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COMPARATIVE STUDIES OF GALVANIZED AND EPOXY COATED STEEL REINFORCEMENT IN CONCRETE

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SYNOPSIS

Comparisons of the corrosion performance and pullout strength of black, hot dip galvanized and fusion bonded epoxy coated steel reinforcement in concrete have been undertaken. Accelerated exposure testing confirmed that zinc coating was able to considerably delay the onset of corrosion and epoxy coating effectively eliminated corrosion provided the coating was not damaged.

Where coated reinforcement was left with cut ends unrepaired, the epoxy coated bars showed early corrosion of the exposed steel with corrosion progressing along the bar under the coating. Even where cut ends were repaired, the epoxy coated bars showed many sites of breakdown of the repair and corrosion of the underlying steel. The sacrificial nature of the zinc coating provided positive protection to the underlying steel where the coating was damaged.

Pullout testing revealed that there is no significant difference in the ultimate bond strength of black, epoxy coated or galvanized deformed bars. For plain reinforcement, the ultimate bond strength of epoxy coated bars is some 17% less than that for black steel bars, while that for galvanized bars is some 31% greater than for black steel. The ultimate bond strength of deformed bars is up to 50% higher than that of plain bars. The passivation of galvanized plain bars by chromate additions to the concrete mix water in the range 15-150 ppm could not be shown to significantly improve the bond strength. Further work is being done in this area with much larger sample populations to clarify this result.

1. INTRODUCTION

Since 1987, a program of work has been undertaken to investigate the characteristics and behaviour of galvanized and epoxy coated reinforcement in concrete (1,2). Whilst considerable work has been done over many years to investigate the use of coated reinforcement in concrete (see for example 3,4), questions of the comparative behaviour of the two systems often arise. In particular, the integrity of the coatings after bending or cutting, the role of concrete cover and the severity of the environment, the development of bond and the simple economics of the systems, are all matters which need to be addressed.

2. HOT DIP GALVANIZED STEEL

Since the 1930's, hot dip galvanized reinforcement has been used successfully in many types of concrete structures, particularly so in recent years in pre-cast construction. Though there are some concerns whether zinc can adequately protect reinforcing steel in extreme chloride environments, experience over many years and in a variety of exposure situations has shown that the use of galvanized reinforcement and fittings in concrete offers the following main advantages (5):

- a) an increased structural life, with a much reduced risk of cracking, rust staining and spalling of concrete;
- b) thinner covers can be tolerated, though this is not a desirable or recommended design practice;
- c) the placement of reinforcement is less critical than with black steel and fittings can safely protrude from the surface; and
- d) protective surface coatings to the concrete or other forms of corrosion protection are largely unnecessary.

Where black steel in concrete typically depassivates below pH 11.5 (even higher in the presence of chloride), zinc coated reinforcement can remain passivated to somewhat lower pH (perhaps as low as pH 9.5) thereby offering protection to the effects of carbonation. The passivation of zinc in the highly alkaline environment of concrete generates hydrogen which may reduce the bond strength. The hydrogen evolution can be eliminated however, by passivation of the zinc with hexavalent chromate ions (Cr^{6+}) either by the addition of dichromates to the concrete mixing water at a concentration in the range 70-100 ppm by weight of concrete (3), or by quench passivating freshly galvanized bars in a 0.2% sodium dichromate solution.

Chloride ions are able to depassivate zinc and initiate corrosion though at chloride concentrations substantially higher than can be tolerated by black steel. Various research has indicated that galvanized steel can withstand chloride contents in concrete some 4-5 times (6) to as much as 10 times higher (7) than that tolerated by black steel before corrosion occurred.

Early work (8,9) reported that for plain reinforcement the bond strength of galvanized bars was between 30% and 50% greater than for similar black bars, while for deformed bars the bond strengths were the same. Recent testing (10,11) has confirmed this and also demonstrated the beneficial effects of passivation. Though there are some discrepancies in the published literature, the general consensus is that

galvanized bars have at least equal or better bond performance than equivalent black steel bars provided the zinc/alkali reaction is inhibited by passivation.

