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OPTIMIZING THE PERFORMANCE OF GALVANIZED REINFORCEMENT FOR CORROSION PROTECTION

Gagné, M.[1,4], Pole, S.[1], Goodwin, F.[2] and Dallin, G.[3]
[1] International Zinc Association, Canada
[2] International Zinc Association, United States
[3] Galvinfo Centre, Canada
[4] mgagne@zinc.org

Abstract: Continuous Galvanized Rebar [CGR] is a new process now available in North America for the production of corrosion resistant rebar. Traditional hot-dip galvanized [HDG] rebar has been protecting concrete structures for decades with a strong metallurgically bonded coating that provides both barrier and sacrificial protection. As with HDG rebar, CGR is fully immersed in zinc. However, as an in-line process, the bar is fluxed, induction heated and coated with a uniform zinc layer in a matter of seconds. The CGR coating is also metallurgically bonded and is durable and resistant to abrasion that is routine during transport and construction. However, due to the very short immersion time the coating structure is almost entirely pure zinc. This coating structure is highly ductile and can be bent without cracking to diameters of less than 4x the rebar diameter. Tests also show that zinc provides excellent bond strength to concrete, all while providing barrier and sacrificial protection against corrosion.

1 INTRODUCTION

The continuous galvanizing process has been used for decades to coat steel sheet for automobiles, architectural panels, and more recently to coat long products such as tubes, angles and rebar. In the continuous process steel is cleaned, usually by pickling, deoxidized by fluxing or inert atmosphere, then fully immersed in liquid zinc to coat the steel. Zinc alloys used for continuous galvanizing range from CGG grade, with the addition of 0.2%Al, to Galfan with 5%Al and Galvalume with 55% Al.

The use of galvanizing is so prevalent since it is by far the most effective way to protect steel from corrosion (Porter, 1994). The corrosion protection provided by zinc – both as a barrier and sacrificial anode - extends the life of steel, whether exposed to the atmosphere or used in reinforced concrete structures exposed to aggressive environments that promote corrosion of steel reinforcement. In concrete, galvanized rebar 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 and is also very effective in combating the effects of carbonization-induced reinforcement corrosion (Yeomans, 2004).

In the CGR coating process, CGG zinc with 0.2%Al is used. In this process, the rebar is mechanically cleaned, rather than pickled. To deoxidize the steel before coating, the rebar is immersed in a flux, although a heat-to-coat method in an inert atmosphere could be used to de-oxidize the steel before galvanizing. Using a flux to deoxidize the steel allows for more flexibility in production schedules. Induction heating is used to dry the flux, and/or to preheat the bar surface temperature before galvanizing. Including the preheating stage, the total time the steel is at the temperature of the molten zinc (465°C) is about 4-5 seconds. This allows all grades of steel (normal and high strength) to be galvanized with no change in the coating structure or mechanical properties. All grades, including high strength, will have the same coating of essentially pure zinc, with the normal continuous galvanizing iron/aluminum reaction that forms the thin and ductile intermetallic alloy layer [Gagné 2016, Gagné 2018].

The bond strength between concrete and reinforcing steel is the most important requirement of reinforced concrete as a composite building material. The structural behaviour of reinforced concrete requires the interaction between the concrete and the steel reinforcement. The steel reinforcement transfers tensile forces into the concrete by bond action. Crack widths and crack spacing are therefore significantly dependent on the bond properties of the steel reinforcement. 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. For corrosion resistant rebar, the nature of the surface of the bar will also play a role. A study completed by Patnaik in 2019 conducted a variety of tests, including direct tension testing for bond strength, on stainless steel, epoxy coated rebar, MMFX bars and continuously galvanized rebar (CGR), in both corroded and non-corroded conditions. The results of the testing show that CGR outperformed all the other corrosion-resistant bars, leading to the conclusion that “CGR will provide better structural and corrosion performance”. (Patnaik, 2019)

This paper will describe how galvanized reinforcing bar outperforms black bar and other corrosion protection options for reinforcing bar through several primary mechanisms, including increased resistance to chloride corrosion; immunity from corrosion due to carbonation of concrete; less voluminous corrosion products than iron; increased time before crack initiation on concrete; and exceptional bond strength to concrete. These outcomes are demonstrated from multiple referenced studies, including those looking at average corrosion losses at crack initiation; average time to crack initiation; bond strength on different types of reinforcing bar; and differences in crack width on concrete reinforced with different type of bar.

2 PROTECTING REBAR WITH ZINC

The high pH of concrete passivates zinc coatings very quickly. The passivation of zinc occurs below a pH of 13.2 through the formation of a compact and adherent layer of calcium hydroxyzincate (CHZ). The initial passivation enhances the long-term corrosion protection of the galvanized rebar during years of service. Pure zinc coatings are known to rapidly and completely passivate (Yeomans, 2004).

