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Galvanized Reinforcement in Bridge and Coastal Construction

Dr Yeomans is known internationally for his research on galvanized reinforcement. He has lectured and published widely on this topic and edited the reference text "Galvanized Steel Reinforcement in Concrete".

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1 Abstract

This paper discusses the use of galvanizing for the corrosion protection of steel reinforcement in bridges and coastal structures exposed to deicing salts or the marine environment. Whilst providing both barrier and sacrificial protection to the base steel, the galvanized coating is also effectively immune to carbonation effects in concrete. More importantly, zinc has a significantly higher chloride tolerance than black steel and a chloride threshold some 2-3 times higher than that for uncoated "black" steel is widely accepted. This combination of factors provides for a significant life extension with the use of galvanized reinforcement and is fundamental to achieving a 50-100 year service life for concrete infrastructure exposed to high-chloride conditions.

The characteristics and behaviour of traditional hot dipped galvanized reinforcement in concrete and the recent development of the continuous coating of steel reinforcement are explored. The important role of the presence of pure zinc for the passivation of galvanized steel in concrete and the long-term behaviour of the coating are discussed. Design and construction issues specific to galvanized reinforcement are briefly reviewed. Field studies of existing infrastructure and recent applications of galvanized reinforcement in new bridge and coastal construction are presented.

Keywords:. galvanized reinforcement; hot dipping, continuous coating, chlorides, field studies; applications

2 Introduction

Galvanizing affords multi-faceted protection to reinforcement and other embedded steel in concrete. While the coating provides both barrier and sacrificial protection to steel and is essentially immune to the effects of carbonation, it also has a significantly higher tolerance to chlorides than uncoated steel. In bridge and coastal structures exposed to deicing salts or the marine atmosphere, the higher chloride tolerance in particular translates into reduced corrosion rates and the extension of service life - a key factor in the sustainability of concrete infrastructure where 50-100 year design lives are required.

The characteristics and behaviour of galvanized reinforcement has been widely investigated in both laboratory-based studies and also field investigations of long-term structures. A detailed record of this research has been published [1-4].

Since the 1950s, galvanized reinforcement has been used extensively in high-chloride exposure structures including bridges, culverts, road surfaces, crash barriers and other transport infrastructure (Figure 1), as well as marine and coastal structures such as docks and wharves, pontoons, marinas and aquariums and in power generation, chemical plants and treatment facilities.

Figure 1. Galvanized reinforced bridge deck and crash barrier installation.

3 Galvanizing Process

3.1 Hot-dip galvanizing

Galvanizing involves immersing lengths of reinforcing steel in a bath of molten zinc at about 450°C. The galvanizing time ranges from a few minutes for small diameter bars to as much as 10-20 minutes for heavy bars and prefabricated cages.

This results in the formation of a series of iron-zinc alloy layers (gamma, delta and zeta) that grow from and are metallurgically bonded to the base steel. A layer of pure zinc (eta), generally 40-50 microns thick, remains on the coating surface on withdrawal from the bath. A “bright” hot-dipped coating is shown in Figure 2.

Hot dipping produces a strongly adhered, tough coating that allows reinforcement to be transported, stored and fabricated as for uncoated “black” bars. All general galvanizing standards, and those for reinforcement such as ISO14657 [5] and ASTM A767 [6] specify a minimum total coating thickness of 85-87 microns (600-610 g/m^2) for product thicker than 5 mm. In practice, the galvanized coating is generally 110-120 microns thick though may be 150-200 microns for heavy product.

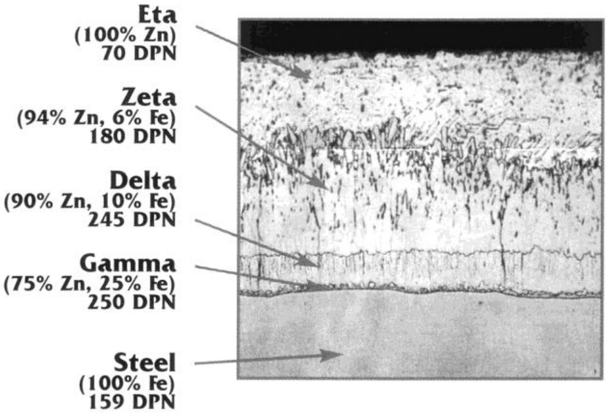

Figure 2. Hot dipped galvanized coating (~120 microns thick) showing underlying alloy layers and outer layer of pure zinc.