The bending of galvanized reinforcement can be performed either before or after galvanizing, however it is often economically advantageous to bend after galvanizing. If cracking and flaking of the zinc coating occurs, repair is best done by the application of a suitable inorganic zinc rich paint (AS 1650 - Galvanized Coatings Code).

The average cost of galvanizing in Australia adds about 50% to the base cost of the reinforcing steel and, at current costs, about 7% (per m³ placed) to the average cost of in-situ reinforced concrete. By restricting the use of galvanized reinforcement to exposed or high risk areas such as precast cladding elements and facades, surface exposed beams and so on, the premium paid for galvanized reinforcement commonly reduces to between 0.5 and 1.0% of total building costs (5). Further, since galvanized reinforcement can be handled and placed in much the same way as for black steel reinforcement, special facilities and additional skills are not required at the workplace.

3. FUSION BONDED EPOXY COATED REINFORCEMENT

The coating of reinforcement with epoxies has been used successfully to combat corrosion in salt contaminated concrete and to minimize the early age deterioration of reinforced concrete since the mid-1970's. Though epoxy coatings are quite flexible with good adhesion to steel, the coating can be easily damaged with a consequent reduction in its corrosion resistance. As a result, a great deal of emphasis is placed on the protection of epoxy coated reinforcement during handling and fabrication, as well as repairs to damaged areas of the coating (12-13).

The inert nature of the epoxy coating and its smooth surface reduces the bond with concrete by as much as 20% from that of uncoated steel bars (14). It also has been reported that coating thickness has an adverse effect on bond and the reduction in bond is more pronounced in larger diameter deformed bars than smaller ones (15).

The cost of fusion bond epoxy coating of steel reinforcement in Australia is about twice that of galvanizing (1), thereby essentially doubling the cost of the reinforcement. It should be noted that the availability of epoxy coating facilities is very limited indeed, there being only one commercial plant capable of continuously coating reinforcement in any great quantity. The reinforcement is coated in straight lengths and then fabricated. Where damage to the coating occurs, such as at cut ends or where the bend radius has been too tight, it is usual practice to repair the coating by touch-up. Equipment for handling the bars should have protected contact areas and nylon slings or padded wire rope slings are recommended. Additional expense may be incurred because of the time and effort required to ensure careful handling and to make good any damage to the coating.

4. EXPERIMENTAL PROCEDURE

Accelerated corrosion testing and pullout testing has been done on reinforced concrete specimens with 16 mm diameter black steel, epoxy coated (175 micron coating) and hot dip galvanized reinforcement (105 micron coating thickness). The details of the two concrete mixes used for the specimens are given in Table 1.

4.1 Corrosion Testing

Two accelerated environments were used, namely: alternate wetting for 3 days in a 3.5 % salt bath (NaCl) at 40°C and drying for 4 days at 60°C; and continuous exposure in a salt fog chamber at 40°C. While it was recognized that the results of accelerated corrosion testing may not relate directly to the effects of natural exposure, it was not intended to derive absolute results from this, rather comparative performance data. Also, consideration of the time span necessary to produce degradation effects was an important consideration in the decision to accelerate the rate of corrosion.

Two different forms of corrosion specimens were prepared. The first, identified Type A, were 200 x 100 mm cylinders each containing 4 x 100 mm bar lengths vertically positioned to have a cover of 10-15 mm to the cylindrical surface and 50 mm above and below (1). The second, identified Type B, were 300 x 150 mm cylinders each containing a 'tree' of reinforcement consisting of a vertical central piece 300 mm long and lateral pieces of varying length to give a cover in 10 mm increments from 0 mm for the vertical piece to 10-40 mm for the different horizontal pieces (2).

Prior to casting, the black steel was lightly sand blast cleaned, while the epoxy coated and galvanized steels were washed and rinsed. For the Type A specimens, both ends of the 100 mm long coated reinforcement pieces were repaired: the epoxy samples were coated on the exposed ends with SCOTCHCOTE^R Patch Compound 213 PC; and the galvanized samples were repaired with a zinc rich primer. For the Type B specimens, one end only of each piece of coated reinforcement was repaired as above. The cast specimens were given an initial 7 day fog room curing before exposure.

