

Hot-Dip Galvanized Rebar Performance in Bridge Decks

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ABSTRACT

The long-term corrosion protection that hot-dip galvanized steel provides can be used to protect reinforcing steel used in concrete bridge decks. Some of the first bridge decks that used hot-dip galvanized reinforcing steel were constructed in the early 1970's. Examination and testing of these bridge decks reveals that the hot-dip galvanized reinforcing steel is still protected by the zinc coating and, in some cases, the zinc coating exceeds the minimum amount for a newly galvanized article. The chloride levels on some of these bridge decks exceed the corrosion initiation threshold for black reinforcing steel by as much as 500%. Hot-dip galvanized reinforcing steel has a higher chloride threshold and a slower corrosion rate than black reinforcing steel. The zinc corrosion products move away from the reinforcing bar and do not create the pressure situation that is present when black reinforcing bars are used. The migration of the corrosion products of zinc minimizes the surface layer spalling in bridge decks with hot-dip galvanized reinforcing bars.

Keywords: Hot-dip Galvanizing, Zinc Coating, Galvanized Rebar, Rebar Corrosion, Galvanizing, Corrosion Control, Reinforcing Steel, Concrete Spalling, Zinc Corrosion, Concrete Bridge Decks

INTRODUCTION

Zinc metal has a number of characteristics that make it well suited for use as a coating for protecting iron and steel products from corrosion. The excellent field performance of zinc coatings is due to its ability to form dense, adherent corrosion product films, and a subsequent rate of corrosion considerably below that of ferrous materials, some 10 to 100 times slower, depending on the atmosphere. While a fresh zinc metal surface is quite reactive, the zinc metal forms a thin film of corrosion products on exposure to the atmosphere. This film of corrosion products transforms into a dense, transparent barrier layer that prevents strong attack on the zinc metal. Further, the barrier film is not water-soluble and erodes slowly over time. (1, 2)

In addition to creating a barrier between the steel and the environment, zinc also has the ability to galvanically protect steel. If the coating is damaged and the underlying steel exposed to the environment, zinc - being anodic to iron - will preferentially corrode and sacrificially protect the exposed steel against rusting. In this form of corrosion protection, broadly known as cathodic protection, the base metal becomes the cathode in the corrosion cell, and the coating metal the anode. Figure 1 shows the relative positions of zinc and steels in the galvanic series of metals. In a bimetallic couple, anodic metals (e.g. zinc, aluminum, cadmium) will sacrifice themselves to protect more cathodic metals (iron or steel in this case) against corrosion.

This dual mode of corrosion protection afforded by zinc coatings on iron and steel, in that there is both barrier protection due to the presence of the coating and sacrificial protection in the event that the underlying steel is exposed, and the fact that the zinc coating is robust and can be easily transported and handled, has resulted in the widespread use of galvanizing for corrosion protection of a wide variety of iron and steel products exposed to many different environmental conditions.

Zinc coatings on steel reinforcement in concrete have some significant features that extend the service life of the reinforcement. The first important property is the higher chloride threshold for the zinc coating. This higher threshold significantly delays the onset of active corrosion. The second feature is the smaller, more mobile corrosion products of the galvanized coating. Since the zinc corrosion products are small, they will migrate away from the zinc coating surface and will not swell the concrete like the black steel corrosion products causing cracking and spalling. The zinc corrosion products will also form a barrier to chloride penetration to the bar surface and, thereby, delay the time it takes to reach the chloride threshold for the start of corrosion. These important features of the zinc coating can result in projected lifetimes of greater than 75 years.

HOT-DIP GALVANIZING

Hot-dip galvanizing is the most common of the zinc coating methods. In this process, steel parts are cleaned and dipped into a bath of molten zinc either as individual pieces or as a continuous strip of sheet or wire product. The resultant coating comprises a series of zinc

and zinc-iron alloys layers that are metallurgically bonded to the steel. The overall coating itself is quite thick, generally more than 4.0 mils, is tough and damage resistant, and is strongly adhered to the base steel. Due to the high impurity levels, especially silicon and phosphorus, in reinforcing steel, the galvanized coating grows very quickly in the zinc metal bath and can vary between 4.0 and 20.0 mils. Steels that contain low silicon levels, <0.3%, have a galvanized coating growth process that is limited by the interdiffusion of iron and zinc and reach a maximum coating thickness between 4.0 and 6.0 mils. Steels that contain high silicon levels, >0.3%, have a galvanized coating growth process that is linear with time and has no maximum thickness. (3, 4) These coating thickness variations do not affect the corrosion protection of galvanized coatings. They can affect the coating adhesion when the coating thickness is over 15.0 mils.