When aggressive species, such as chloride ions or a carbonation front, pass through the concrete and reach the reinforcement, the corrosion of rebar begins. However, in order to initiate corrosion of galvanized rebar, these aggressive 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 Zn corrosion is very low. As a result, galvanized rebar does not generally corrode in carbonated concrete. Chlorides are more aggressive, and come from the raw construction materials, marine environments or de-icing salts. The concentration of chloride ions required to start corrosion of zinc is up to 4 times higher than the concentration needed to start corrosion of black steel (Yeomans, 2004).

Corrosion of steel in concrete, caused by the presence of chlorides, proceeds through a two-stage mechanism of initiation and propagation (Tuutti, 1982). Most efforts to achieve long-term durability of reinforced concrete have been directed at postponing as long as possible the initiation of corrosion of the rebar. Once the chloride concentration reaches a critical threshold, and corrosion commences, the build-up of iron corrosion products on the rebar create the tensile stresses that crack the concrete cover, eventually leading to spalling and further steel degradation. Using corrosion resistant rebar is one way to delay the initiation of corrosion. For galvanized rebar, the presence of a pure zinc layer on the surface of the steel rebar has a much higher chloride threshold than black steel (Yeomans, 2004).

The build-up of corrosion products on the surface of the rebar is seen as an important factor in understanding the degradation of concrete structures. Zinc corrosion products are less voluminous than iron corrosion products.

2.1 Test Method for Average Corrosion Losses at Crack Initiation for Conventional and Galvanized Rebar

In a recent study, it was shown that galvanized reinforcing steel requires more than twice the corrosion losses before crack initiation when compared to uncoated steel in concrete (O'Reilly, 2018). Samples of both uncoated and standard batch galvanized bars were cast in concrete and tested with three different levels of concrete cover. Impressed current was used to accelerate corrosion on some samples while other samples were tested without impressed current. The magnitudes of corrosion loss required to initiate cracking in concrete are similar for bars tested with and without impressed current.

2.2 Test Results for Average Corrosion Losses at Crack Initiation for Conventional and Galvanized Rebar

Table 1 shows the average corrosion loss causing crack initiation for conventional and galvanized reinforcement for samples subjected to impressed current, based on the percentage of bar surface area showing active corrosion, measured in microns. There was one very high result for galvanized rebar with 12.5mm cover which has skewed the results, but generally, the galvanized rebar needs more than twice the corrosion loss for crack initiation compared to conventional rebar. 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.

Table 1: Average corrosion losses at crack initiation for conventional and galvanized reinforcement for specimens with impressed current, um, based on percentage of bar surface area showing active corrosion (O'Reilly, 2018)

Depth of Cover (mm)	**Conventional Rebar um - Avg (std)**	**Galvanized Rebar um - Avg (std)**	**Ratio Galv/Conv**
12.5	10.5 (2.8)	65.5 (24.3)	6.2
25.4	22.4 (5.5)	55.1 (10.7)	2.5
51.0	29.7 (4.6)	68.8 (20.3)	2.3

The samples that were conventionally tested showed similar behavior to the samples subjected to accelerated corrosion using impressed current, although the samples without impressed current exhibited much lower average corrosion losses at crack initiation than those with impressed current. The samples with galvanized reinforcement cracked at an average corrosion loss of 12.4 μm, which is over twice the average corrosion loss required to crack concrete with conventional reinforcement at 5.41 μm. The corresponding ratio is 2.3.

After corrosion testing the samples were autopsied. The similarities in corrosion products between the galvanized and the conventional rebar suggests that the staining and cracking observed for the galvanized rebar may be due to corrosion of the intermetallic iron-zinc layers or of the underlying steel. Staining increased for samples with both conventional and galvanized reinforcement as the tests progressed, although, in general, samples with galvanized reinforcement exhibited less staining than those with conventional reinforcement. The observations suggest that for both samples the bulk of the corrosion products applying pressure to the surrounding concrete were corrosion products of iron and not those of zinc (O'Reilly, 2018).

2.3 Test Results for Average Time to Crack Initiation for Conventional and Galvanized Rebar

Table 2 summarizes the average time, measured in weeks, required to initiate cracking for the six samples of conventional and galvanized rebar. Due to the length of time required, the conventional testing was terminated upon the appearance of a crack. The galvanized samples needed almost four times as long to crack as the conventional rebar samples.

