

Laboratory Corrosion Tests of Galvanized Steel in Concrete

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Concrete test specimens containing galvanized and black reinforcing steel were partially immersed in saturated salt solution. The results were that (a) corrosion began at about the same time for both the galvanized and black (mild) steel exposed in the same concrete system; (b) the greater the thickness of zinc was, the earlier concrete cracking occurred; and (c) in concrete of high quality, galvanized steel caused cracking earlier than black steel. Observations indicate that galvanizing is either inefficient or ineffective in preventing rusting of underlying steel in concrete. Most significant in postponing concrete cracking caused by corrosion of black or galvanized steel was increasing the cement factor. There does not appear to be a half-cell potential value per se that discloses the corrosion activity of galvanized steel in concrete.

Several sources report various aspects of the use of galvanized steel (1, p. 69) as a means for postponing concrete distress due to corrosion of the black reinforcing steel (5 through 9). However, the various reports (1, 2, 3, 4, 9) do not consistently indicate a significant benefit to using galvanized instead of plain reinforcing steel in concrete subjected to salt (chloride ion) contamination.

Zinc is a widely accepted rust-protective coating in a normal atmospheric environment. Because of this demonstrated property, galvanized steel rebars have been used in concrete to reduce the rate of steel corrosion in the presence of salt.

The environment under which a galvanized steel rebar exists in concrete with a pH of about 12.5 and is subject to attack by chloride ions is one about which comparatively little is known. The corrosion of zinc is inhibited through the formation of a mixture of zinc compounds such as the oxide, hydroxide, and carbonate. In addition, the zinc can serve sacrificially to protect steel exposed through scratches and cracks. To find how these protective measures react in portland cement concrete in an aggressive environment is the purpose of this research.

TEST PROCEDURE

The test procedure (8, p. 28) was to partially immerse the reinforced concrete specimens to a depth of 8.9 cm ($3\frac{1}{2}$ in) in a saturated solution of sodium chloride and in plain tap water. The level of solution and water was maintained by periodically adding water to compensate for that lost by evaporation and by having an excess of salt in the bottom of the tanks. Each addition of water was thoroughly stirred into the solution. All tests were performed in the laboratory, which had an air temperature of about 22°C (72°F). The relative humidity was assumed to range between 30 and 45 percent.

The specimens consisted of No. 4, or 1.3-cm-diameter ($\frac{1}{2}$ -in), reinforcing steel bars embedded in concrete bars 11.4 cm ($4\frac{1}{2}$ in) wide by 6.4 cm ($2\frac{1}{2}$ in) thick by 38.1 cm (15 in) long. The amount of cover was designed to be not less than 2.5 cm (1 in).

The cement used was ASTM type 2, modified low-alkali, which complies with California State standard specifications.

Eighty replicate specimens were cast from 10 batches of 279 and 418-kg/m³ (5 and 7 $\frac{1}{2}$ -sack) concrete for the laboratory tests. Half of each batch was cured with steam plus water, and the other half was cured with water only. Twenty replicate samples of either black or galvanized steel were used in each test of cement factor and curing.

In addition, 10 specimens were cast from 335-kg/m³ (6-sack) concrete. All had galvanized steel reinforcement. Half of the specimens were moist cured, and the remainder were steam cured.

Those specimens that were cured with steam plus water were subjected to a temperature of 59 ± 3°C (138 ± 5°F) for approximately 16 h and then submerged in tap water at 25 ± 2°C (73 ± 3°F) for a total cure period of 28 days. The water-cured specimens were submerged in tap water for 28 days before testing. The concrete mix data are given in Table 1.

In conjunction with corrosion testing, concrete absorption tests were performed in accordance with Test Method Calif. 538-A. Some details of the absorption test have been reported (8). Essentially, the test consists of oven drying the concrete specimens at 110°C

(230°F) and then submerging them in water. Table 2 gives the results of the concrete absorption tests.

After the specimens were placed in the testing solutions, electrical half-cell potential measurements were made thrice weekly. The purpose of these measurements was to determine when a corrosive quantity of salt had penetrated to the metal surface and to determine, if possible, an active (corroding) or passive (non-corroding) potential for the galvanizing existed.

For the galvanized steel specimens, the reinforcing steel was first sandblasted, weighed, and then galvanized. The weight of the zinc coating was calculated from the difference of the before and after galvanizing weights. The hot-dip galvanizing of the steel complied with the California standard specifications dated January 1969 and ASTM designation A 123.

It was intended that the thickness of the galvanized coating be the equivalent of 610 g/m² (2 oz/ft²) to provide an average thickness of about 0.086 mm (0.0034 in) of zinc. However, weight measurements showed that the average amount of zinc deposited was equivalent to about 915 g/m² (3 oz/ft²) and varied from 739 to 1420 g/m² (2.60 to 4.65 oz/ft²).

RESULTS OF TESTS OF CONCRETE WITH GALVANIZED AND BLACK STEEL

As shown in Figures 1 through 4, the time to initiation of corrosion (as measured by the change in half-cell potentials) of galvanized and black steel in comparative concrete environments is similar irrespective of cement factor or method of curing. The difference in the time to cracking of the concrete caused by the corrosion of either steel or zinc showed that, in relatively porous (279 kg of cement/m³ of concrete or 5-sack) moist-cured concrete, the mean time for 20 galvanized specimens to crack was 315 days, and in the concrete containing 20 black steel bars the mean time to cracking was 175 days. For the 279-kg/m³ (5-sack) steam-cured specimens, the mean time to concrete cracking was 243 days for the galvanized steel and 124 days for the black steel.

In the dense (418-kg/m³ or 7½-sack) moist-cured concrete, the mean time for the 20 galvanized steel specimens to crack the concrete was 549 days, while only 7 out of 20 black steel specimens had cracked at the end of the 622-day test period. The last galvanized specimen cracked in 678 days.

In the case of the galvanized steel specimens partially immersed in Sacramento city tap water (about 20 to 40 ppm Cl), three moist-cured concrete specimens out of the five cracked about 7.6 cm (3 in) above the waterline after about 600 days of testing.

At the conclusion of the test period of 1700 days, all 10 tap water specimens were opened for inspection of the galvanizing. On all but one specimen, relatively minor rust spots were observed on the zinc surface. The one exception was where rust was absorbed by the steam-cured concrete and was on the surface of the metal for a distance of about 0.32 cm (1/8 in). Zinc corrosion products were observed at the tap waterline and below, but above the waterline the zinc was generally free of corrosion products.

Three concrete samples from the 418-kg/m³ (7½-sack) concrete were chemically analyzed and found to contain about 100 ppm chromate as CrO₃. This is estimated to be greater than that found necessary in cement pastes to prevent hydrogen gas evolution from zinc (9). Minor evidence of gas evolution was observed at the concrete-zinc interface, and many of the galvanized steel bars exposed showed no evidence of mortar porosity or of it sticking to their surfaces. The source

of the chromate was found to be in the aggregate and the cement.

A chemical analysis of the concrete section immersed in tap water showed about 3.3 kg of chloride ion per cubic meter of concrete (5.6 lb/yd³). The chloride content of the atmospherically exposed concrete was found to be about 0.95 kg/m³ (1.6 lb/yd³). The source of the chloride in concrete was not determined. For the underwater concrete sections exposed to the saturated sodium chloride solution, the average amount of absorbed chloride was 37.6 kg/m³ (63.3 lb/yd³).

Table 2 gives concrete absorption test results. Based on the consistency of results, differences in concrete absorption do not appear to have affected any comparative test results.

As a further evaluation of the relationship between zinc and concrete cracking, the 20 galvanized specimens in each test were ranked in ascending order of actual weight of zinc and then separated into two groups. The two groups consisted of 10 that had the lightest weight of zinc in the particular test series and the other group of 10 that had the heaviest weight of galvanizing. Then the average of days to concrete cracking for each group in each test series was calculated and tabulated (Table 3). In each case the group of bars with the heaviest galvanizing cracked first.

DISCUSSION OF RESULTS

The test data showed that, for greater weights of zinc coating, the concrete cracked earlier. Also, because heavier weights of zinc coating resulted in earlier concrete cracking, it is obvious that the corrosion products of zinc exert sufficient pressure to crack a 2.5-cm-thick (1-in) concrete cover.

