

**ZE-341**

**FURTHER STUDIES OF THE  
COMPARATIVE PROPERTIES AND BEHAVIOUR OF  
GALVANIZED AND  
EPOXY COATED STEEL REINFORCEMENT**

**by**

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## EXECUTIVE SUMMARY

Further studies of the characteristics and properties of fusion bonded epoxy coated steel reinforcement and hot dip galvanized reinforcement have been undertaken. The comparative corrosion performance of black, galvanized and epoxy coated reinforcement was investigated in which the influence of exposed cut ends of coated reinforcement and the repair of cut ends was examined. Pullout testing of black, galvanized and epoxy coated plain (i.e. non-deformed) reinforcing steel was also done, as well as pullout tests using galvanized plain reinforcement in which varying amounts of hexavalent chromate ion were added to the concrete via mix water additions.

The corrosion investigation utilized two accelerated regimes namely, continuous salt fog and alternate wetting and drying in artificial salt water. Reinforced concrete cylinders were prepared containing a tree-like frame of reinforcement with varying depths of cover (0-32 mm). The coated reinforcement pieces were cut to length, one end of which was left bare while the other end was repaired in the recommended manner.

The results from the corrosion testing clearly indicated that the zinc coated reinforcement was able to considerably delay the onset of corrosion and epoxy coating effectively eliminated corrosion provided the coating was not damaged. Where cut ends of coated reinforcement were unrepaired, the epoxy coated steel showed early corrosion of the exposed steel with corrosion progressing along the bar under the epoxy layer causing local detachment of the coating. In contrast, the zinc coating on the bar protected the exposed steel at the cut end for some considerable time even in the most severe exposure regime. Even when corrosion of the galvanized bar did commence, only minor rust staining at the centre of the exposed cut end was evident and the zinc coating itself was unaffected.

Where the cut ends of coated reinforcement were repaired, the epoxy coated bars showed many sites of local breakdown of the repair and corrosion of the underlying steel. Again, in contrast, the repairs to the galvanized bars performed very satisfactorily with little or no evidence of breakdown of the repair even in the wet and dry salt water environment. The increasing depth of concrete cover to the ends of the reinforcement pieces clearly provided a measure of protection to the steel by delaying both the onset of and extent of corrosion in all cases.

Pullout testing of plain reinforcement revealed that the ultimate bond strength of epoxy coated bars is some 17% less than that for plain black steel, while that for galvanized bars is some 31% greater than for equivalent black steel reinforcement. Chromate additions to the concrete mix did not produce a statistically significant difference in the bond strength of galvanized plain bars, though further work needs to be done with larger sample populations to verify this result.

## 1. PREVIOUS WORK - PROJECT ZE-341

Work done under ILZRO Project ZE-341 through 1987 and 1988 (Yeomans, 1989) investigated aspects of the comparative corrosion and pullout behaviour of black, fusion bonded epoxy coated, and hot dip galvanized steel reinforcement for concrete. A review of the literature dealing with the nature, characteristics and use of coated reinforcement a means of providing "further protection" to steel reinforcement was undertaken. This work also included the results of a questionnaire on attitudes to the use of galvanized steel in reinforced concrete construction as seen from the viewpoint of an engineering consultant and a pre-casting contractor.

The corrosion testing indicated that in very high chloride environments (several times higher than the recommended chloride levels in concrete) galvanized reinforcement does not appear to be able to prevent or arrest reinforcement corrosion much beyond the period over which black steel remains passivated. In more moderate chloride exposure however, the zinc coating exhibited a higher tolerance to the effects of chlorides compared to equivalent black steel reinforcement. While the fusion bonded epoxy coated reinforcement was apparently unaffected by this harsh exposure, it does require special handling practices to maintain the integrity of the coating and any steel exposed by cutting or bending (for example) must be repaired.

The experimental techniques used in this corrosion investigation included visual assessment, weight loss determinations, chloride analysis and Cu/CuSO<sub>4</sub> half-cell potential measurements. The accelerated exposures used were wet and dry cycling in 3.5% salt water and continuous salt fog. A summary of the visual assessment reports at the various inspection intervals and trends in the half cell potential measurements are reproduced below for the purpose of clarifying some of the earlier corrosion results, in particular that of the apparently rapid deterioration of the zinc coating in the wet and dry regime.