Table 2: Average time to crack initiation for conventional and galvanized reinforcement for specimens tested without impressed current, weeks (O'Reilly, 2018)

Conventional Rebar Weeks – Avg (std)	**Galvanized Rebar Weeks – Avg (std)**	**Ratio Galv/Conv**
21.2 (3.7)	80.7 (3.4)	3.8

3 ZINC BOND STRENGTH IN CONCRETE

The calcium hydroxyzincate layer also serves to strengthen the bond between the reinforcing steel and the concrete. The CHZ forms as small platelets on the surface of the rebar, becoming almost micro ribs adhering to the concrete. In Figure 1, the load slip characteristics are compared for black steel, galvanized, and epoxy coated rebar. At all load levels the galvanized rebar has lower slip compared to both black and epoxy bars. Based on the data shown below, it is possible to reduce the lap lengths of galvanized rebar below the requirements of black bar. However, in practice this means no change of lap lengths are needed to use galvanized rebar. (Yeomans, 2004)

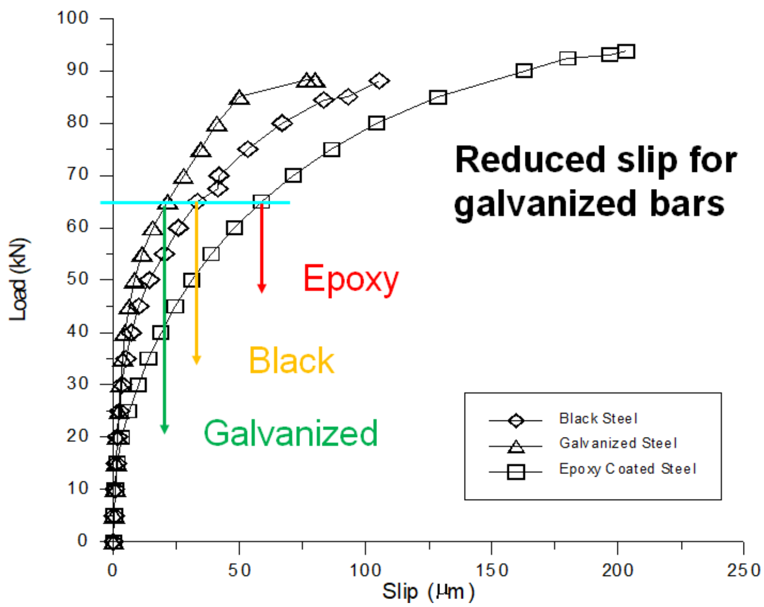

Figure 1- Load-Slip Characteristics of Reinforcing Steel (Adapted from Yeomans, 2004)

3.1 Test Method for Bond Strength of Different Corrosion Resistant Rebar Types

Pull-out tests were used to investigate the bond strength of several corrosion resistant rebar types in plain and fibre reinforced concrete, before and after accelerated corrosion testing (Patnaik 2019). The corrosion resistant rebar samples included CGR, MMFX, stainless steel and epoxy coated rebar. Pull-out tests were conducted using multiple prism specimens cast with each type of rebar, with and without 5.94 kg/cm polypropylene fibre. Half of the prism samples were subjected to accelerated corrosion for a period of 10 days before testing.

3.2 Test Result for Bond Strength of Different Corrosion Resistant Rebar Types

In all conditions, as shown in Figure 2, the CGR rebar samples exhibited the highest pull out strength compared to other corrosion resistant rebar types.