Figure 1. Galvanic Series of Metals

Of all the coating systems available to apply zinc to steel, the only coating that forms both a metallurgical bond with the steel and coatings of sufficient thickness to provided extended protection in a variety of environments, is the hot-dip galvanizing process. As a result, hot-dip galvanizing is widely used throughout the world for the coating of steel products and components, fabricated items and structural sections, and also for steel reinforcing products including bars, wire and welded mesh.

It is worth noting that the term *galvanizing*, the chief characteristic of which is the formation of a metallurgical bond at the zinc-iron interface, is often loosely used to mean *the coating of steel with zinc*. This may include, of course, all of the zinc coating systems and for this reason it is important to be precise when specifying galvanizing in order that the requisite coating thickness and coating morphology will be obtained. Thus, where substantial alloy layer coatings are required on structural sections for example, including reinforcing steel, *hot-dip galvanizing* should always be specified.

HISTORY

Hot-dip galvanizing was first patented in 1836 by a French chemist named Sorel. One year later a British patent was issued for a similar process and by 1850 over 10,000 tons of zinc was being used by the corrosion protection industry in the UK. For over 150 years hot-dip galvanizing has been used to protect steel in all types of environments. For reinforcing steel there have been installations in high corrosion areas such as docks and waterfronts where the high traffic and salt water exposure generate very high corrosion rates and hot-dip galvanizing has been used to protect the reinforcing steel.

The use of hot-dip galvanized rebar was beginning to accelerate during the early 1970's when the forward movement of the industry was halted by a ban on hot-dip galvanized rebar by the Federal Highway Administration based upon poor results from accelerated tests. The galvanizing industry appealed this ban and, eventually, had the ban lifted because the correlation between accelerated tests and real world performance was never performed. The use of hot-dip galvanized rebar has steadily grown since the ban was lifted. The states now have the flexibility to use whatever deck corrosion protection methods they have determined to be cost effective.

