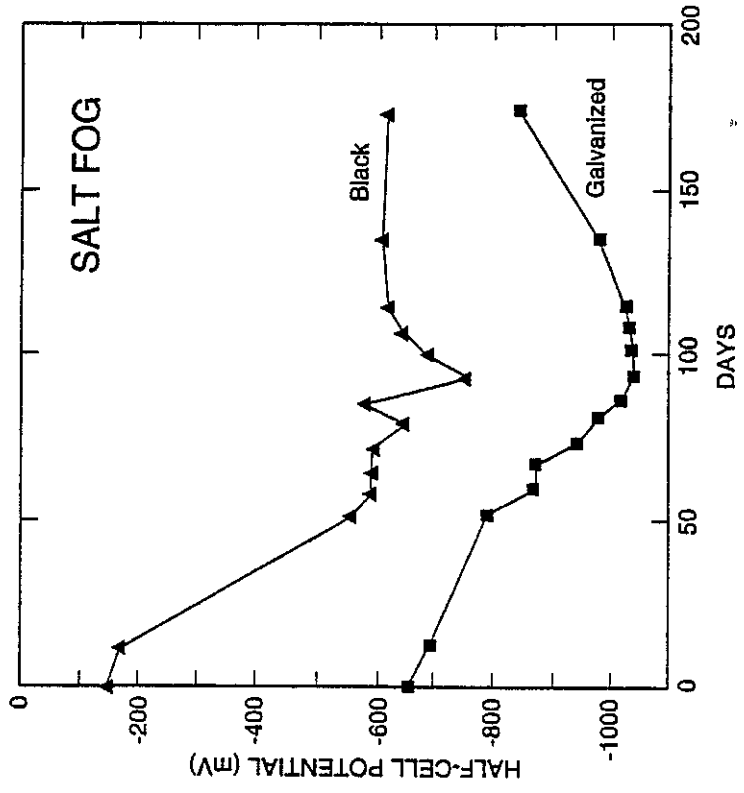
31

Figure 14. Half-Cell Potentials for Black Steel and Galvanized Steels in Continuous Salt Fog Exposure
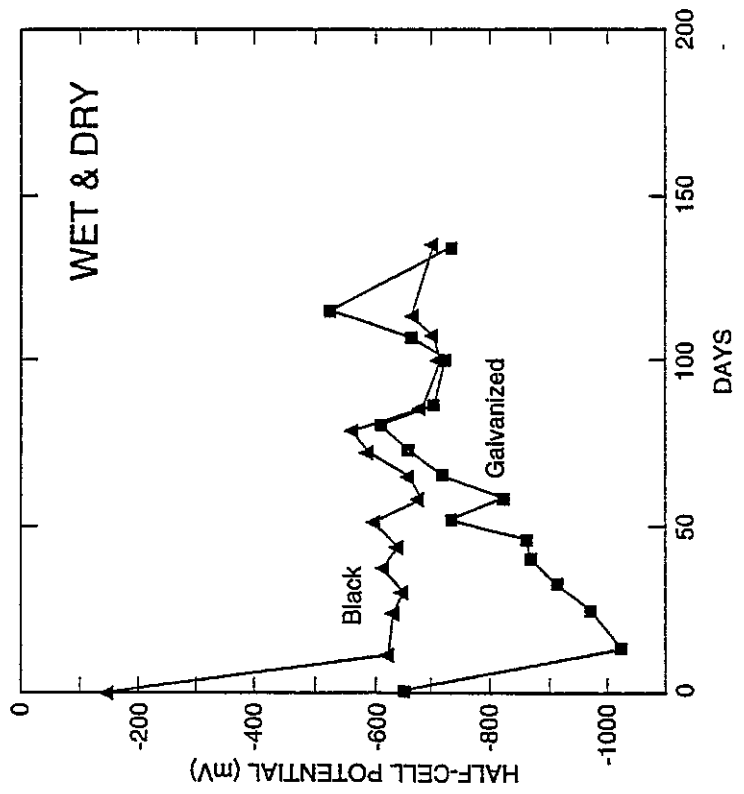

