ZINC COATED REBAR FOR SUSTAINABLE CONCRETE INFRASTRUCTURE[1]

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Introduction

The use of galvanizing is so prevalent since it is by far the most effective way to protect steel from corrosion (Porter, 1994). Whether exposed to the atmosphere or used in reinforced concrete structures exposed to aggressive environments, zinc protects steel against corrosion first as a barrier coating, and more importantly as a sacrificial anode. In concrete, galvanized reinforcementalso increases resistance to chloride corrosion both by increasing the threshold chloride level where corrosion begins and by slowing the rate of corrosion after that threshold is exceeded. Zinc corrodes slowly near neutral pHwhich makes it very effective in combating the effects of carbonization-induced reinforcement corrosion (Yeomans, 2004). Galvanized reinforcement will extend the life of concrete structures considerably compared to black steel reinforcement.

Galvanized steel reinforcement is produced by general (batch) or continuous hot-dip galvanizing. General galvanizing(HDG) is most widely used and involves the immersion of cleaned steel bars into a bath of molten zincfor several minutes. The steel and zinc react together during immersion in the molten zinc to produce a coating on the steel made up of a series of zinc-iron intermetallic layers with a pure zinc layer on top. This coatinggrows perpendicular to all surfaces, ensuring that ribs and main bar have the same coating thickness.The composition of these coatings, including the thickness of the zinc surface layer, can vary as a function of the steel chemistry and of the operating parameters of the galvanizing process.

Continuously galvanized reinforcement(CGR) is also fully immersed in liquid zinc but only for a few seconds. Due to the short immersion time, the formation of the zinc-iron alloy layers that occurs during the general galvanizing process is avoided. A thin zinc-iron-aluminum alloy layer is formed at the surface of the steel, while the rest of the coating is essentially pure zinc (Gagné 2016). All grades of steel reinforcement, including high strength, will have the same coating of essentially pure zinc, regardless of the chemistry of the steel being coated.

The most important requirement of reinforced concrete as a composite building material is the bond strength between the concrete and the reinforcing steel. The steel reinforcement transfers tensile forces into the concrete by bond action. Therefore, the bond properties of the steel reinforcement significantly impact the crack widths and crack spacing in the concrete. Thus, stiffness and deformation behaviour of reinforced concrete structures are directly influenced by the bond properties (Lemnitzera, 2009).The bond strength is achieved primarily by mechanical interlocking of the steel ribs and the surrounding concrete, while for galvanized reinforcement, the nature of the surface of the bar will also play a role.

Specifications for Galvanized Reinforcement

The quality of galvanized reinforcement can be ensured by ordering material to recognized product standard specifications. In North America, ASTM standards are generally specified for galvanized reinforcement. ASTM A767/A767M ‘Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement’, is a specification that covers steel reinforcing bars with protective zinc coatings applied by general galvanizing. The specification A1094/A1094M ‘Standard Specification for Zinc-Coated (Continuous Hot-Dip Galvanized) Steel Bars for Concrete Reinforcement’, covers steel reinforcing bars with protective zinc or zinc-alloy coatings applied by the continuous galvanizing process.

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Internationally, galvanized reinforcing steel bar is covered by the International Standard ISO 14657 Zinc-Coated Steel for the Reinforcement of Concrete. This standard covers a wide range of coating thicknesses from 140g/m^2 up to 600g/m^2 and has no specific language about galvanizing methods.

While the coating standards are important, the specifications for the reinforcing steel itself are just as important. ASTM has two standards for reinforcing steel, one for carbon-steel bars and one for low-alloy steel bars, thatcover bar sizes up to 63.5mm diameter. The specification A615/A615M 'Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement', covers five mechanical properties classes based on minimum yield strength (up to 690 MPa).The specification ASTM A706/A706M 'Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement'covers concrete reinforcement intended for applications where restrictive mechanical properties and chemical composition are required for compatibility with controlled tensile property applications or to enhance weldability. The controlled chemistry required for weldability also helps with galvanizability by the hot-dip process.

Behaviour of Galvanized Reinforcement in Concrete

Whether produced using general or continuous galvanizing, zinc coatings on reinforcing steel passivatewhen exposed to fresh concrete. The pH of cement in contact with the zinc coating controls the formation of a compact and adherent layer of calcium hydroxyzincate (CHZ). This compound passivates the surface of the zinc coating from further reaction with the concrete. The threshold for passivation of zinc in concrete pore solutions is at a pH of between 12.8 and 13.2 +/- 0.1 (Tan 2008). A coating with a pure zinc layer is known to quickly and completely passivate (Yeomans, 2004).