Samples for chloride analysis were taken from the specimens at intervals during the exposure by drilling to depths of 10, 20, 30, 40 and 50 mm at four locations along the specimen. The dust from each drilling site was extracted and mixed with that from the other sites before proceeding to the next depth. The chloride content was determined by the potentiometric titration of chloride with silver nitrate as described in ASTM C114.

4.2 Pullout Tests

Some 50 samples were prepared in which 200 mm lengths of 16 mm reinforcement were cast into 100 x 100 mm prisms with 100 mm embedment using both plain (R16) and deformed (Y16) bars. Prior to casting, the black steel was lightly sand blasted to remove surface rust and mill scale, and the epoxy coated bars were wiped clean. The galvanized bars were cast as follows:

- G1 - weathered bar, as received;
- G2 - cleaned and rinsed;
- G3 - chromate conversion treated by activation in 0.5% nitric acid followed by immersion in 2% by weight Na₂Cr₂O₇ solution per AS 1791 - Chromate Conversions Coatings on Zinc and Cadmium;
- G4 - chromate additions were made to the mix water in the proportions 15, 35, 70 and 150 ppm expressed as CrO₃ by mass of cement. (Note: 104 g/tonne of cement of Na₂Cr₂O₇.2H₂O or 103 g/tonne of cement of K₂Cr₂O₇ is equivalent to 70 ppm (16).

The bars were pulled from the concrete using a purpose designed jig mounted

in a universal testing machine with restraint being applied against one end of the concrete prism. Load-slip measurements were taken until the ultimate bond strength was reached.

5. RESULTS AND DISCUSSION

5.1 Type A Specimens

A summary of the visual assessment for the accelerated corrosion testing of the Type A specimens (1) is given below, and Cu/CuSO₄ half-cell potentials are given in Table 2. Figures 1 and 2 show the changes in the half-cell potentials for the black steel and the galvanized steel respectively with a concrete cover in the range 10-15 mm.

65 Days Wet & Dry:

- Black steel - corrosion well progressed;
- Epoxy - all samples unaffected;
- Galvanized - shift to less negative potential from 10 to 65 days with white reaction products forming on the zinc.

65 Days Salt Fog: No distress to any specimens.

103 Days Wet & Dry:

- Black steel - gross corrosion (-700 mV) and all cylinders cracking;
- Epoxy - unaffected other than local rust spotting;
- Galvanized - potential shift to -705 mV, extensive zinc loss with corrosion well progressed and cylinders cracking.

103 Days Salt Fog: No distress to any specimens.

142 Days Wet & Dry:

- Black steel - gross corrosion (-690 mV) and cylinders cracking;
- Epoxy - little change (-535 mV) from condition at 103 days;
- Galvanized - complete zinc loss with heavy corrosion (-708 mV) and cylinders cracking.

142 Days Salt Fog:

- Black steel - corrosion initiated locally (-603 mV);
- Epoxy coated - all samples unaffected (-612 mV);
- Galvanized - all samples unaffected (-953 mV).

The most significant features of the half-cell measurements concern the rapid shift in the potential of the black steel to about -600 mV indicating active corrosion, and the variation with time (and chloride) of the potential of the galvanized bar.

For the black steel in the wet and dry regime (Figure 1a), the potential shift to -600 mV occurred within the first 10 days or so, while the galvanized steel reached -1050 mV at about the same time then shifted to -600 mV over the next 60-70 days (Figure 1b). The rate of this change in the salt fog regime was slower, as was the chloride ingress. The black steel reached a steady potential around -600 mV after 50 days in the salt fog (Figure 2a) whereas the galvanized steel reached its maximum potential of -1050 mV at 100 days and was only slightly changed to -950 mV at 142 days (Figure 2b).

potential of -1050 mV at 100 days and was only slightly changed to -950 mV at 142 days (Figure 2b).