The potential of the galvanized bar in initially salt-free concrete was found to vary between -0.19 and -0.75 V SCE (saturated calomel half cell). This voltage difference of 0.56 V might result in localized corrosion of the zinc coating.

In highly salt-contaminated concrete the potential of the galvanized bar varied between -0.62 and -1.02 V SCE, which could cause sections of zinc to have a galvanic voltage difference of 0.40 V—a difference that could induce localized corrosion of itself. When zinc is in concrete of variable salt contamination (potential at 1.02 V SCE) (Figure 2) and a potential of -0.19 V SCE (Figure 5), then the corrosion of zinc in the salt-contaminated concrete could be initiated by a maximum of about 0.83 V driving the associated current flow.

For steel in concrete specimens exposed to a saturated sodium chloride solution, it was reported (16) that the mean potential of corroding black steel was -0.36 V SCE to a maximum mean of -0.48 V SCE. Therefore, when black steel in salt-contaminated concrete begins to corrode (potential of -0.36 to -0.48 V SCE) and is electrically interconnected to galvanized steel in relatively low salt concrete (minimum potential of -0.19 V SCE), then the reversed polarity zinc might cause the black steel to have accelerated corrosion as a result of the 0.17 to 0.29-V differential.

For the average indicated range of half-cell potentials of zinc (this report) and black steel in salt-free concrete (8, 16), it seems likely that the black steel would normally tend to cause accelerated corrosion of galvanizing in salt-free concrete.

Under certain conditions, the polarity of zinc can reverse, which may cause accelerated corrosion of black steel. For example, at temperatures of about 60°C (140°F) or higher in aerated hot waters, it was determined (12) that zinc does not act as a sacrificial coating but becomes noble and induces pitting of steel. It was

also found that waters high in carbonates increase the tendency of the polarity reversal of zinc to iron couple (13, p. 330)

It was reported that the formation of ZnO as a corrosion product of zinc is responsible for the polarity reversal instead of the porous Zn(OH)₂ or the basic zinc salt, which is normally anodic to iron (14, p. 16). The compound ZnO is reported to be a semiconductor that in

Table 1. Concrete mix variables.

Variable	Mix (kg/m ³)		
	279	335	418
Maximum aggregate size, cm	1.9	1.9	1.9
Actual cement content, kg/m ³	277	332	418
Slump, cm	7.6	6.4	7.6
Net water/cement (by weight)	0.63	0.51	0.43
Gross water/cement (by weight)	0.72	0.59	0.47
Air (entrapped), percent	2.15	2.6	1.6

Note: 1 kg/m³ = 0.062 lb/ft³, 1 cm = 0.39 in.

Table 2. Concrete absorption (percent by volume).

Cement (kg/m ³)	Cure	Galvanized Bars	Black Steel Bars
		279	Moist
	Steam	15.53	15.64
335	Moist	14.83	—
	Steam	14.84	—
418	Moist	13.84	13.83
	Steam	13.42	13.48

Note: 1 kg/m³ = 0.062 lb/ft³.

Figure 1. Potentials of black and galvanized steel in 279-kg/m³ concrete (moist cured).

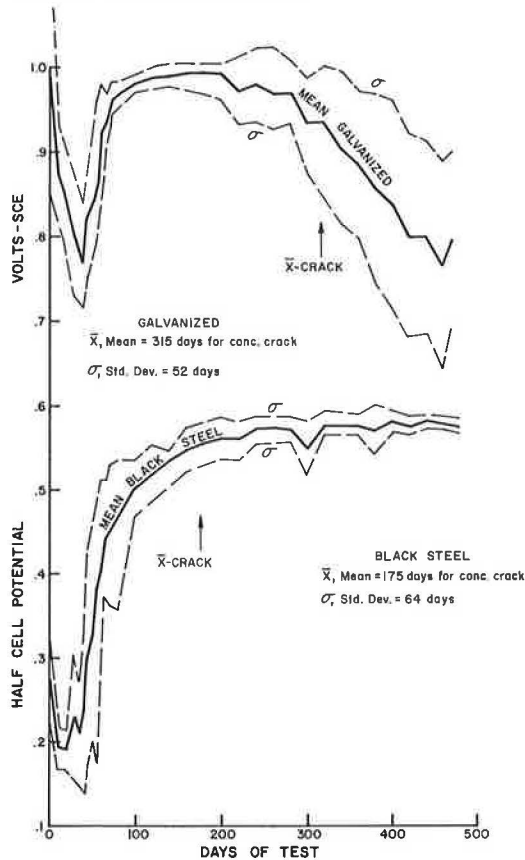


Figure 2. Potentials of black and galvanized steel in 279-kg/m³ concrete (steam cured).

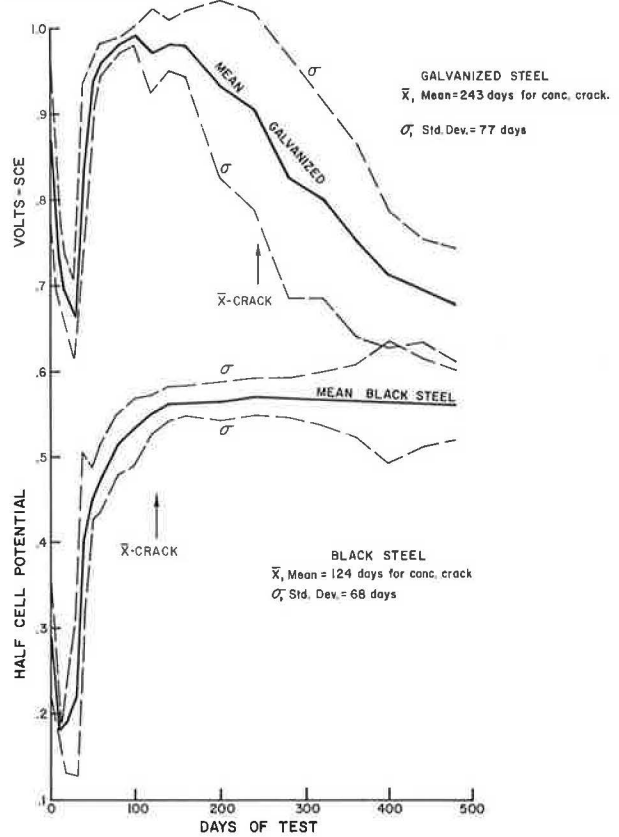
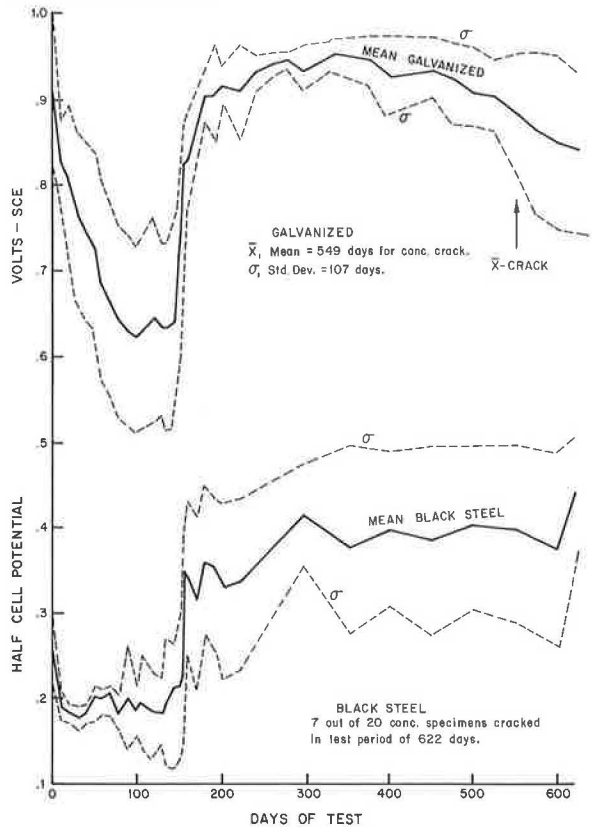


Figure 3. Potentials of black and galvanized steel in 418-kg/m³ concrete (moist cured).



aerated waters acts as an oxygen (O₂) electrode whose potential is noble to zinc and iron (15). A noble potential may accelerate the corrosion of metals with a less noble potential.