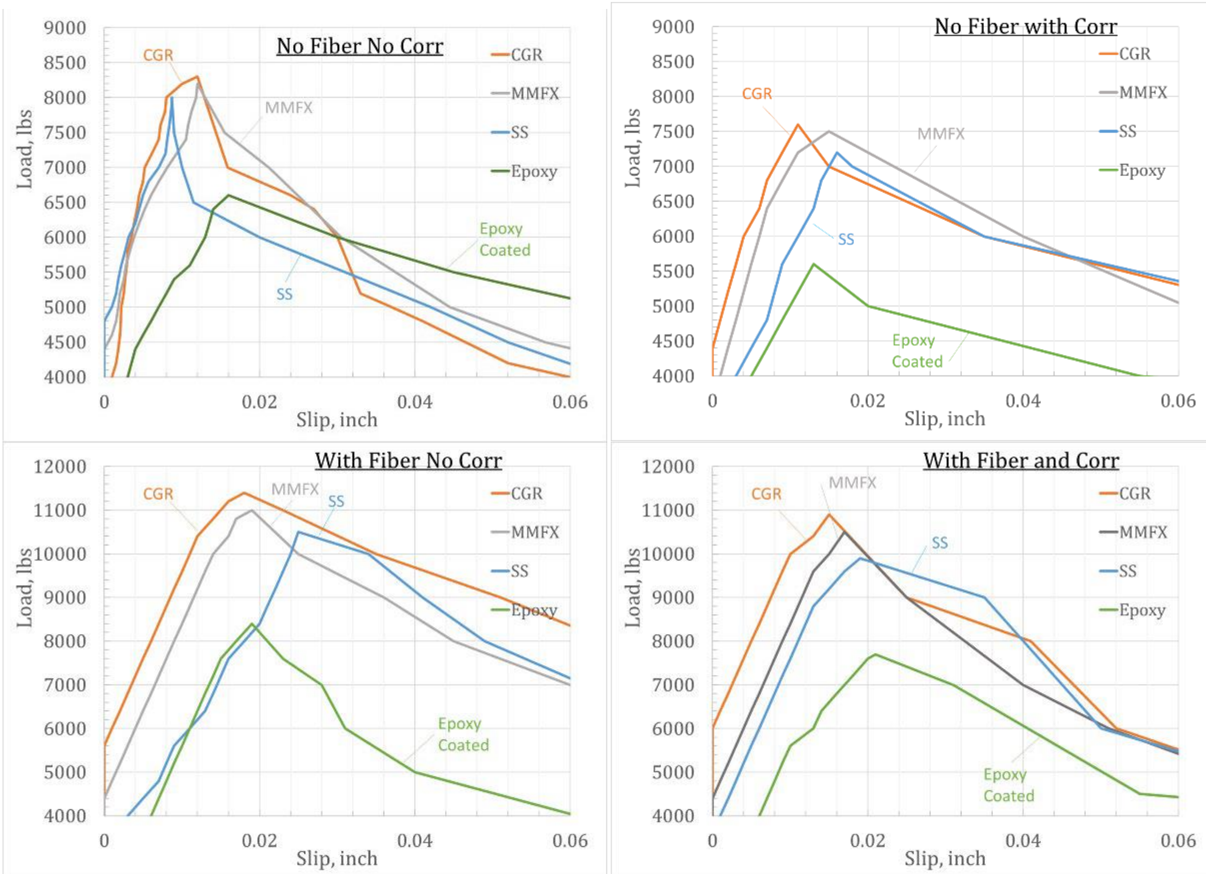

Figure 2: Comparison of Load-slip Curves of CGR with Those for Other Corrosion-Resistant Bars

3.3 Test Method for Crack Width Resulting on Concrete with Different Corrosion Resistant Rebar Types

Direct tension tests were also performed to study crack development in the prism specimens cast with different types of corrosion resistant rebar (Patnaik 2019). These tests 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 rebar is bonded to the surrounding concrete. The smaller the crack width, the better the bond strength, as a strong bond will see the tensile forces transferred to the reinforcing steel.

3.4 Test Results for Crack Width Resulting on Concrete with Different Corrosion Resistant Rebar Types

Table 3 compares the measured crack thickness for each bar type tested at a stress of 275 MPa. In all cases the CGR samples exhibited the lowest crack width. The crack widths for specimens with fibre were smaller by about 25% as compared to the corresponding specimens without fiber. Flexural cracking tests also revealed the stronger bond strength of continuously galvanized rebar to concrete than the other corrosion resistant bars.

Table 3: Comparison of Crack Widths at a Stress of 275 Mpa for Specimens with and without Fiber (Patnaik, 2019)

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

4 CONTINUOUSLY GALVANIZED REBAR IN USE

Buffalo Creek Bridge in Independence, Iowa is a 2 lane, 200’ composite bridge where galvanised steel was used for the h-piles, beams, guardrails, and all miscellaneous steel while the concrete abutments, parapets and bridge deck used continuously galvanized reinforcing steel.

Figure 3: Buffalo Creek Bridge in Independence, Iowa

Like many small towns, Independence relies on its small bridges for connectivity to larger centres and bridge closures can result in detours that significantly impact travel times. In these cases, there is added pressure to minimize closures and therefore improve longevity of the structures. In this situation, Independence engineers decided to galvanize all the steel infrastructure including the reinforcing steel. In this case Continuously galvanized rebar was selected for its added corrosion protection, bond strength and formability properties in addition to its competitive cost compared to other options.

5 CONCLUSIONS

Zinc coatings on steel rebar increase the 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 coatings are immune to corrosion at the pH levels of carbonization-induced reinforcement corrosion.

Zinc corrosion products are less voluminous than iron corrosion products, suggesting that the bulk of the corrosion products applying pressure to the concrete surrounding the rebar were corrosion products of iron and not those of zinc.

Continuously galvanized rebar [CGR] provides excellent corrosion resistance and exceptional bond strength, in plain or fibre reinforced concrete. The high bond strength translates into reduced crack widths.

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