3.2 Continuous galvanizing

The continuous coating of bar or coil product offers an ease, speed and economy of production compared to hot dipping, is more energy efficient and has less environmental impact. Pre-heated bar is fed at around 10 m/min through a molten zinc bath such that the bar remains in the bath for only a few seconds.

The addition of 0.2% aluminum to the bath allows the formation of a coating typically 50-60 microns thick that is essentially pure zinc with a very thin layer (0.1 micron) of a ternary alloy at the zinc/steel interface. A continuously galvanized coating is shown in Figure 3.

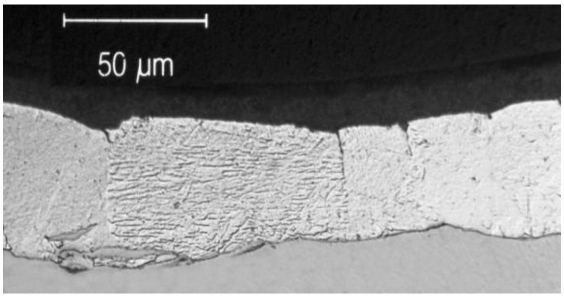

Figure 3. Continuously galvanized coating largely comprising pure zinc.

The speed of reaction and the aluminium addition retards the development of the zinc-iron alloy layers typical of the hot-dip process. This significantly improves the formability of continuously coated bar. A recent standard for continuously galvanized reinforcement, ASTM

A1094 [7], specifies an average coating thickness of not less than 50 microns (360 g/m^2).

4 Zinc in Concrete

4.1 Passivation

Zinc passivates in wet cement by the formation of an adherent layer of calcium hydroxyzincate (CaHZn), the morphology of which varies with pH. At about pH 12.6 the zinc surface is totally covered with a dense and compact layer of CaHZn crystals though as the pH increases the crystals coarsen and cannot completely cover the surface. As the passivation reaction progresses about 10 microns of pure zinc is consumed though this reaction diminishes as the passive film develops. Once the passive film has formed it remains intact even if the pH increases to about 13.6 [8].

Passivation occurs with both hot dipped and continuously coated bars due to the presence of the pure zinc layer at the coating surface. With hot dipping, this layer can be of variable thickness but would always be sufficient to sustain the 10 microns consumed during passivation. Continuously coated bar on the other hand provides a significant reserve of pure zinc to sustain the passivation reaction.

While hot-dip coatings do have good corrosion performance, the zinc-iron alloy layers are less corrosion resistant than pure zinc and do not contribute significantly to the corrosion performance. Continuous coatings however, with a generally greater reserve of pure zinc, are able to provide on-going protection in the event that corrosion commences on coatings with a thin or non-existent pure zinc top layer, such as may be the case with reactive steels.

4.2 Carbonation

Carbonation reduces the pH of the cover concrete and corrosion of black steel commences when the pH at the depth of the bar reaches 11.5. Galvanized reinforcement is however not significantly affected by the carbonation of concrete due to the increasing corrosion resistance of zinc as the pH reduces well below 11.5. As such, galvanized reinforcement is effectively immune to the effects of carbonation [4,8].

4.3 Chlorides

A pH dependent threshold concentration of chlorides is required to initiate corrosion. The chlorides disrupt the passive film on steel even at high pH and prevent it from re-forming resulting in highly localised pitting attack. For black steel, a chloride threshold of 0.4% by mass of cement is often cited for low corrosion risk [9].

While there is some divergence of opinion on a precise chloride threshold for galvanized steel in concrete, a conservative value of 1% chlorides by mass of cement is often used, thus 2.5 times higher than for black steel [10]. More recently, Darwin [11] reported a 3-4 times higher threshold for galvanized over black steel at an average of 1.6, while Presuel-Morento and Rourke [12] reported chloride levels 4-5 times higher than for black steel.