It was also reported that, when zinc is used as an anode in water or dilute NaCl, the current output decreases gradually because of the insulating corrosion products formed on the zinc surface. In one series of tests, the current between zinc and iron decreased to zero in 60 to 80 days, and a slight reversal of polarity was reported (15, p. 204).

Based on these reports by others, it is obvious that zinc will not always be a sacrificial metal and thus inhibit or reduce the corrosion of black steel.

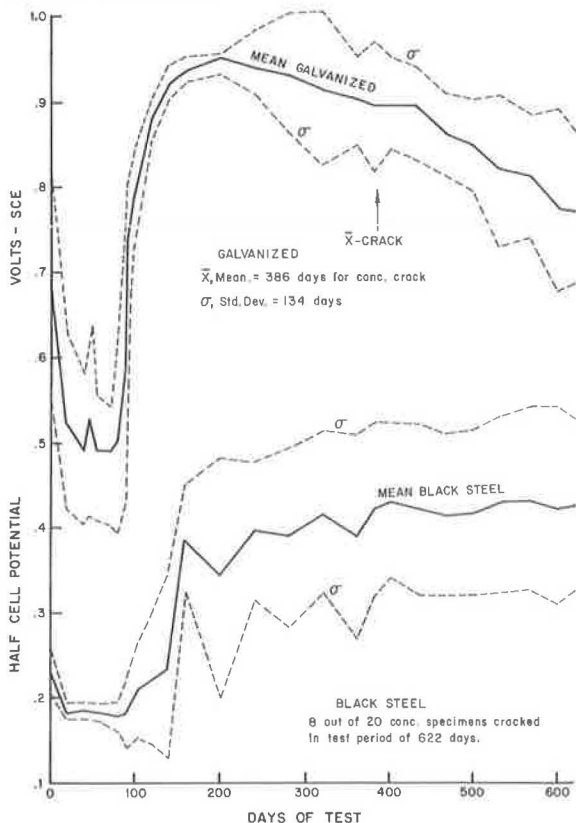
In other studies it was found that, when zinc was placed in concrete, the high alkalinity of the cement caused it to react and evolve hydrogen gas (9, 17).

Table 3. Weight of zinc and concrete cracking.

Cement (kg/m ³)	Cure	Days to Concrete Cracking		Weight of Zinc ^a (g/m ²)	
		Average	Standard Deviation	Average	Standard Deviation
279	Moist	327	56	895.4	46.7
		302	48	1038.1	71.6
	Steam	248	82	873.7	41.5
		239	75	979.9	36.6
418	Moist	600	56	901.6	43.5
		498	123	1124.2	173.0
	Steam	390	69	916.0	55.4
		381	182	1137.1	106.9

Note: 1 kg/m³ = 0.062 lb/ft³; 1 g/m² = 0.0033 oz/ft².
^aFor 10 bars.

Figure 4. Potentials of black and galvanized steel in 418-kg/m³ concrete (steam cured).



When mixing cement with distilled water, researchers found that the resultant pH was 12.8—well into the alkaline range—which is highly corrosive and causes hydrogen evolution from the zinc (9, 18). It has also been reported that, if more than 100 mg/kg of CrO₃ is added to the mixing water (17), the evolution of hydrogen gas will be inhibited.

In short time tests, it was reported that the corrosion rate of zinc is lowest at a pH range of 7 to 12 and is quite rapid when pH is 12.5 (15) or near the values of 12.6 or 12.7 (9).

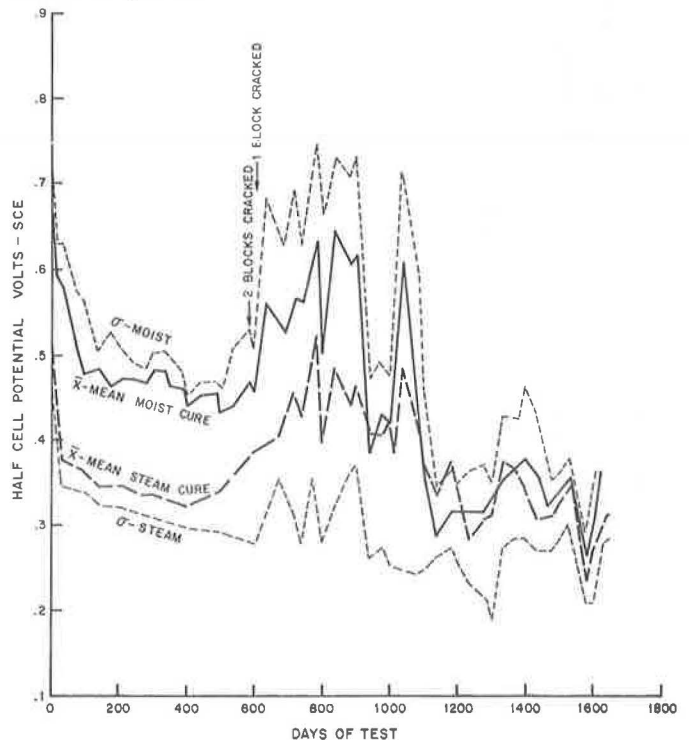
In these tap water tests, black steel as a control for the galvanized steel specimens was omitted because, in previous tests of concrete with the same cement factor as that used in this test, the authors observed no corrosion of the bars. Also, because this test was to evaluate galvanizing it was originally thought that there would be no corrosion of the zinc and that the galvanized specimens would be a control for the specimens exposed to the salt. Such was not the case; however, the test of the galvanized specimens in tap water did demonstrate the wide range of half-cell potentials that could be expected in zinc, and the measured values are subject to a great deal more interpretation and investigation than anticipated.

SUMMARY AND CONCLUSIONS

Galvanized and Black Steel

When the steel-reinforced concrete specimens used in the tests were partially immersed in saturated sodium chloride solution, the chloride ion penetrated the concrete and caused both the galvanized steel and the black steel to begin to corrode at essentially the same time. In a relatively porous concrete, corrosion-caused concrete cracking required a longer time when the steel was galvanized than when it was not. In a high-quality struc-

Figure 5. Potential of galvanized reinforcing steel in 335-kg/m³ concrete in tap water.



tural grade concrete, corrosion of the galvanizing hastened the time to cracking. It appears that the porosity of the concrete can govern the time to cracking: The greater the porosity is, the greater will be the amount of zinc corrosion products that can be absorbed before bursting pressures develop.

The test results showed that, irrespective of the concrete quality or method of curing used, thicker coatings of zinc (up to 1420 g/m² or 4.65 oz/ft²) resulted in a shorter time to corrosion-caused concrete cracking. This test result indicates that the greater the amount of galvanizing used, the greater will be the amount of corrosion products available to cause concrete cracking. This could indicate that the galvanizing corrodes rapidly in salt-contaminated concrete. Otherwise, there should be no difference in time to cracking for different thicknesses of zinc.

Electrical potential measurements indicate that galvanized steel can assume electrically noble potentials in low-salt concrete and initially serve as a cathode to cause accelerated corrosion of both galvanized and black steel in highly salt-contaminated concrete. The amount of corrosion that occurs will depend on many variables such as polarization and anode to cathode area. On the basis of data plots, it was estimated that the lower mean potential of galvanized steel in concrete exposed to tap water was about -0.36 V SCE with a standard deviation of about 0.12 V (Figure 5). However, it was not determined whether this or other potentials indicate a passive or noncorroding condition for the galvanized steel. But zinc and steel corrosion products were observed on the surfaces of the steel bars. As a result, in concrete of variable salt concentration, there does not seem to be a definitive half-cell potential that would clearly indicate an active (corroding) or passive (noncorroding) condition of the zinc.

It appears that zinc behaves similarly to steel in salt-contaminated concrete; it corrodes and causes concrete cracking.

Zinc does not have a consistent half-cell potential in concrete whereby it can be depended on to be a sacrificial metal and protect steel from corrosion by galvanic action.