The epoxy coated steel in both regimes showed much the same potential shifts as for the black steel though over a longer period. Corrosion of the bar only occurred, however, where the coating was damaged.

In both environments, the galvanized steel showed a steady shift in potential to about -1050 mV after which the potential slowly changed to a plateau value of about -600 mV (Figures 1b and 2b). It seems that the -1050 mV value is characteristic of the potential of the zinc when actively protecting the steel, and that the change to the -600 mV level is indicative of the gradual loss of the zinc coating.

Thus, even though the black steel and the galvanized steel showed much the same corrosion activity at the inspection intervals in the wet and dry regime, the half cell potential measurements show that the zinc coating was protecting the steel well beyond the time at which the black steel was corroding, i.e. at the 65 day first inspection. However, by 103 days the sacrificial protection of the zinc had been exhausted and the potential of the bar had changed sufficiently for it to be actively corroding. In the salt fog, corrosion of the black steel was well progressed at 142 days though the galvanized steel had not yet shifted far from its potential of -1050 mV and was still actively protecting the steel.

Some measurements were made of weight loss for the black steel bars (following the method described in ASTM G1-81 using Clarke's solution) and coating thickness loss (metallographic) for the galvanized bars (1). The weight loss data indicated a much higher average weight loss in the wet and dry regime (1.1-3.3%), with individual values up to about 3.9% after 142 days. For the salt fog regime, there was essentially no weight loss (less than 0.1%) until after 116 days, and then only minimal weight loss to 142 days (about 0.25%).

The different depth of cover had only a small effect on the corrosion loss, though as would be expected the lesser cover of 10 mm did show a slightly higher average weight loss than the 15 mm cover. Measurement of the zinc thickness loss in the wet and dry specimens showed that some 10-15% of the coating was lost at 65 days, primarily the pure outer zinc layer, increasing to essentially total loss in some areas at 103 days. It does seem that once the passivity of the zinc is destroyed by the high chloride presence, rapid removal of the zinc occurs leading ultimately to loss of the sacrificial protection of the steel.

The variation in chloride ion content with depth from the cylindrical surface of the specimens is given in Table 3. Measurements from equivalent atmospheric exposure specimens after 41 days gave concentrations at the surface less than 0.02% chloride by weight of cement and less than 0.01% at depth. The chloride levels in specimens from both accelerated environments were quite high and in several instances, particularly for the wet and dry regime, exceeded the threshold chloride levels nominated by a number of sources.

For example, the American Concrete Institute has proposed that for conventional concretes in moist conditions and exposed to chloride, the limiting value is 0.10% and for those not exposed to chloride it is 0.15% by mass of cement. On the other hand, AS 3600 - Concrete Structures Code specifies the maximum chloride ion content in concrete as 0.8 kg/m^3 , which for a concrete containing say 280 kg/m^3 cement equates to 0.28% chloride by mass.

chloride levels built up by wetting and drying. For both regimes, continued exposure has clearly resulted in a steady increase in the chloride level at each depth.

In the case of the salt fog samples in particular, this work has confirmed the higher tolerance of zinc to moderate chloride levels compared to black steel. At 142 days, when the chloride content is of the order of 0.15% at the 10-15 mm depth of the reinforcement, the black steel is showing localised corrosive attack, whereas the zinc coating showed only slight signs of reaction and no red rust corrosion.

5.2 Type B Specimens

For the black steel specimens in the atmospheric exposure, corrosion had commenced on the exposed bar (0 mm cover) by 41 days. The extent of this was more severe in the salt fog where corrosion had progressed some 15 mm from the free surface after the same time. More serious attack occurred in the wet and dry where corrosion at 41 days had progressed some 20 mm from the free surface. After 98 days in the salt fog, corrosion was observed at points 15-25 mm below the surface, while for the wet and dry regime corrosion was observed some 20-30 mm below the surface. By 132 days, little further change occurred in the salt fog, though in the wet and dry regime corrosion was well developed on the bars with about 30 mm cover.