When corrosive species, such as chloride ions or a carbonation front, pass through the concrete and reach the reinforcement, corrosion will begin. In order to initiate corrosion of galvanized reinforcement, these corrosive species must first disrupt the physical barrier of the CHZ film. Carbonation lowers pH from highly alkaline to neutrality (pH 7), where the rate of corrosion of zinc is very low. As a result, galvanized reinforcement does not generally corrode in carbonated concrete.

Chlorides are more aggressive and come mostly from the use of de-icing salts. Once the chloride concentration reaches a critical threshold, and corrosion commences, the build-up of iron corrosion products on the steel reinforcement create the tensile stresses that crack the concrete cover, eventually leading to spalling and further steel degradation. The concentration of chloride ions required to start corrosion of zinc is up to four times higher than the concentration needed to start corrosion of black steel (Yeomans, 2004). The zinc will then corrode uniformly at less than one-tenth the corrosion rate of the base steel, thereby delaying the onset of corrosion of the galvanized reinforcement. Through galvanic protection, the zinc will continue to protect the steel as the coating is consumed or damaged. It should also be noted that the zinc corrosion products migrate away from the corrosion site and help densify the concrete surrounding the reinforcement, further delaying the onset of corrosion, and also increasing bond strength.

The build-up of corrosion products on the surface of the reinforcement is a key factor in the degradation of concrete structures. Zinc corrosion products are less voluminous than iron corrosion products and migrate into the concrete matrix. Galvanized reinforcing steel requires about two and a half times the corrosion loss before crack initiation when compared to uncoated steel in concrete (O'Reilly, 2018). It was also found that in addition to the losses corresponding to crack initiation, the losses required to produce a given crack width were considerably higher for galvanized reinforcement than for conventional reinforcement. As zinc corrodes more slowly than iron, and the corrosion products take up less volume, thereby putting less stress on the concrete, it takes significantly longer for cracks to develop in concrete with galvanized reinforcement than with conventional black steel. Concrete with galvanized reinforcement needed almost four times as long to crack compared toconcrete with conventional reinforcement.The overall behaviour depends on the source of the chloride ions, the state of the galvanized surface and the degree of protection provided by the concrete cover.

As well as passivating the zinc surface, the formation of the dense Calcium Hydroxyzincate crystals on the surface of the galvanized reinforcement has been shown to improve the bond between the reinforcement and the surrounding concrete. The suggested mechanism is that the crystals act as bridges between the metal surface and the concrete thereby strengthening the adhesion of the bars (Yeomans, 2004). Pull-out tests used to investigate the bond strength of several types of corrosion resistant reinforcement in plain and fibre reinforced concrete, before and after accelerated corrosion testing showed the galvanized reinforcement to have the highest pull-out strength in all conditions (Patnaik 2019). The corrosion resistant reinforcementtested included CGR, MMFX, stainless steel and epoxy coated.

Direct tension tests, using the same types of reinforcement, were designed to gain insight into the effects of each reinforcement type on cracking in direct tension and were performed to determine how well the reinforcement is bonded to the surrounding concrete (Patnaik 2019).The smaller the crack width, the better the bond strength. Table 1 compares the measured crack width for each bar type tested at a stress of 275 MPa. In all cases the continuously galvanized reinforcement exhibited the lowest crack width. The crack widths for specimens with fiber were smaller by about 25% as compared to the corresponding specimens without fiber. The bond strength of galvanized reinforcement to concrete was also revealed to be stronger than the other corrosion resistant reinforcement in flexural cracking tests.

Table 1 - Comparison of Crack Widths at a Stress of 275 Mpa

Bar Type	Crack Width No Fibre (mm)	Crack Width with Fibre (mm)
CGR	0.356	0.279
MMFX	0.432	0.330
Stainless steel	0.533	0.394
Black	0.584	0.445
Epoxy	0.762	0.597

Physical deformities in the concrete, such as cracks, facilitate the movement of chlorides through the concrete to the reinforcement, which can significantly accelerate corrosion. The superior bond strength of zinc to concrete enhances the corrosion protection provided by zinc by keeping cracks widths to a minimum.

Galvanized Reinforced Concrete in Service

Galvanized reinforcement has been used for decades to significantly extend the life of concrete bridge structures in a wide range of corrosive environments, whether in tropical climates from exposure to seawater or in northern climates with winter freeze-thaw cycles that requiredeicing salts. The passivation of zinc in concrete, the resistance of zinc to carbonation, the high chloride threshold needed to start corrosion of zinc, the slow rate of corrosion of zinc, the migration of zinc corrosion products, the barrier and sacrificial properties of zinc, and the bond strength of zinc all combine to extend the life concrete structures.