In salt-contaminated concrete, the data (Figures 1 through 4) indicate that galvanized steel can have a half-cell potential that ranges between -0.62 and -1.02 V SCE (potentials within the limits of standard deviation). It is assumed that such potentials indicate an active or corroding state for the galvanized steel.

Also, the potential measurements show that galvanized steel can, under some conditions, initiate corrosion of itself in salt-free concrete. The potential of zinc in relatively low salt-containing concrete can vary between about -0.19 and -0.75 V SCE (Figure 5), which can result in a galvanic voltage difference of 0.56 V to initiate localized corrosion of itself. The amount and rate of corrosion will depend on many variables.

In tap water galvanized steel corroded initially in relatively salt-free concrete and, after about 600 days of test, caused three out of five moist-cured specimens to crack (Figure 5). The five steam-cured specimens did not have concrete cracking.

Concrete Curing

In this series of tests, as well as in those previously reported (8, 16), there is a more rapid penetration of chloride into steam-cured concrete and earlier corrosion of the embedded steel as compared to a water-cured concrete of the same quality.

Concrete Absorption

Concrete absorption or porosity, per se, indicated that it had a significant effect on the results of the corrosion behavior of galvanized steel. In highly absorptive concrete, the time to cracking caused by corrosion of galvanized steel will differ greatly from that of black steel. However, concrete absorption is not a reliable indicator of the protective qualities of concrete when the value is controlled by variables other than cement factor (8).

It is likely that the corrosion products are partially absorbed by the adjacent mortar or aggregate in highly absorptive concrete, which postpones an internal pressure buildup by the corrosion products that can cause rupture of the concrete.

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Discussion

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My comments refute the highly speculative and largely unsupported conclusions put forward by Hill, Spellman, and Stratfull. The comments address the following subjects: test conditions, zinc corrosion products, and coating thickness in some detail.

TEST CONDITIONS

Although they do not mention it in the test procedures, the authors do comment about the lack of control specimens in the experiment. Their rationale for omitting control specimens is unsatisfactory and most disturbing. Also, I am concerned about the variability introduced into the experiment by the use of 10 different batches of concrete, even when made to the same nominal specification. In addition, no mention is made of how the bars were assigned to the test prisms. It appears that they were assigned systematically and not randomly, as should have been required. Therefore, it seems that the design of this experiment may have been so poorly controlled at the outset as to raise serious doubts about the validity of the results and conclusions.

Besides, the test conditions themselves were apparently so poorly controlled that they produce extreme distortions of the real-world conditions that the authors should have attempted to simulate. A chloride level of 37.6 kg/m^3 (63.3 lb/yd^3) does not appear to be typical at bar level for either a full-scale structure such as a bridge deck or that found in other experiments of this type. In addition, differential cell effects generated under the exposure conditions used for this study appear to have been totally unaccounted for in the data presented in the paper.

The critical reader who is familiar with the work of other researchers in this field must question test conditions that led to the cracking performance found by the authors, particularly the black bar specimens, which apparently did not crack even after 622 days of exposure. For example, Clear and Hay (21), using "the utmost in [cement] quality control," found that, for "typical bridge deck concrete," i.e., cement factor of 7.0, $w/c = 0.50$, and 2.5 cm (1 in) of cover, the time to corrosion for black steel was only 1 week in most cases for a surface application of a total of only 0.6 kg (1.4 lb) of salt. For the test specimens cited by Clear and Hay, rust stains appear as soon as about 15 weeks and no later than 45 weeks. It would have been very enlightening had our

authors been more thorough and conducted further analyses. They would have then been able to give the reader some quantitative indication of the conditions that led to the highly unusual performance for black steel.

Also, from the data presentations adopted by the authors, it is evident that they assumed that the data on time to cracking were normally distributed and that they were therefore justified in using mean and standard deviation values in the presentation of the data. This assumption is open to serious question and must be justified before the arguments presented can be considered. Judging from the relatively large values presented for standard deviation, the authors should have felt impelled to examine the nature of their data more carefully before adopting such a statistical format for their results. Without a presentation of the authors' data, one can only speculate on the more precise nature of the statistics of the experiment. However, from the very nature of this type of experiment and from what is apparently typical of the statistics of related corrosion experiments, the assumption of normal distribution statistics is highly suspect.

ZINC CORROSION PRODUCTS

The authors suggest several times that the formation of zinc corrosion products generates bursting pressures, which have a direct relationship to the time to cracking. Neglecting for the moment the authors' unsupported correlation between a time to cracking criterion and the underlying corrosion mechanism, let us examine some of the features of the corrosion model that has been suggested. The authors state "... it is obvious that the corrosion products of zinc exert sufficient pressure to crack a 2.5-cm-thick (1-in) concrete cover." Unfortunately, what appears to be obvious to the authors was in no evident way measured in the experiment described. Even a casual reading of Reis, Mozer, Bianchini, and Kesler (22) or Houston, Atimtay, and Ferguson (23) should have dissuaded the authors from using such a simplistic model, particularly since they failed to support their assumption with data from the experiment. As further reinforcement for this point, Cornet and Bresler (24) show that a significant difference in time to cracking (as well as extent of cracking) in test prisms can be attributed to differences in rebar geometry (e.g., deformed or plain bars) and that cracking during the earlier stages of exposure can be unrelated to corrosion effects for either black or galvanized bars.

The authors also speculate, again without any indication that measurements were made, that zinc corrosion products migrate away from galvanized bars to account for their apparent improved performance in more porous concrete material. This assumption may be refuted with the authors' own data. From the absorption data given in Table 2 and Figures 1 through 4, it can be shown that the porosity data cannot always be correlated with time to cracking criteria. It can be demonstrated that the data presented for the 279-kg/m^3 and 418-kg/m^3 (5 and $7\frac{1}{2}$ -sack) mixes are consistent in this regard.

Further, when one examines the relative magnitude of changes in absorption that are suggested by the authors as the reason for differences claimed in performance as measured by time to cracking, one finds that, for the 279-kg/m^3 (5-sack) material, a change of only 1.5 percent in absorption appears to produce a 23 percent change in time to cracking. For the 418 kg/m^3 ($7\frac{1}{2}$ -sack) material, a change of 3.1 percent in absorption appears to produce a 23 percent change in time to cracking, in the opposite direction. For a relationship that is so highly leveraged (even if it was consistent), I am curious about how accurately absorption was measured with regard to the relatively small magnitude of change that was cited.

Further, one is led to assume from the absorption testing temperature specified that the porosity measurements were made on samples prepared for that purpose and not made on the rebar test specimens. There is no mention of any controls to ensure that the concrete in the specimens was properly consolidated or of any measurements made of the unit weight of the specimens to determine how well consolidation was effected in the preparation of the samples.

How can the authors seriously suggest that their major conclusion can even be remotely ascribable to cement factor and absorption when they have apparently overlooked (or failed to control) the consolidation of their specimens? Clear and Hay (21) have convincingly demonstrated that a variation of as little as 5 percent in the in-place density can result in increasing chloride ion penetration through a 2.5-cm (1-in) concrete cover by a factor of 6.33.

It is also interesting to note that Stark and Perenchio (25) found no correlation between cement factor and galvanized rebar performance in any of the full-scale or simulated bridge deck structures they investigated. Inasmuch as scale factors in laboratory tests can often produce misleading results, particularly if the laboratory tests are poorly designed or executed, they generally cannot be given the same credence as tests on full-scale structures. Stark and Perenchio concluded that "... this investigation shows that galvanized steel clearly outperformed the untreated steel where a corrosive environment exists as defined by chloride ion content and condition of the steel."

COATING THICKNESS

The most anomalous assertion in the paper is that galvanized material with lighter coating weight performs better than does material with a heavier coating. This is particularly troubling since the conclusion is the result of a pseudo-statistical argument. It is supported only by speculation and not by any apparent analysis of the specimens themselves.