Galvanizing of the reinforcement provided positive protection to the steel. After 41 days there was only a slight amount of reaction product at the unrepaired end of the exposed bar, and there was no evidence of corrosion at greater cover for any of the exposure regimes. After 98 days in the salt fog, there was some red rust staining at an exposed unrepaired end and some white zinc reaction product was evident on bars with about 10 mm cover. The situation was somewhat worse in the wet and dry regime where localised red rust was evident at the exposed ends (both repaired and unrepaired) and white reaction product on bars with about 25 mm cover. After 132 days in the salt fog, reaction product was observed near the surface though all the reinforcement below the surface was in good condition including the cut ends. In the wet and dry regime, near surface corrosion was well progressed and many of the other sections at depth showed white reaction product though no red rust even at cut ends.

The epoxy coated specimens did not behave as well as expected. After 41 days in the atmospheric exposure, corrosion was evident over the entire cross section of the exposed cut end of the bar, while the exposed repaired end had some 7 locations of failure of the repair compound. At this time there was no sign of corrosion within the specimen. In the salt fog, the exposed cut end was heavily corroded and some slight corrosion was evident on one cut end at about 30 mm depth. The wet and dry regime severely corroded the exposed cut end as well as causing failure at some 13 locations of the repaired exposed end of the bar. On bars with cover of 15-20 mm, rusting of the cut end was evident and the opposite repaired end was showing distress to the coating. After 98 days in both regimes, corrosion of cut ends was occurring at depths of 30 mm or more, and the repair compound had broken down by isolated pitting at depths up to about 25 mm. By 132 days, both exposed ends had well developed corrosion which was progressing along the bars into the concrete mass. In the wet and dry regime, all cut ends with cover up to about 30-35 mm were rusting, while the repaired ends were showing localised pitting to depths of about 10-15 mm with corrosion developing along the bar a further 5-8 mm into the concrete.

These tests on the Type B specimens clearly demonstrated the beneficial effect of zinc in protecting steel in exposure situations where black steel was freely attacked. The zinc coating was able to resist chloride levels somewhat higher than

black steel, and the sacrificial nature of zinc protected cut ends for some considerable time. The presence of white product on the zinc indicated that some reaction was occurring, but most likely this was only the pure outer zinc layer being removed in the early stages, thereby exposing the more corrosion resistant underlying Fe/Zn alloy layers. It should also be mentioned that the repairs to the zinc using the recommended products performed extremely well.

Though the epoxy coated steel was largely unaffected where the coating was intact, where the coating was damaged or completely removed rapid attack on the steel occurred with corrosion penetrating under the adjacent coating. Even where the coating was repaired using proprietary compounds and recommended methods, corrosion often occurred prematurely even at depth within the concrete mass.

5.3 Pullout Testing

The results of the pullout tests (1,2) using both deformed and plain reinforcement are summarised in Table 4. Statistical analysis of these results was via the Null Hypothesis Method at a 5% significance level.

For the deformed reinforcement, analysis indicates that there is no significant difference between the ultimate bond strength of the black, epoxy coated and galvanized reinforcement. For the different types of galvanized bars, there is also no significant difference in the mean bond strength, even though it does appear that the chromate conversion treatment may have had a positive effect on bond.

Failure of all the deformed bar specimens was by splitting of the concrete prism. These results are consistent with what would be expected for deformed reinforcement where the mechanical interlock provided by the rib pattern overshadows effects due to chemical bonding at the reinforcement interface, providing the thickness of the coating is such that it does not alter the effective height or contact angle of the deformation ribs (17).

For the plain reinforced samples, all of which failed by slippage of the bar without splitting the concrete mass, analysis indicates that the results for the three groups of reinforcement are all different. In summary, the ultimate bond strength of the epoxy coated steel is some 17% less than that for black steel, while the weathered galvanized steel is some 31% higher. This result for the epoxy coated bars is in good agreement with other data (14), and that for the galvanized bars compared to the black steel is also as would be expected.