In the Mexican Caribbean, Maldonado [13] indicated a 2.6–3 times higher threshold over black steel. Further, Bertolini [14] reported a threshold 1.5-2 times that for black steel in chloride contaminated concrete, Sanchez [15] cited a 2 times threshold from laboratory and field studies, and Hegyi [16] indicated a chloride threshold for galvanized bars 3.1 times that of black steel in concrete admixed with $CaCl_2$.

While measuring the chloride threshold is quite straightforward in simulated cement pore water, the conditions in concrete are quite different and variable. Differences in the alloy layer structure of the galvanized coating, especially the pure zinc outer layer, are known to affect corrosion initiation and thus the measured chloride levels.

It is thus not unexpected that differences in the chloride threshold are reported. Despite this, it is apparent the chloride threshold for galvanized steel is several times that for black steel and a factor of 2-3 times is now widely reported [4].

4.4 Coating behaviour

Once the passivating CaHZn film has formed, the remainder of the coating (generally 100 microns or more) remains intact for extended periods until threshold levels of chloride reach the depth of the reinforcement. If the coating subsequently depassivates, dissolution of any remaining free zinc occurs from the surface and around the alloy layers. The zinc-rich corrosion products so formed, primarily zinc oxides/hydroxides, are friable minerals that are significantly less voluminous than ferrous corrosion products and migrate into the adjacent concrete matrix where they fill voids and micro-cracks [17].

In contrast to the situation when black steel corrodes in concrete, zinc corrosion products do not significantly disrupt the interfacial cement matrix, thereby maintaining the integrity of the cover concrete.

There is also evidence that the filling of the pore space in the interfacial zone creates a barrier in the matrix of reduced permeability that not only increases the adhesion of the matrix to the bar but also reduces the transport of chlorides through the matrix to the coating surface [17].

4.5 Design and construction

Extensive testing has demonstrated that galvanizing does not adversely affect the strength and ductility of reinforcing steels, including the higher strength grades [18,19].

Further, research on the bond capacity of galvanized reinforcement reveals no reduction in the bond capacity of galvanized bars compared to equivalent black steel bars. In practice, galvanized bars typically have improved bond capacity [4,20].

Due to the robust nature of galvanized coatings there are no special transportation and handling requirements for galvanized reinforcement other than the use of appropriate bend radii to minimize cracking of the coating.

There are also no special precautions or work practices needed in the placement of the reinforcement or in the pouring, compaction and finishing of the concrete [18,19].

In essence, the design and construction of galvanized reinforced concrete is, to all intents and purposes, the same as for conventional steel reinforced concrete [21].

5 Field Studies

Evidence from numerous existing structures, in particular bridge deck installations in the US, has demonstrated that galvanizing extends the life of reinforcement in concrete and provides a safe-guard against premature cracking and spalling [4, 22, 23].

Bridge decks dating from the early 1970s in Iowa, Pennsylvania and Florida were examined to compare the performance of galvanized and black reinforcement exposed to deicing salts or humid marine conditions [24].

After 24 years the galvanized bars had suffered only superficial corrosion even when the chloride levels were high, and the average thickness of zinc remaining on the bars exceeded the minimum 84 micron requirement of ASTM A767 [6]. Later re-examination of the Athens (28 years) and Tioga bridges (27 years) in Pennsylvania revealed average chloride levels 2.5 times higher than that for black steel and the remaining coating thickness also exceeded the specified minimum [25].

In Bermuda, examination of docks and jetties dating from the 1950s, verified the long-term durability of galvanized reinforcement in marine environments [26]. A 1991 survey showed that galvanizing was providing corrosion protection at chloride levels well in excess of black steel threshold levels.

A further examination of marine structures at least 42 years old confirmed these findings with the galvanized bars retaining coatings well in excess of the specified minimum thickness. Cores taken at this time showed the zinc corrosion products had migrated 300-500 microns into the adjacent concrete matrix with no visible effect on the concrete mass.

5 Recent applications

A recently completed large infrastructure project is the 3.1 mile Mario Cuomo Bridge, formerly the New NY Bridge, crossing the Tappan Zee section of the Hudson River.