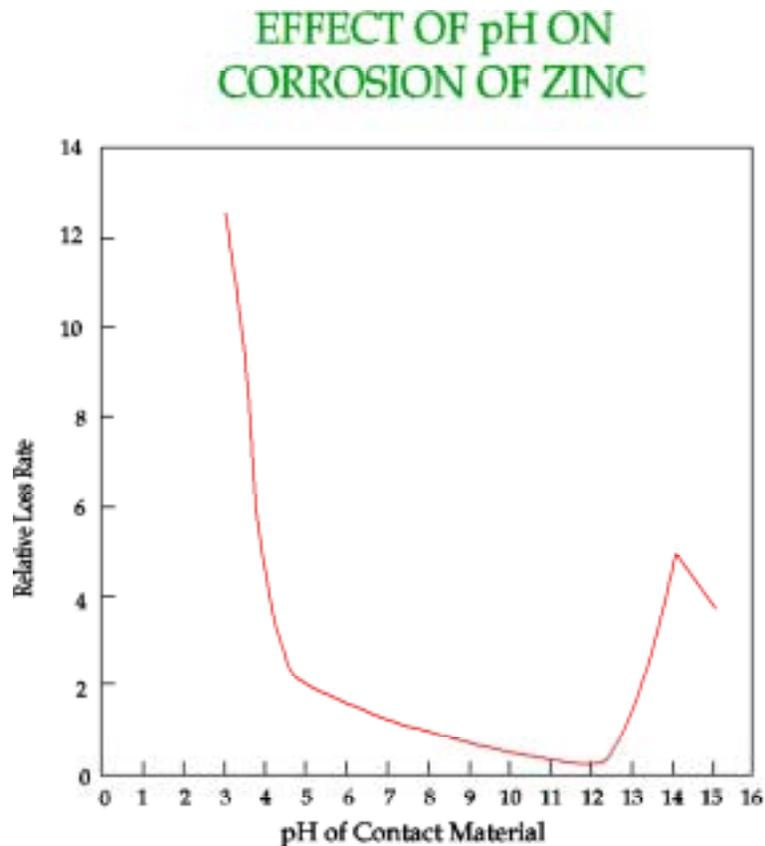
ACCELERATED TESTS

The purpose of accelerated testing is to isolate one environmental parameter and to increase this parameter until the sample fails. In the actual installations of reinforcing bar there are many parameters that affect the corrosion performance of the bar. The correlation must be made from the accelerated testing performance to the actual causes for failure in real world applications. If this correlation cannot be made then the accelerated test should not be used as a determination of acceptable performance for the reinforcing bar.

Some parameters can be accelerated but the actual lifetime data in the test environment cannot be correlated to the field performance. Accelerated test of chloride threshold for reinforcing bars have found that zinc coatings have higher thresholds than bare steel by a factor of between 5 and 10 to 1. (5, 6, 7) This higher threshold for chloride attack on the zinc coating indicates that galvanized reinforcing steel should have a significantly longer lifetime than bare steel. In addition to the higher threshold for chloride attack, the zinc corrosion products migrate away from the bar and fill the small capillaries and voids that will allow chloride ions to penetrate the concrete and come into contact with the reinforcing steel. Zinc

corrosion products actually fill the voids and capillaries making the chloride ions path to the bar surface very difficult and further delaying the onset of chloride attack. (8, 9)

Another parameter that is often used in accelerated testing is pH. Figure 2 shows the relative loss rate or the corrosion rate of zinc versus pH. (10) The accelerated tests use very high pH solutions to simulate the conditions of freshly poured concrete. The problem with the accelerated test is that the galvanized reinforcing bars are not allowed to dry during the testing. In the field when wet concrete becomes dried, the pH of the concrete environment may be a high number near 12.5 but the drying of the concrete allows the zinc coating to form a protective passivation layer. This passivation layer will mean that the zinc coating corrosion rate will drop significantly. The accelerated tests maintain the pH at high values in solution and, therefore, maintain a rapid attack on the zinc coating leading to a low estimate of the actual service life of the coated reinforcing bar.



Source: B. Roethlis, G. Cox and W. Littreal "Metals and Alloys" 3.73 (1963)

Figure 2. Relative Loss Rate of Zinc Coatings versus pH of contact Material

Another common difficulty with accelerated testing is the use of solutions with only NaOH or KOH as the salt constituent. The inclusion of calcium salts along with NaOH and/or KOH changes the chemical reactions on the surface of the zinc coating. (7) Without the calcium ions, the results of a pure NaOH or KOH solution in contact with a galvanized reinforcing

steel bar are that the corrosion rate of the zinc coating is very high and the corrosion proceeds with no passivation of the zinc surface. With the inclusion of calcium ions into the solution the zinc coating surface passivates and the corrosion rate drops after the passivation. These types of tests are nearly impossible to relate to real world performance of hot-dip galvanized steel in concrete.

FIELD TEST RESULTS

If accelerated tests are not reflective of the actual corrosion rate of hot-dip galvanized reinforcing steel, how do we discover the performance of galvanized reinforcing steel in actual field conditions? There are two particularly severe environments where corrosion protection of reinforcing steel is essential to preserving the bridge decks. The first is the coastal areas and over salt water bodies where the attack on the concrete comes from the salt water deposits on the bridge surface as well as salt spray underneath the bridge deck. The second is the bridge surfaces where ice and snow can build-up and road salt is used to keep the bridge surface open for traffic. Both of these environments introduce chlorides into the concrete through moisture that is saturated with salts. The chlorides penetrate the concrete and eventually accumulate to sufficient concentration at the bar surface to begin a corrosive attack on the metal. The threshold concentration of the chlorides depends on the metal surface. Since the zinc corrosion products accumulate around the bar surface, the chloride penetration to the bar becomes more difficult so the time to reach the chloride threshold is significantly longer with galvanized reinforcing steel.