The conclusion regarding coating weight is based on a simple comparison of arithmetic means after the data were ordered into two populations based on coating weight. If valid, this comparison must satisfy at least a basic test for significance between the difference of mean values. Applying the universally accepted Student's t-test to the means clearly shows that something is very wrong with the authors' conclusion on coating weight. At a 99 percent confidence level (a common criterion for such testing), all the tests fail to show any statistically significant differences between the mean values used by the authors. At a 95 percent confidence level, three out of four comparisons fail to show any differences between the mean values cited. Based on this, the coating weight conclusion presented by the authors is seriously flawed and is rejectable. What is puzzling is why the authors did not include electroplated zinc bars with coating weights of a lesser order of magnitude into their test matrix. It appears that such an examination would have resolved this question much more directly than was attempted by the authors.

In the Stark and Perenchio report, there are no differences in galvanized rebar performance that could be attributed to coating weight. They were dealing with the almost exact same range of coating weights as were the authors.

The space available for these comments does not permit a detailed discussion of other defects in the Hill, Spellman, and Stratfull paper. However, a close examination of their arguments concerning potentials and potential reversal shows deficiencies of a magnitude

similar to those cited here. It is hoped that these topics will be addressed by other commentators.

In conclusion, the Hill, Spellman, and Stratfull paper is flawed to the extent that it should be essentially rejected and the experiment reperfomed under controlled conditions.

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Albert R. Cook, International Lead Zinc Research Organization, Inc.

Tonini's comments seem to be well founded. I too believe that important conclusions reached by the authors are wrong, that they are not supported by the data presented, and that in any case the data obtained cannot be relied on because the tests were poorly designed, not subject to comparison with control tests, and not supported by essential data concerning the materials used. Also, many of the data can be used to support entirely contrary conclusions.

I make these forthright comments because I believe it would be a pity if, because of this laboratory study, galvanized steel was neglected for bridge deck reinforcement. Galvanized reinforcement has been proved to extend the life of a wide range of reinforced concrete structures. Core tests of a 21-year-old bridge deck made by the Portland Cement Association showed that in concrete, with chloride levels above those considered aggressive to untreated steel, a galvanized coating was still protecting the basic steel, and between 60 and 75 percent of the original galvanized coating remained after 21 years.

The results reported in this paper are not consistent with previous laboratory tests nor with practical experience. It is reasonable therefore to question the test rather than the subject of the test.

Accelerated tests in general are notoriously inconclusive and are only indicative of what might happen under the conditions under which the test was made. A corrosion engineer will seldom rely on such data without having demonstrated that the kinetics of the reactions can at least be related to those taking place in practical situations.

Of paramount importance to the corrosion resistance

of galvanized reinforcing steel is the nature of the galvanized coating. No data have been provided concerning this important variable. The authors have, however, pointed out that a wide variation in coating weight was noted. This indicates lack of control of the galvanizing operation or inadequate control of the composition of the basis steel or both.

Let us consider the summary and conclusions. The authors state, "The greater the porosity [of the concrete] is, the greater will be the amount of zinc corrosion products that can be absorbed before bursting pressures develop." No data are presented that show the porosity of the concrete. We cannot agree with the view that a 10 percent difference in absorption, which the authors noted between a mix containing 279 kg/m^3 (5-sack mix) and a mix containing 418 kg/m^3 ($7\frac{1}{2}$ -sack mix), considered in the absence of permeability data, justifies the speculation that this indicates a difference in porosity that could account for differences in pressure, which in turn are caused by an unknown amount of corrosion product.

Concrete cracking is caused by a number of factors unrelated to corrosion of the reinforcement. The authors could have examined the galvanized specimen after testing to confirm the presence and composition of zinc corrosion products and determine the degree of any zinc absorption. Instead, they were content to rely on pure conjecture concerning this fundamentally important point.

The authors also state that thicker coatings of zinc result in a shorter time to cracking. They write that this could indicate that galvanizing corrodes rapidly in salt-contaminated concrete. They ignore the evidence in the literature that the diameter of any reinforcing bar, the depth of cover, and the time to cracking are related. It seems more likely that the effect reported is due to geometry rather than to any special corrosion susceptibility of the zinc.

The authors appear to be relating the open-circuit potentials that they have seen at different times for zinc in low-salt concrete and the open-circuit potentials of steel in lightly salt-contaminated concrete. However, it is closed-circuit potential, among other things, that is important to the course of any corrosion and not open-circuit potential. They correctly state that any corrosion that might occur will depend on many variables. It would be more realistic if they had pointed out that these variables are so poorly defined by their available data that their remarks are entirely speculative. In my view, such far-fetched speculation has no place in such a paper.

A series of papers by Gouda and Mourad (26, 27, 28) stresses the effect of differences in pH, salt concentration, surface condition, carbon dioxide, and oxygen concentration on the corrosion of untreated (black) steel reinforcement. Hill, Spellman, and Stratfull attempted to simulate, in an accelerated manner, the corrosion of reinforcing steel in a bridge deck by taking concrete specimens 38 by 6.4 by 11.4 cm (15 by $2\frac{1}{2}$ by $4\frac{1}{2}$ in) and placing them to act as a wick, immersed to a depth of 8.9 cm ($3\frac{1}{2}$ in) in concentrated salt solution. This salt solution was able to evaporate on penetrating the specimen, carrying with it usual amounts of dissolved carbon dioxide and oxygen, and also it was able to build up a level of salt contamination and of chloride concentration cells far more severe than would have been likely in practice. All this produces conditions in no way comparable to what might have occurred in practice.

Also, the quality control exercised in the investigation can be questioned. Similar specimens were placed in tap water, and, even in tap water, the specimens built up 1.9 kg/m^3 (5.6 lb/yd^3) of chloride ion. They found that atmospherically exposed concrete specimens contained 0.55 kg/m^3 (1.6 lb/yd^3) of chloride. Where did

all this salt come from? In one northern state, about 2.42 kg/m^3 (7 lb/yd^3) of chloride ion is the maximum expected. Clear and Hay (21) suggest that 0.38 to 0.45 kg/m^3 (1.1 to 1.3 lb/yd^3) of chloride ion is the threshold level for chloride-initiated corrosion of untreated reinforcing steel in concrete. Yet the authors refer to their specimen as being relatively salt free. The presence of these unexplained large amounts of chloride in the tap water specimens and in the atmospherically exposed specimens justifies serious doubt about the manner in which the concrete was prepared. Furthermore, the consolidation of the mix can be critical to the behavior of the concrete and its reinforcement. Equal consolidation of specimens is therefore vital to ensure the validity of comparative tests. This variable was not judged worthy of mention. Furthermore, to ensure comparable results of course requires that the concrete be uniform in composition from one specimen to another, and yet 10 separate mixes were prepared for the mixes containing 279 and 418 kg/m^3 of cement (5 and $7\frac{1}{2}$ sack).

Regarding paragraph 4, galvanized steel is generally accepted as an excellent protective coating for steel. In 1973, 1.5 Tg (1 535 000 metric tons) were used for this purpose. Those wise enough to make use of it in this fashion would not quarrel with the authors' statement, "Zinc behaves similarly to steel. . . . It corrodes. . . ." It has however been shown to increase the life of the steel out of all proportion to the increased cost incurred, and that is why such a tremendous amount of zinc is used for corrosion protection.

The authors suggest that zinc may reverse its polarity and cause accelerated corrosion of black steel. Given the miniscule amount of data relating to half-cell potentials that they feel justifies placing such a suggestion in the open literature and given the findings of others that in the presence of chloride ion, or calcium or silicate ions, no such reversal has been seen, and given that cases of reversal of zinc potential in practice have been involved with domestic water falling within certain limits of composition and usually with elevated temperature and under pressure of oxygen, I can only characterize their statements as irresponsible.

It is entirely beyond reason to draw any analogy between corrosion processes taking place under neutral conditions in domestic water and what might take place in concrete. Even in the case of distilled water, two investigators (29) concluded that "The cathodic depolarization arising from oxygen at atmospheric pressure is insufficient to bring about polarity reversal of zinc-steel couple" and that "The presence of chloride ions in solution reduces any tendency towards ennoblement of zinc." The authors covered 3 to 5 ppm (Cl^-) and 100 ppm (Cl^-).