The Watford Bridge in Bermuda is the only road link between Somerset and the Watford Islands. The 140m long bridge is required for commercial, industrial, residential and tourist traffic and is located in a coastal marine environment. A post-tensioned concrete bridge was built in 1957 with unprotected reinforcement. Red rust spots appeared on the flanges of the concrete beams only three years after construction. In 1960 a maintenance program of chipping, repairing and sealing was started in an ongoing attempt to protect theblack steel reinforcement. Despite the remediation work, deterioration became progressively more severe. A bridge survey in 1977 confirmed that there was widespread and severe corrosion. It was decided that no repair and maintenance system would extend the life of the bridge for any reasonable time and the bridge would need to be replaced. The bridge was demolished in 1980 after only 23 years of service.

Rebuilt in 1982, the reconstruction criteria for the Watford bridge called for a 120-year life span with no maintenance for up to 10 years and only minor maintenance up to 20 years. The final composite bridge design used galvanized structural steel beams supporting a galvanized reinforced concrete deck. A duplex coating was used for the bridge structure itself. The structural steel plate girders were hot dip galvanized and painted with a four-coat paint system. All nuts, bolts and washers were also galvanized and painted. Careful attention to design was made throughout the structure, to avoid accumulation of moisture and condensation at joint details, and circular concrete columns were used for all piers to eliminate chipping of corners in the splash zone(Yeomans, 2004). Inspections show that both the galvanized reinforced concrete deck and the galvanized plate girders are performing extremely well. The new bridge has already exceeded the life of its predecessor and is on track to meet and surpass the design criteria for a 120-year life. Meeting this design life will provide almost five times the life of the original reinforced concrete bridge in a severe marine environment.

The performance of galvanized reinforcing steel in bridge decks subjected to deicing salts has been evaluated for several bridges in the states of Michigan, Pennsylvania, Vermont and Wyoming. The bridges were all built in the 1970's and inspected in the early 2000's after approximately 30 years of service.Concrete core and powder samples, along with direct measurements on the bridge structures were undertaken to asses the condition of the bridges and the galvanized reinforcement. The bridges are evaluated using electrical potential measurements and visual examinations.Theconcrete core samples were used to determine water-soluble chloride ion levels in the concrete, for petrographic examinations, and for metallographic examinations of the galvanized coatings.

The critical chloride level needed to initiate corrosion of bare steel in concrete is 0.65 kg/m^3 (Kinstler, 2002), while the concentration of chloride ions required to start corrosion of zinc is up to four times higher(Yeomans, 2004).In all the bridges studied, the galvanized reinforcing steel remains intact with significant zinc cover still remaining. Yetthe chloride levels measured at the surface of the galvanized reinforcement range from 1.34 kg/m^{3}to 4.13 kg/m^{3}or from two to six times higher than the critical chloride threshold needed to start corrosion of black steel. The results from the inspections show the galvanized coatings have experienced only superficial corrosion in sound, uncracked concrete, with mild to moderate corrosion in areas of cracked concrete. Concrete deterioration related to corrosion of the galvanized steel reinforcement was not evident (Nagi 2004).

The National Research Council of Canada found that galvanized reinforcing steel had corrosion rates 5-10 times lower than carbon steel in heavily contaminated concrete containing 2% of chlorides by mass of cement. The corrosion rate of galvanized steel reinforcement remained low and stable while the corrosion rate for carbon steel reinforcement was found to increase exponentially with time in corrosive environments (Zhang, 2015). A low corrosion rate is an important part of the corrosion resistance provided by galvanized reinforcing steel that significantly prolongs the time to concrete cracking, spalling and delamination. Examinations of two concrete bridges crossing Highway 30 in the greater Montreal area that were constructed in 1965 and 1966 showed that the galvanized reinforcing steel in the bridge columns were undergoing low corrosion rates, despite chloride levels above the threshold for corrosion. The low corrosion rates for zinc, the low volumes of zinc corrosion products, and the migration of zinc corrosion products into the matrix of the concrete explain the fact that no corrosion-induced cracking was found on these concrete bridges after 50 years in service.

Conclusions

The barrier and sacrificial properties of galvanized reinforcement provide decades of proven corrosion protection performance in concrete bridge structures. Zinc coatings passivate in concrete, are immune to carbonization-induced corrosion, and resist chloride corrosion both by increasing the threshold chloride level where corrosion begins and also by slowing the rate of corrosion after that threshold is exceeded.

By extending the life of concrete bridge structures, galvanized reinforcementreduces maintenance costs, and also the indirect costs – site accessibility, loss of productivity during maintenance, commuter delays, etc. – incurred when a structure needs repair. More importantly, by extending the life of concrete infrastructure, galvanized reinforcement reduces the use of natural resources and the environmental impact of mining and manufacturing steel, zinc and cement.

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