It can also be shown that the ultimate bond strengths of deformed bars for these same reinforcement types are statistically different to that for the plain bars, the bond of the deformed bars being in the range 12-48% higher.

The results for the galvanized plain bars which had been passivated by chromate additions to the concrete mix water cannot be said to be statistically different (at the 5% significance level), either within the group of galvanized specimens G4 or when compared individually to the weathered galvanized bar G1. On the basis of comparing mean values only, the data does indicate an overall higher bond for this chromate treatment, and there may be an effect indicated due to the changing chromate levels. However, because of the restricted size of the sample population available for this analysis, the standard deviations on the individual results are such that the means cannot be said to be statistically different.

Further work is being done to specifically address the issue of chromate

population available for this analysis, the standard deviations on the individual results are such that the means cannot be said to be statistically different.

Further work is being done to specifically address the issue of chromate effects on galvanized bars, and the results are expected to be more conclusive. In the first instance, much larger sample populations for each type of specimen will be tested (of the order of 15-20 samples each) which should provide an opportunity to reliably discriminate between the data sets. Further, a modified pullout specimen will be used with a through cast 16 mm diameter plain bar having a 60 mm embedment length set in the middle of the specimen (18). The benefit of this more standardized specimen geometry is that it will isolate the effect of restraint at the face of the concrete where the load is applied for pullout.

6. SUMMARY

- 6.1 Measurement of half-cell potentials has shown the beneficial effect of galvanizing in protecting black steel reinforcement from corrosion. Where black steel is actively corroding once its potential reaches -600 mV, galvanized steel has a shift in potential to about -1050 mV after which a steady change over an extended period to -600 mV indicates sacrificial loss of the coating. The rate at which this occurs depends largely on the chloride content of the concrete.
- 6.2 Galvanizing provides positive protection to steel where the coating is damaged, while repair to the damaged area provides additional protection. Galvanizing is also able to withstand higher chloride levels than black steel, though this work did not enable specific threshold values to be determined.
- 6.3 Epoxy coating provided excellent protection to the steel as long as the coating was not damaged. Where the coated bars were cut, corrosion of the exposed steel occurred freely and progressed along the bar under the coating. Even when the cut end was repaired in the recommended manner, localized corrosion still occurred at many repair sites. This behaviour is indicative of the care with which epoxy coated bars must be handled, and the necessity for high quality repairs to damaged areas in order to realize the excellent corrosion protection that epoxy coating offers.
- 6.4 The epoxy coating of reinforcement in Australia costs approximately twice that of galvanizing. Where galvanizing increases the initial cost of the reinforcement by about 50%, epoxy coating essentially doubles the bar cost. Further, the extra care and skill that is required in the handling, fabrication and repair of epoxy coated steel can result in additional costs over the use of black steel or galvanized reinforcement.
- 6.5 There is no significant difference between the ultimate bond strengths of black, hot dip galvanized and fusion bonded epoxy coated deformed reinforcement. The ultimate bond strength of deformed bars is thus independent of the presence of these surface coatings, and is up to 50% higher than for coated plain bars.
- 6.6 The ultimate bond strength of epoxy coated plain steel bars is some 17% lower than for plain black steel bars, while that for weathered galvanized plain bars is some 31% higher.

- 6.7 Chromate additions to the concrete mix water in the range 15-150 ppm could not be shown to produce a statistically significant change in ultimate bond strength of galvanized plain bars. Additional work needs to be done to further investigate this effect.