Also in the summary, the authors "assume" that, based on half-cell potential, the galvanized steel in their salt-contaminated concrete is in an active or corroding state. Yet in a previous paragraph they state that this was "not determined."

I confess that I am unable to comprehend what the authors are getting at in the last paragraph of their results. Do they seriously suggest that, for example, when a rebar with 7.92 g/m^2 (3 oz/ft^2) of zinc showed 390 days to concrete cracking with a standard deviation of 69 days and a rebar with 9.85 g/m^2 (3.73 oz/ft^2) showed 381 days to concrete cracking with a standard deviation of 182 days, these data can be used to help form any conclusion whatsoever? Surely impartial examination of this set of data, given the limits of error noted, cannot bolster the authors' view that galvanized bars with heaviest galvanizing will crack first.

We feel that publication of this paper may cause wrong conclusions to be formed by readers who are not able to assess the questionable statistical methods used and who

may be unused to evaluating the extent to which laboratory tests can be applied in practice.

We prefer to rely on the many other tests and long practical experience to support the use of galvanized steel in concrete. One example would be the 2-year tests and practical experience that justified the statement by an area engineer in Bermuda: "The use of fresh water, Stateside aggregate, adequate cover and galvanized steel is required to provide concrete in Bermuda guaranteed to have no rust," and it should be borne in mind that a good deal of reinforced concrete in Bermuda is exposed fully immersed or partially immersed in seawater.

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The paper by Hill, Spellman, and Stratfull presents information that demonstrates the need for further research on corrosion of metals in concrete.

A few minor items may be noted. In Table 3 the 279-kg/m³ (5-sack) concrete steam-cured specimens average 275 and 239 days, which would give an arithmetic mean of 257 days to concrete cracking. Figure 2, however, gives a mean of 243 days. For the same Table 3, the 418-kg/m³ (7½-sack) concrete moist-cured specimens average 600 and 498 days, which would give an arithmetic mean of 549 days to concrete cracking. Figure 3 gives a mean of 475 days. For purposes of this discussion it is assumed that table values are correct, and an arithmetic mean is intended in the figures.

The authors are perhaps unduly negative and pessimistic about their findings. Their data show substantially a two to one improvement in performance of galvanized steel over black steel in prism specimens of 279-kg/m³ (5-sack) concrete exposed to saturated sodium chloride solution. Moreover, there is clear indication that an optimum thickness of zinc coating might give even greater improvement over black steel, as shown in Figure 6. Black steel is 0 g/m² (0 oz/ft²) in this figure. For the black steel each observed point is the average of 20 specimens; for the galvanized, each observed point represents 10 specimens. Predictions of the average days to cracking for black steel specimens are taken from earlier publications by Spellman and Stratfull (8, 30), based on data shown in Figure 7. Observe that there is excellent agreement between the experimental observations and the predicted time to cracking for the 279-kg/m³ (5-sack) concrete specimens.

The authors are to be congratulated on demonstrating a two to one improvement in corrosion resistance for the 279-kg/m³ (5-sack) concrete. Such concrete may be regarded as average for construction practice. Control of water-cement ratio may be very important in securing

best performance, but practical improvements and economies may be obtainable by galvanizing. The authors should publicize this work on the 279-kg/m³ (5-sack) concrete.

It is more complicated to analyze the performance of galvanized steel in the 418-kg/m³ (7½-sack) concrete. Figure 6 shows clearly that there may be an optimum thickness of galvanizing to give greater corrosion resistance in concrete. Obviously there is need for more research on the effect of thickness of zinc on corrosion resistance of reinforcement. Comparisons between galvanized and black steel reinforcement require prediction of when the black steel reinforced specimens would have cracked, because tests were terminated before all of the black steel specimens had cracked. Fortunately Spellman and Stratfull have provided a prediction equation for the average days to concrete cracking:

$$C = 1.12P + 115 \quad (1)$$

where P = average days to active potential. The predicted C = 289 days is shown in Figure 6. Incidentally, Spellman and Stratfull state that "the time to the active potential of steel in concrete is mathematically related to the time to concrete cracking due to corrosion" (8). They furthermore state that "visual observations not only are of questionable accuracy depending on the observer but also are a more time-consuming and expensive procedure than is the measuring of half cell potentials" (8). Accordingly, one can place considerable confidence in the predicted time to cracking of concrete due to corrosion of black steel.

It is not really necessary to predict the time for cracking on the 418-kg/m³ (7½-sack) concrete with black steel. Spellman and Stratfull have published data for a 446-kg/m³ (8-sack) concrete with no admixtures, for both moist and steam curing. Days to concrete cracking reported for the 446-kg/m³ (8-sack) concrete are all confined to specimens cast vertically. However, Spellman and Stratfull (30, p. 14) state that "the effect of orientation of the steel to the time to an active potential appears to be relatively minor." They also state that "the time to the active potential . . . is mathematically related to the time to concrete cracking due to corrosion" (30, p. 33). The data are given in Table 4, and the points for moist cure are shown in Figure 7.

The galvanized reinforcement does better than the black in the statistics given in Table 4, but it is not clear why the two to one improvement in performance found for the 279-kg/m³ (5-sack) concrete is not maintained in the 418-kg/m³ (7½-sack) concrete. Incidentally, a 279-kg/m³ (5-sack) concrete even with a 0.63 ratio of water to cement can hardly be called porous, particularly in the absence of permeability data. An air content of 2½ percent falls in the range of normal nonporous concrete.

If Hill, Spellman, and Stratfull had continued the tests until cracking for black reinforced concrete with the 418-kg/m³ (7½-sack) concrete, the average data points might have fallen far from the prediction equation line shown in Figure 7. This might have happened if something had gotten into the concrete. For example, a 335-kg/m³ (6-sack) concrete with admixture No. 1 falls way off the curve. Or the visual observations of cracking may have been of questionable accuracy, as stated by Spellman and Stratfull (8). If one did rely on such observations, one would, in effect, be discarding entirely the concept developed by Spellman and Stratfull (8) that "the time to active potential of steel in concrete that is partially immersed in a saturated sodium chloride solution is mathematically related to the time to concrete cracking due to corrosion."

It is appealing to have such a useful concept. As

Figure 6. Time to cracking versus weight of zinc.

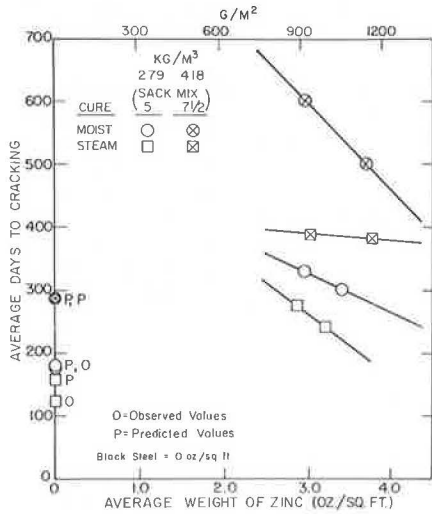


Figure 7. Days to concrete cracking versus days to active potential (black steel).

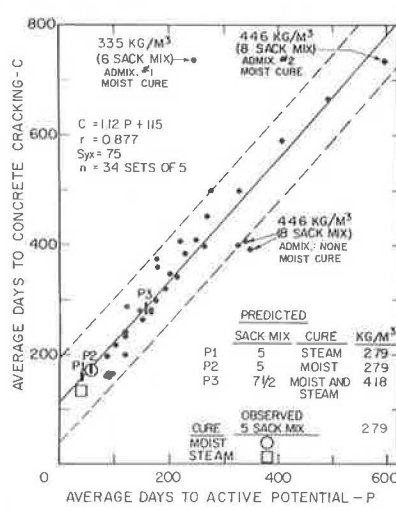


Figure 8. Days to concrete cracking versus days to active potential (galvanized steel).

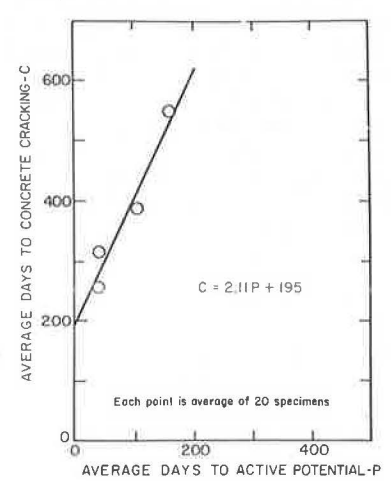


Table 4. Average days to active potential and concrete cracking.