Designed for a 100 year life, 30,000 tons of hot dip galvanized reinforcement was used in the construction of all critical elements of the new bridge including 43 pairs of reinforced concrete support piers as well as all approach spans and abutments. Some 6,000 galvanized reinforced pre-cast panels form the road deck surface (Figures 4, 5).

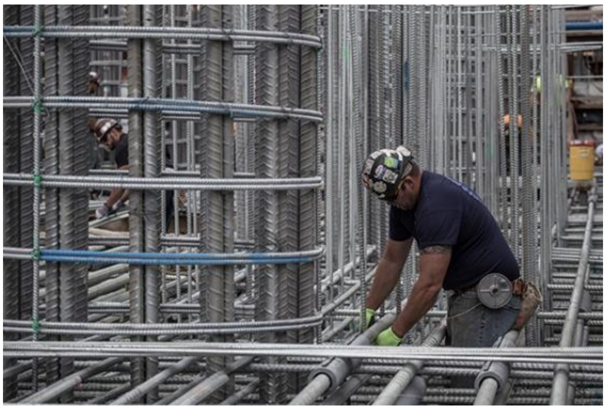

Figure 4. Installing galvanized reinforcement in the main span towers.

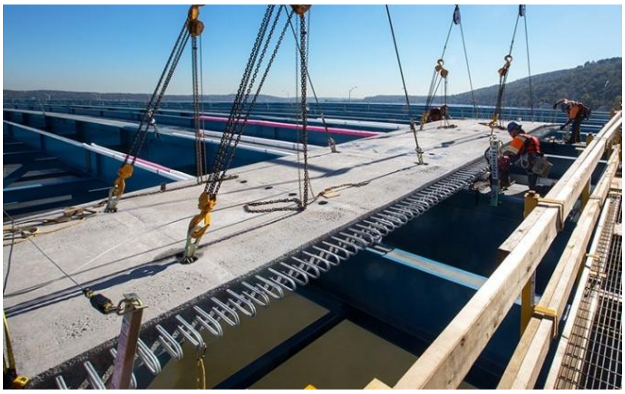

Figure 5. Placing galvanized reinforced precast road deck panels.

The first bridge constructed with continuously galvanized reinforcement was recently completed in Independence, Iowa (Figure 6) using 75 tons of continuously galvanized bar in the concrete abutments, parapets and the bridge deck.

Figure 6. Continuously galvanized reinforcement in the Buffalo Creek Bridge, Independence, Iowa.

Being able to fabricate the continuously coated bar onsite saved construction time and reduced local road disruption [27]. Further installations are progressing in Salem Indiana, Athens Ohio and a 56 MW duel fuel power plant in Bermuda.

In coastal applications, 1,200 tons of galvanized reinforcement was used in 3,200 foundation piles for the Changi Water Treatment facility in Singapore. Designed for a 100 year life and located on the coast, the facility is subject to a highly corrosive tidal saltwater table.

A further 10,000 tons of coiled galvanized bar was used in 1300 effluent discharge pipes placed in dredged seabed channels (Figure 7).

Figure 7. Prefabricated galvanized reinforced pipe cages ready for slip forming.

In Chile, galvanized reinforcement was used in the seawater reticulation systems for a thermal power station at Coronel Port and also in the concrete deck of the Artisanal fishing pier project. In Spain, galvanized reinforcement was used extensively in the new marina at the Port of Torrevieja and in precast seawall sections in the sea port dock in Denia, Alicante (Figure 8).

Figure 8. Precast galvanized reinforced seawall sections for Denia Port, Spain.

6 Conclusions

The galvanizing of reinforcement has a long history of successful world-wide use in a wide variety of concrete construction exposed to moderate and severe exposure conditions. While there are many applications in building and general construction, galvanized reinforcement is also extensively used in transport infrastructure such as bridges, road decks and crash barriers and also in marine and coastal structures including sea walls, docks, pontoons, channels and marinas.

Resistance to the presence of high chloride levels in these environments, either due to deicing salts or the marine atmosphere, is vital in ensuring the sustainability of concrete. Galvanized reinforcement, with its multi-faceted corrosion protection mechanisms, in particular its resistance to carbonation and its high chloride tolerance compared to uncoated steel, is a key factor in its ability to provide long-term protection of reinforcement in concrete.

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