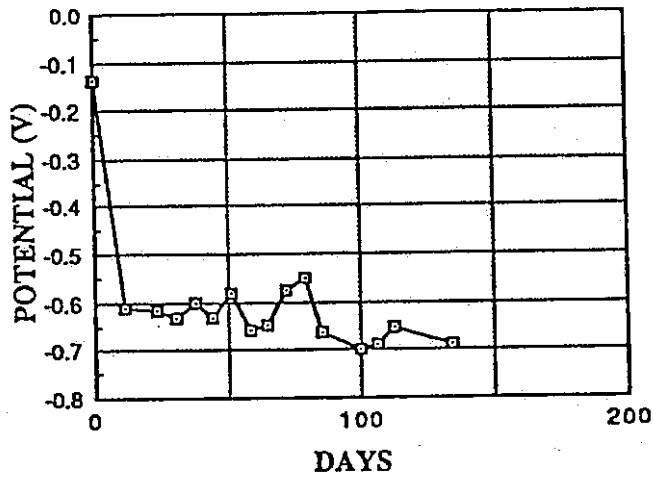
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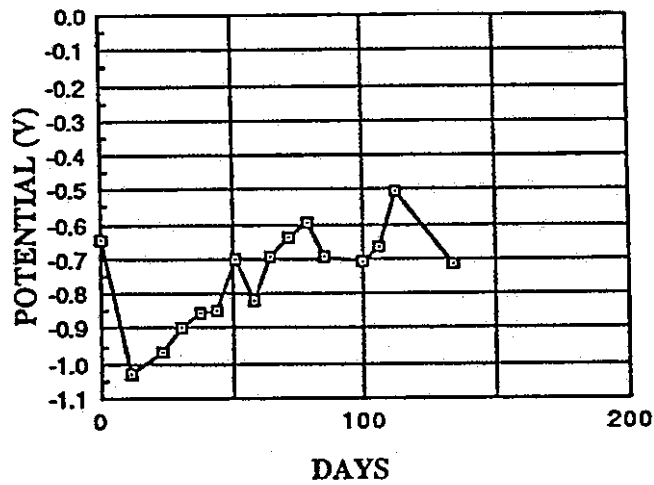
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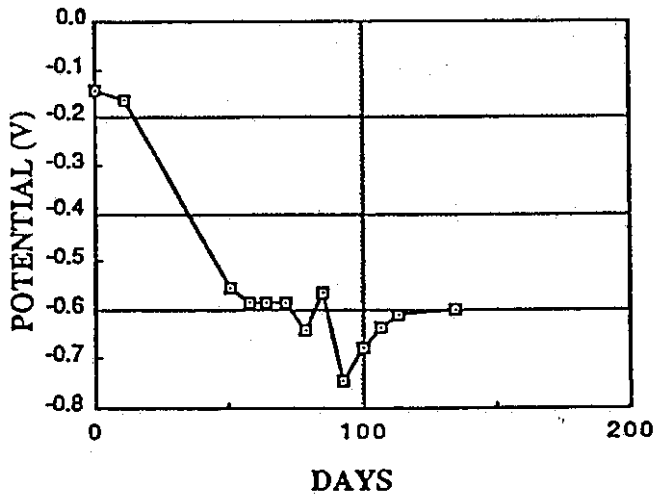


a) Black Steel

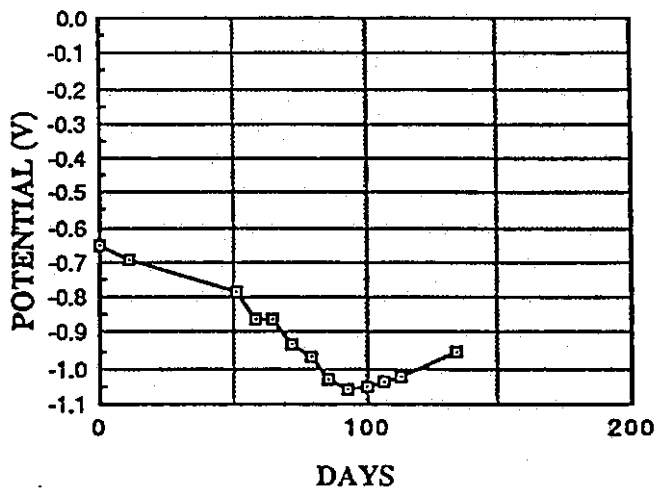


b) Galvanized Steel

Figure 1. Variation in Cu/CuSO₄ Half-Cell Potentials for Wet and Dry Exposure Specimens.



a) Black Steel



b) Galvanized Steel

Figure 2. Variation in Cu/CuSO_4 Half-Cell Potentials for Salt Fog Exposure Specimens.