Steel	Concrete (kg/m ³)	Cure	Observed Days to Active Potential	Days to Concrete Cracking	
				Observed	Predicted
Black	279	Moist	55	175	177
		Steam	40	124	160
	418	Moist	155	622	289
		Steam	155	622	289
	446 ^a	Moist	348.6, 339.0	390.8, 406.8	505.4, 494.7
		Steam	212.4, 174.8	341.2, 296.8	352.9, 310.8
Galvanized	279	Moist	40	315	279
		Steam	40	257	279
	418	Moist	160	549	532
		Steam	105	387	417

Note: 1 kg/m³ = 0.062 lb/ft³.
^aFor slumps of 5.1 and 10.2 cm (2 and 4 in).

Spellman and Stratfull have shown, one can save time and money in laboratory tests by obtaining a potential-time history, noting when the potential of the black steel becomes active and calculating the time to concrete cracking by using equation 1. An attempt to obtain such an equation for galvanized steel is shown in Figure 8. Figures 1 through 4 show that galvanized steel starts out at a potential of -0.7 to -1.0 V SCE in these tests. The galvanized steel passivates in a few days and reaches a potential of -0.5 to -0.75 V SCE. The chloride ion then permeates the concrete. In a few weeks, the chloride ion reaches the reinforcement and attains a sufficiently high concentration to break down the passivity. The potential then rises to become active at -0.80 to -0.85 V SCE. This is an arbitrary selection from the curves, but it does permit us to obtain a time to research active potential and to derive a correlation equation:

$$C = 2.11P + 195 \quad (2)$$

Note that galvanized steel has some tendency to re-passivate or at least to change potential considerably after some period of corrosion. Note also that Hill, Spellman, and Stratfull present a complicated picture in Figures 1 through 4. These are mixed potentials for zinc, zinc-iron alloy, and steel in chloride solution in concrete, and the curves are averaged curves. One must be cautious in going from such averaged data to an individual case.

It is regrettable that the authors could not at this time give information on their tests of corrosion of zinc

electroplated steel reinforced concrete prisms exposed to saturated sodium chloride solutions. These were designed to have 152, 305, and 610 g/m² (1/2, 1, and 2 oz/ft²) of zinc. Apparently tests were discounted when the specimens failed to crack when they were expected to. Specimens that were cut open were found to have corrosion products other than the white zinc corrosion products anticipated. Still it might be illuminating to give details on these tests. We understand that the coatings may have been cadmium rather than zinc, which unfortunately was discovered long after the tests were terminated. Under these circumstances it should be noted that the authors did not complete the program they originally planned, and further work is required.

Statements on porosity are highly speculative. No porosity or permeability was measured. Table 2 shows only a 10 percent difference in absorption between the 279 and 418-kg/m³ (5 and 7 1/2-sack) concrete. A 279-kg/m³ (5-sack) concrete with 0.63 water-cement ratio can hardly be called porous, particularly in the absence of permeability data.

There are misleading speculations that galvanized steel can assume noble potentials in low salt concrete and cause accelerated corrosion in highly salt-contaminated concrete. The authors are discussing a chloride concentration cell in which either steel or galvanized steel in a low chloride concentration will be noble relative to steel or galvanized steel in concrete that is highly contaminated with salt.

The authors do not show any instance in which the zinc would not be sacrificial to steel in salt-contaminated

concrete. They also confuse open-circuit potentials with polarized potentials that would exist if current were flowing.

They speak of tests in tap water. They had 0.95 kg/m³ (1.6 lb/yd³) of chloride ion in the atmospherically exposed concrete. They note that the source of the chloride ion in the concrete was not determined. The concrete had 3.33 kg/m³ (5.6 lb/yd³) of chloride ion in sections immersed in tap water. It is not obvious how tap water with 20 to 40 ppm of chloride ion could contaminate concrete with so much salt. It is misleading to call this a tap water test.

Regarding concrete absorption, the 279-kg/m³ (5-sack) concrete is not "highly absorptive," nor are there any test data given that bear on the porosity per se.

In their results, specimens were partially immersed in Sacramento City tap water initially containing about 20 to 40 ppm of chloride. The authors should note that none of the steam-cured specimens cracked in the tap water in 1700 days of exposure. This is somewhat inconsistent with other data reported in which steam-cured specimens lasted only three-fourths as long as the moist-cured specimens before cracking.

The authors state in their results that there does not appear to be any indication that differences in concrete absorption affected any comparative results. This makes it particularly difficult to understand their emphasis on porosity.

In evaluating the relationship of zinc thickness to corrosion resistance, the authors present mean values and overlook the wide variation of values about the mean. The standard deviation indicates considerable overlap in days to concrete cracking for thick- and thin-coated specimens, and the present data may be of questionable statistical validity. If, however, further testing confirms the trends claimed by the authors, it is likely that there can be an optimum thickness of galvanizing that could provide more than twice the crack-free life of the black steel reinforcement.

In the discussion of the results, much information is highly speculative and not supported by test data. The authors confuse a concentration cell effect, low chloride versus high chloride concentrations, with "reversed polarity of zinc." They also confuse open-circuit potentials with polarized potentials.

The discussion of reversal of polarity of zinc is particularly erroneous and highly misleading since the authors themselves have referred to a publication by Hoxeng and Prutton (13). In aerated solutions, bicarbonates and nitrates promote cathodic zinc potentials, particularly in potable waters at temperatures above 60°C (140°F). This reversal in potential does not occur in chloride concentrations of more than about 30 ppm. Silicates also inhibit the reversal of potential. It is farfetched and misleading to liken the alkaline solution in salt-laden concrete to a potable water at elevated temperatures.

It should be noted that the corrosion rate of zinc is at a minimum when the pH is about 12.5.

The authors produce a control series for their tap water tests that is quite unconvincing. No chloride analyses are presented for the earlier tests, which lasted over a period of about 3 years compared to the present 1700-day test. Nor is there any explanation of why the steam-cured galvanized specimens failed to crack in 1700 days.

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Authors' Closure

In the closure below, the authors comment on specific statements made by the discussants. Our response follows their comments.

DISCUSSION BY TONINI

The lack of control specimens is unsatisfactory.

Control specimens were used.

The use of 10 batches of concrete raises serious doubts about the validity of the results.

When more than one batch is used, then any effect of a singular batch of concrete is eliminated.

The assumption that the data were normally distributed is open to serious question and must be justified in using the mean and standard deviation.

We observed that Tonini used the Student's t-test to evaluate the difference in our reported arithmetic means without justifying the type of distribution curve.

It is not obvious that zinc corrosion products can crack concrete. Cornet and Bressler (24) show that cracking during earlier stages of exposure can be unrelated to corrosion effects for either black or galvanized bars.

Cornet and Bressler stated: "Specimens stored in air showed no cracks or rust stains after 24 months' exposure."

It is assumed that absorption testing was made on samples prepared for that purpose and not on the rebar test specimens.

Correct! We overlooked to mention that 15 by 15-cm (6 by 6-in) concrete specimens were obtained from the test batches to measure absorption.

How can the authors seriously suggest that their major conclusion can even be remotely ascribable to cement factor and absorption when they have overlooked (or failed to control) the consolidation of their specimens?

We neither overlooked nor failed to control the consolidation of the concrete. All concrete was prepared in the laboratory and consolidated by means of vibration and checked by unit weight. Cement factor as a means to reduce water-cement ratio has been well established as a control on the time to corrosion of steel in concrete.

Stark and Perenchio (25) found no correlation between cement factor and galvanized rebar performance in any of the full-scale or simulated deck structures they investigated.

The simulated deck structures on which they reported had the same cement factor (6 sack), so no relationship could possibly be derived.

Stark and Perenchio (25) concluded that "... this investigation shows that galvanized steel clearly outperformed the untreated steel where a corrosive environment exists as defined by chloride ion content and condition of the steel."