Figure 13. Half-Cell Potentials for Black Steel and Galvanized Steel in Cyclic Wet and Dry Exposure

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In the wet and dry exposure (Figure 13), corrosion of the black steel commenced after about 10-20 days while the galvanizing protected the steel for about 70-80 days.[5] In the less severe salt fog (Figure 14), the black steel showed signs of corrosion after about 45 days though the galvanized steel remained intact when the test was discontinued at 180 days. Had the test continued, the data from Figure 14 indicates that the potential of the galvanized steel would increase to that of the corroding uncoated black steel (about -600 mV) at around 230 days.

These results indicate that the period during which the galvanized coating provided sacrificial protection to steel in concrete was at least 4-5 times the interval for the onset of corrosion of black steel in equivalent concrete and exposure conditions. If this factor could be verified such as by testing in other accelerated environments and also natural exposure, there would be an opportunity to construct a model for the prediction of the service life of galvanized reinforcement in concrete similar to those proposed for corrosion of black steel in concrete (Tutti, 1982).

It is proposed that during the delay period for the galvanized reinforcement, when the zinc is reacting and sacrificially protecting the steel, the change in potential observed coincides with the exposure of the various zinc and iron-zinc alloys comprising the coating. Similar changes in the electrode potential of zinc coatings on steel dissolving in various electrolytes have been reported, and an electrochemical dissolution technique has been used to facilitate zinc-iron phase identification and alloy layer thickness in the manufacture of continuously galvanized steel sheet (Lucas et al, 1989).

As an example of this effect, the data presented in Figure 15 gives the dynamic dissolution potentials (versus the saturated calomel electrode[6]) of the various alloy layers in galvanized coatings on steel sheet. From this work it was confirmed that the major plateaus of increasing potential observed, commencing with "pure" zinc at about -1065 mV, coincide with exposure of progressively iron rich alloys as the coating is dissolved leading to exposure of the steel substrate at a potential of about -540 mV (Landriult and Harrison, 1986).

These results show surprisingly close agreement with the changing half-cell potentials for galvanized reinforcement in concrete as given in Figures 13 and 14. Overall this supports the view that the half-cell potentials measured for galvanized reinforcement in concrete during the delay period can be related to the dissolving zinc alloy layers which afford sacrificial protection to the steel substrate.

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5. Measurements of the zinc coating thickness during this exposure period indicated that some 10-15% of the coating was lost at 65 days, primarily the outer "pure" zinc (eta) layer, with essentially total coating loss at 103 days.

6. The difference in the saturated calomel and copper sulfate reference potentials is 0.07 V.
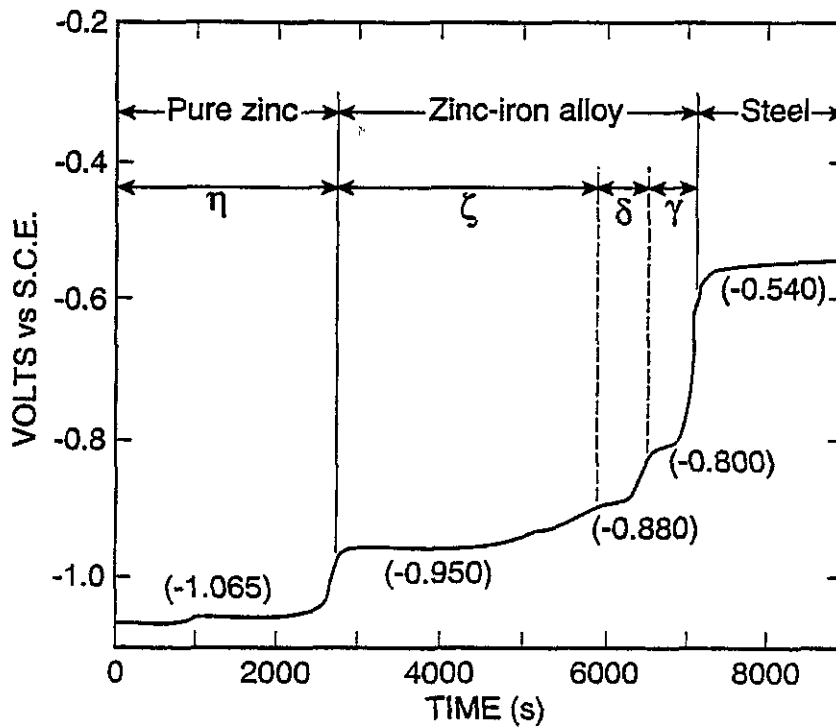
Figure 15. Alloy Phase Identification in Galvanized Coating (Landriault and Harrison, 1986)
Note approximate compositions of layers comprising the coating:

Eta   = 100% Zn - outer pure zinc layer;
Zeta = 6.7-12.2% Fe - outer intermetallic layer;
Delta = 7-11.5% Fe; and
Gamma = 21-28% Fe - inner intermetallic layer.

It is interesting to note that in a number of reports where half-cell potentials were used in condition assessment of concrete structures incorporating galvanized reinforcement, potential-time data of the same general form as given here had been reported but little substantive interpretation was attempted (Cornet et al, 1968; Hill et al, 1976; Mahn and Sorensen, 1986; Turgeon, 1987). In several cases the same basic features were observed, namely: more negative potentials for zinc compared to black steel of 400-600 mV; passivation potentials for black steel of the order of -150 to -200 mV (versus SCE) and for zinc in the range -500 to -650 mV; active potentials for black steel in the range -450 to -600 mV and for zinc below about -950 mV; and a shift in the active potential for zinc to less negative values typical of the corrosion of steel in concrete over a period up to about 5 times as long as that for the corrosion of uncoated black steel.

7.4 In-Situ Assessment of Galvanized Reinforcement in Concrete

Based on the above discussion, it could be inferred that measurement of the half-cell potentials of galvanized reinforcement in concrete while in service could be used to predict

the remaining life of the zinc alloy coating before the onset of corrosion of the steel substrate. The proposed method would be:

a) Use the measured potential to predict the composition of the iron-zinc alloy exposed at the coating surface. This would require detailed understanding of the relationships between the metallurgical structure of the galvanized coating, the half-cell potentials of the alloy layers when exposed in concrete, and the relative rate of dissolution of the alloy layers.

b) Approximate the thickness of the galvanized coating remaining on the reinforcement and thus estimate the remaining life of the coating. This would require knowledge of both the initial coating thickness and the thickness of the various alloy layers comprising the coating.

Note that it may not be possible to make this assessment based on an isolated half-cell potential survey, or for that matter a series of surveys at close time intervals. This is because a particular potential value or range of potentials, while they may be generally related to one or other of the zinc or zinc-iron alloys layers, will not indicate what proportion of the alloy layer has been dissolved at the time of the measurement. Only when a long term series of measurements are made, perhaps over many years, showing the major potential shift from plateau to plateau, presumably as one alloy layer then the next is exposed, would it be possible to predict with any certainty the status of the remaining galvanized coating.

At the present time, the only practical method by which the performance of galvanized reinforcement can be assessed is to core the concrete, extract the reinforcement and directly measure the coating thickness, generally metallographically. This is, of course, highly intrusive and damaging to the concrete element and undesirable, especially when there are no visual indications that the reinforcement is corroding and disrupting the concrete mass in the first place. Thus, if a non-intrusive half-cell technique can be developed, continuous assessments of galvanized reinforcement in concrete could be made without unnecessary disruption to the concrete mass.

8. CONCLUSIONS

The main conclusions drawn from the experimental program are:

a) Epoxy coating provides excellent corrosion protection to reinforcing steel providing 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.

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

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

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

e)   Galvanizing affords sacrificial protection to steel in concrete, the period over which the zinc and zinc-iron alloy layers in the coating dissolve effectively delaying the onset of corrosion of the steel substrate. The distance over which zinc sacrificially protected exposed steel at cut ends of bars in this case was of the order of 8 mm.

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

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

9. ACKNOWLEDGEMENTS

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