Table 1. Mix Proportions and Properties of Concrete.

| Mix | Corrosion | Pullout |
|-----------------------|-----------------------|------------------------|
| Slump | 80 mm | 80 mm |
| Aggregate size | 10 mm | 20 mm |
| Mixing Water | 225 kg/m ³ | 200 kg/m ³ |
| W/C ratio (a) | 0.80 | 0.62 |
| Cement content | 281 kg/m ³ | 323 kg/m ³ |
| Coarse aggregate (b) | 828 kg/m ³ | 1116 kg/m ³ |
| Fine aggregate (sand) | 986 kg/m ³ | 703 kg/m ³ |
| Target strength | 15 MPa | 25 MPa |
| 28 day strength | 29 MPa | 37 MPa |

- (a) Non air entrained.
 (b) 10 mm for corrosion specimens;
 20 mm for pullout specimens.

Table 2. Summary of Half-Cell Potentials (mV) for Type A Corrosion Specimens.

| Days | Wet & Dry Exposure | | | Salt Fog Exposure | | |
|------|--------------------|-------|-------|-------------------|-------|-------|
| | Black | Epoxy | Galv. | Black | Epoxy | Galv. |
| 0 | -135 | -205 | -642 | -143 | -265 | -653 |
| 10 | -611 | -582 | -1027 | -163 | -286 | -697 |
| 65 | -646 | -604 | -692 | -598 | -558 | -870 |
| 103 | -700 | -588 | -705 | | | |
| 116 | | | | -613 | -594 | -1023 |
| 142 | -690 | -535 | -708 | -603 | -612 | -953 |

Table 3. Chloride Contents in Exposed Specimens.

| Exposure Period (days) | Drilling Interval | Chloride Content(%) ^(a) | |
|------------------------|-------------------|------------------------------------|----------|
| | | Wet & Dry | Salt Fog |
| 41 | 0-10 mm | 0.12 | 0.07 |
| | 10-20 | 0.07 | 0.04 |
| | 20-30 | 0.06 | 0.03 |
| | 30-40 | 0.04 | 0.01 |
| | 40-50 | 0.03 | 0.01 |
| 98 | 0-10 mm | 0.17 | 0.15 |
| | 10-20 | 0.14 | 0.09 |
| | 20-30 | 0.11 | 0.07 |
| | 30-40 | 0.09 | 0.04 |
| | 40-50 | 0.06 | 0.04 |
| 132 | 0-10 mm | 0.18 | 0.15 |
| | 10-20 | 0.17 | 0.10 |
| | 20-30 | 0.11 | 0.07 |
| | 30-40 | 0.10 | 0.07 |
| | 40-50 | 0.08 | 0.04 |

(a) Expressed as percent by weight of cement.

Table 4. Ultimate Bond Stresses from Pullout Tests with Deformed and Plain Reinforcement.

| Reinforcement Type and Condition | Bond Strength MPa (a) | |
|--------------------------------------|-----------------------|-------------|
| | Deformed Bar | Plain Bar |
| Black Steel | 5.90 (0.57) | 3.80 (0.58) |
| Epoxy Coated Steel | 6.04 (1.11) | 3.17 (0.14) |
| Galv 1 - Weathered | 5.68 (1.21) | 4.99 (0.31) |
| Galv 2 - Cleaned | 5.62 (0.51) | - |
| Galv 3 - Cr ³⁺ conversion | 6.10 (1.45) | - |
| Galv 4 - 15 ppm Chromates | - | 5.35 (0.42) |
| Galv 4 - 30 ppm Chromates | - | 5.99 (0.90) |
| Galv 4 - 75 ppm Chromates | - | 5.28 (0.87) |
| Galv 4 - 150 ppm Chromates | - | 5.37 (0.41) |

(a) Mean and Standard Deviation of six results except for Galv 4 samples with three results for each level of chromate addition to the mix water.