Stark and Perenchio did not compare the corrosion be-

havior of untreated and galvanized steel in bridges.

In the Stark and Perenchio report (25), there are no differences in galvanized rebar performance that could be attributed to coating weight.

Stark and Perenchio did not report any attempt to relate zinc thickness to performance.

The test conditions were so poorly controlled that they produced extreme distortions of real-world conditions. A chloride level of 37.5 kg/m³ (63.3 lb/yd³) does not appear to be typical at bar level for either a full-scale structure or that found in other experiments of this type.

The chloride content was found in the submerged section of about a 6.4-cm-thick (2½-in) concrete sample. We reported (31) the chloride content of a bridge pile exposed to salt water after about 40 years to be 22 kg/m³ (38 lb/yd³).

DISCUSSION BY COOK

Core tests on a 21-year-old Bermuda bridge by the Portland Cement Association showed that galvanizing was still protecting the underlying steel even though the chloride level was above that considered aggressive to untreated steel.

The one concrete core obtained from this bridge showed 0.9 kg/m³ (1.68 lb/yd³) of chlorine at the level of the steel. No report was made on the performance of untreated steel in this bridge. Based on the low level of salt reported for the one core after 21 years of exposure, it may be that Bermuda is a relatively noncorrosive environment as compared to the environment of most bridge decks subjected to deicing salt.

A large variation in coating weight was reported, which indicates a lack of control of the galvanizing operation or inadequate control of the composition of the steel or both.

The coefficient of variation of zinc coating weight was about 7 percent, which we consider to be small. We have normally seen greater variations of weight on galvanized steel construction materials.

The authors ignore the evidence that the diameter of the bar, the depth of cover, and the time to cracking are related. It seems likely that the reason that thicker coatings cracked earlier was geometry rather than any special corrosion susceptibility of the zinc.

The only known difference between the bars was the average thickness or weight of the zinc. If diameter of the bar was of paramount importance, then the thinner zinc-free bars should have consistently performed better than galvanized steel.

It is the closed-circuit potential that is important to the course of corrosion and not the open-circuit potential.

The closed-circuit potential can have less meaning than the open-circuit potential because it is influenced by current flow and polarization; the open circuit does not contain these variables.

The authors suggest that zinc may reverse its polarity. This statement can only be characterized as irresponsible.

We presented data that showed the distinct possibility of polarity reversal in certain cases and cited literature references in which this was found to occur.

DISCUSSION BY CORNET

The mean time to cracking of 7½-sack moist-cured specimens in Table 3 does not agree with that shown in Figure 3.

We have made the necessary correction, which does not alter the conclusions.

For the purpose of this discussion, it is assumed that table values of mean and arithmetic mean are correct, and an arithmetic mean is intended in the figures.

The average, mean, and arithmetic mean are equivalent and all designate the same numerical value.

There is a clear indication that there is an optimum thickness of zinc coating that might give even greater improvement over black steel.

If Cornet is correct regarding an unknown optimum thickness of zinc and variation from optimum is significant, then it is obvious that those who use galvanized rebars in concrete may be endangering the longevity of their structures. Specifications contain no limits for a maximum thickness of zinc, and, as received, it may be too thick to provide maximum or optimum life.

The authors are to be congratulated on demonstrating a two to one improvement in corrosion resistance of the zinc in the 5-sack concrete.

The data did not demonstrate or imply that zinc showed an improvement in corrosion resistance over black steel. Concrete cracking resulting from corrosion of reinforcement is related to its strength and absorptive properties and depends on the contingencies of the formation of corrosion products. Corrosion is the electrochemical behavior of the metal. The data indicate that, in all the concretes studied, galvanized and black steel began to corrode at substantially the same time. Therefore, there is no implication in the data that there is a significant difference in corrosion resistance of zinc-coated steel as compared to that of black steel in a chloride-contaminated concrete. The embedment of zinc or steel does not affect the rate of salt penetration into the concrete.

Comparisons between galvanized and black steel require prediction of when the black steel reinforced specimens would have cracked, because tests were terminated before all of the black steel specimens had cracked.

Cornet's calculations of the predicted time to concrete cracking are incorrect because the equation used was not derived on the basis of the time to a potential of -0.35 V. The equation was derived on the basis of that point in time when the potential of the steel first shifted from the passive to the active. The half-cell potentials in this report are referenced to a saturated calomel half cell (SCE). An active potential of steel referenced to the latter half cell would be -0.27 V (8). Cornet also used the wrong value in his calculations to designate a corrosive potential for steel in concrete.

Five-sack concrete may be regarded as average construction practice.

We do not agree that 5-sack concrete should be regarded as an average construction practice. For California Department of Transportation structures, we require minimums of 6-sack concrete in noncorrosive and 7-sack in corrosive environments. We are aware, however, that much commercial building is done with concrete having a cement factor of about 5 sacks.

Galvanized steel in this test does better when compared to the published statistics for black steel in 8-sack concrete.

When Cornet used data from a previous report, he reached erroneous conclusions because he apparently overlooked half of the data. He states that, in the previous report (30), the average time to concrete cracking for an 8-sack concrete was 390.8 and 406.8 days for 5.1 and 10.2-cm (2 and 4-in) slump. However, this was for the vertically cast specimens. Given in the same table of that report is horizontally cast specimens (the same casting method used in this test), which did not crack in 798 days. In this latter case, Cornet is in error because the galvanized steel specimens had an average time to cracking of 549 days.

Concrete with a water-cement ratio of 0.63 can hardly be called porous.

Permeable or absorptive might have been a better term to use in this case. In the paper, the term porous was used in the context of the ability of the concrete to inhibit the penetration of corrosive chlorides. For piles, architectural concrete, pipes, and rails exposed to fresh water and mild temperatures, ACI Standard 613-54 recommends a maximum permissible water-cement ratio of about 0.49. Therefore, Cornet's statement does not agree with normal concrete standards.

A concrete mix containing 2½ percent entrapped air falls in the range of normal nonporous concrete.

We have reviewed almost all of the references to publications by the American Concrete Institute and can find no one who has related the amount of entrapped air to concrete porosity. (One to 1½ percent of entrapped air is probably more normal.)

A 6-sack mix with admixture No. 1 (a water-reducing agent) falls way off the curve in the previously reported data (30). This may indicate that something might have gotten into the 7½-sack concrete in this test.

Again, Cornet seems to have overlooked some of the data. The data that fell off the curve were the vertically cast concrete. The time to cracking of the horizontally cast concrete (30) fell within the limitation of the standard error of estimate. Nothing got into the concrete.

An arbitrarily chosen potential of -0.80 V SCE is indicative of the corrosion of galvanized steel.

We do not disagree that -0.80 V SCE as an indicator of corrosion of galvanizing is an arbitrary assumption. This is in view of the potentials of galvanizing measured in the tap water tests. In these latter tests, corrosion of zinc and underlying steel was observed even though the half-cell potential, within one standard deviation, did not attain a value of -0.80 V. It was for this reason that we stated in the paper that we did not observe a definitive half-cell potential that would clearly denote an active (corroding) or a passive (noncorroding) condition of the zinc. Therefore, we view Cornet's derived equation and plots also to be arbitrary because his derivations are based on a half-cell potential for zinc that is not verified by test data.

The authors are perhaps unduly negative and pessimistic about their findings.

Our finding that galvanizing in concrete was apparently not cost beneficial is supported by others. For example, Bird and Strauss (4) from South Africa, reporting on their experimental results with galvanized steel in concrete, state: "In the presence of 1 percent salt (by weight of cement), however, sacrificial attack in the vicinity of exposed steel increases by approximately 30

times, while the rate of self-corrosion is accelerated even more." Griffin (3), reporting on his sea salt spraying of concrete panels at the U.S. Naval Civil Engineering Laboratory, stated: "The air-entrainment provided more protection to the concrete than did the zinc coating on the steel. In no case did the zinc coating prevent the formation of red rust."

REFERENCE

31. D. L. Spellman and R. F. Stratfull. Chlorides and Bridge Deck Deterioration. HRB, Highway Research Record 328, 1970, pp. 38-49.