The actual field performance of bridge decks that are constructed with hot-dip galvanized reinforcing steel has been tested by Construction Technology Laboratories. (11, 12, 13, 14, 15, 16) The bridge section is sampled using half-cell potential measurements to locate the highest corrosion spot on the bridge surface. Once the highest corrosion spots have been located, cores are taken of the concrete and reinforcing steel to examine the chloride levels at the bar surface and to measure the zinc coating thickness on the bar section.

One of the oldest bridges with hot-dip galvanized reinforcing steel is the Longbird Bridge in Bermuda. The bridge was first constructed in 1952 and the most recent examination of the bridge's reinforcing steel took place in 1995. After 42 years of service the average coating thickness of the hot-dip galvanized coating still exceeded the minimum requirement for a brand new structure. (11)

Another bridge that is located in the coastal/salt water corrosion environment is the Boca Chica Bridge on Highway 1 and servicing the traffic that crosses the waterways that lead to the Florida Keys. This bridge was constructed in 1972 and was last inspected in 1999. (12, 13, 14, 15)



Figure 3. Boca Chica Bridge on Highway 1 near Key West, Florida

The zinc coating was an average of 6.7 mils while the chloride content at the level of the reinforcing steel was 3.21 lbs per cubic yard of concrete.

One of the galvanized reinforcing steel bridges located in the freeze/thaw environment that is subjected to road salt accumulation is the Athens Bridge on Route 22 in Bradford County, Pennsylvania. This bridge was first constructed in 1973 and inspected in 2001. (12, 13, 14, 16)



Figure 4. Athens Bridge over the Chemung River on Route 22 in Pennsylvania

After 28 years of service the zinc coating on the reinforcing steel was 11.1 mils on average. The chloride concentration at the level of the reinforcing steel was 2.25 pounds per cubic yard of concrete. The overall bridge condition was very good with no evidence of any concrete distress. The chloride content in the concrete on this bridge has been well above the threshold for corrosion of black reinforcing bars for many years. When the bridge was first examined in 1981, the chloride level was 2.54 pounds per cubic yard of concrete. The chloride level will vary slightly from one area to another on the bridge surface due to the location of the core extractions. Even with these high chloride levels for over 20 years the hot-dip galvanized coating is still showing little or no signs of significant corrosion. The thickness of the zinc coating indicates that this bridge can expect corrosion protection for many years to come.

Another bridge in the freeze/thaw environment with significant deicing salts is the Tioga Bridge on Route 15 in Tioga County, Pennsylvania. This bridge is on a heavily traveled route from the industrial areas of Pennsylvania to the Five Finger Lakes area of New York. The area experiences heavy snowfall and constant use of road salt is necessary to keep the bridge open in the winter. The bridge was constructed in 1974 and the last inspection was performed in 2001. (12, 13, 14, 16)



Figure 5. Tioga Bridge over Mill Creek on Route 15 in Pennsylvania

The chloride level on this bridge first showed levels at the black steel corrosion threshold during the 1991 inspection. Since that time the chloride levels have more than doubled at the level of the reinforcing bars. The zinc coating showed a thickness of 7.8 mils on the average

during the 2001 inspection of the bridge. The bridge is in good physical shape with no concrete distress.

SUMMARY

Galvanized reinforcing steel has been used in bridge decks as early as 1952 and the performance has been excellent. The bridges with hot-dip galvanized reinforcing bars are in great shape. Zinc corrosion products are not causing expansion of the concrete that eventually leads to spalling but are migrating away from the bars into the concrete matrix and filling the voids and capillaries close to the bar. This migration of corrosion products also helps to keep chloride ions away from the bar and extends the service life of the corrosion protection system. Lifetimes of existing structures are projected to exceed 75 years of service. Hot-dip galvanized reinforcing steel has been a steadily growing market based on the strength of excellent field performance. The New York State Thruway Authority has specified galvanized reinforcing steel and/or galvanized reinforcing mesh in all elements of concrete structures for all NYSTA and NYS Canal concrete projects let after January 1, 1995. (17) In their evaluations of over 200 projects between January 1995 and March 1998, the average cost of the galvanized reinforcing bars was \$1.28. The average cost for epoxy-coated bars was \$1.12 and for black bars it was \$0.835. All of these costs are on a per pound basis. The NYSTA feels that they are getting materials of the specified quality and that their contractors have readily adjusted to galvanized reinforcement and are giving them good installations.

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