### **65 Days Wet & Dry:**

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

**65 Days Salt Fog:** No distress to any specimens.

### **103 Days Wet & Dry:**

- Black - gross corrosion (-799 mV), cylinders cracking;
- Epoxy - unaffected other than local rust spotting;
- Galvanized - potential shift to -705 mV, extensive zinc loss, corrosion well progressed and cylinders cracking.

### **103 Days Salt Fog:**

No distress to any specimens.

**142 Days Wet & Dry:**

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

**142 Days Salt Fog:**

Black - corrosion initiated locally (-603 mV);  
Epoxy - unaffected (-612 mV);  
Galvanized - 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 ingress) of the potential of the galvanized bar.

For the black steel in the wet and dry regime, 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. 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 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.

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. 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 -1050 mV and was still actively protecting the steel.

Concerning the pullout testing which was done using deformed (i.e. ribbed bars) only, there was no significant difference in the ultimate bond stress for the coated bars compared to that for equivalent black steel bars. There was also no significant difference in the ultimate bond

stress for the galvanized reinforcement whether it be in a cleaned, weathered or chromate passivated condition.

These pullout results were not unexpected and simply reflect the major role of mechanical interlock between the concrete and the rib patterns on the reinforcement in determining the pullout resistance. The use of deformed bars, though the norm in reinforced concrete construction, does thus not allow the effects of chemical bonding and passivation of both black steel and galvanized steel to be explored.

Usual practice with galvanized reinforcement is to recommend chromate passivation (generally by mix water additions to the concrete) to eliminate effects of reduced bond and increased porosity from hydrogen gas evolution around zinc coated steel in concrete. These effects can only be investigated however, with the use of plain reinforcement where the mechanical interlock of the rib pattern is absent.

The earlier work thus identified two major areas where further investigation was required. On the one hand, the effects of concrete cover on the protection afforded to cut ends of coated reinforcement (both bare and repaired); and on the other, the pullout testing of plain black steel and coated reinforcement, and the influence of concrete mix water chromate additions on the bond of galvanized reinforcement in concrete.

The work done through 1989 concentrated on these two areas. The following sections of this report deal with the experimental procedures adopted, and the results and discussion of this most recent program of work.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Accelerated Corrosion Testing

Reinforced concrete cylinders (150 x 300 mm) were prepared in which a tree-like frame of reinforcement was centrally positioned. The reinforcement consisted of a vertical central piece 300 mm long to which were attached four equally spaced lateral pieces of varying length. This arrangement gave a variable cover to the surface of the cylinder in approximate 10 mm increments from zero (the vertical piece intersecting both ends of the cylinder), to 10-40 mm (the horizontal pieces). A sketch of this bar arrangement is shown in Figure 1, and the details of the concrete mix used are given in Table 1.

Table 1: Mix proportions and properties of concrete used for both the accelerated corrosion specimens and pullout testing.

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

Notes: a) - non air entrained; b) - dry rodded weight;  
c) - dry sand; d) - average of two tests.

The reinforcement used was 16 mm deformed TEMPORE<sup>R</sup> bar to AS 1302 Grade 410Y. Four metre lengths of the reinforcement were fusion bonded epoxy coated with the proprietary 3M SCOTCHKOTE<sup>R</sup> powder product, and other lengths were hot dip galvanized. The epoxy coating was a standard 175 micron coating, while the galvanizing was specified as a minimum coating thickness of 85 microns to AS 1650. The average thickness of the zinc coating as supplied was of the order of 105 microns.

In preparing the reinforcement for the specimens, sections were cut to the required length and the reinforcement frame was wired together. Insulating tape was used to isolate each piece from the others in the frame, and stainless steel tie wire was used. On completion of the reinforcement 'tree', one end of each cut piece of coated reinforcement was treated in the recommended manner with an appropriate repair compound. The epoxy coated reinforcement was repaired using 3M SCOTCHKOTE<sup>R</sup> 213PC patching compound while the galvanized coating was repaired with GALVIT E90, a heavy duty cold repair zinc-rich priming paint.

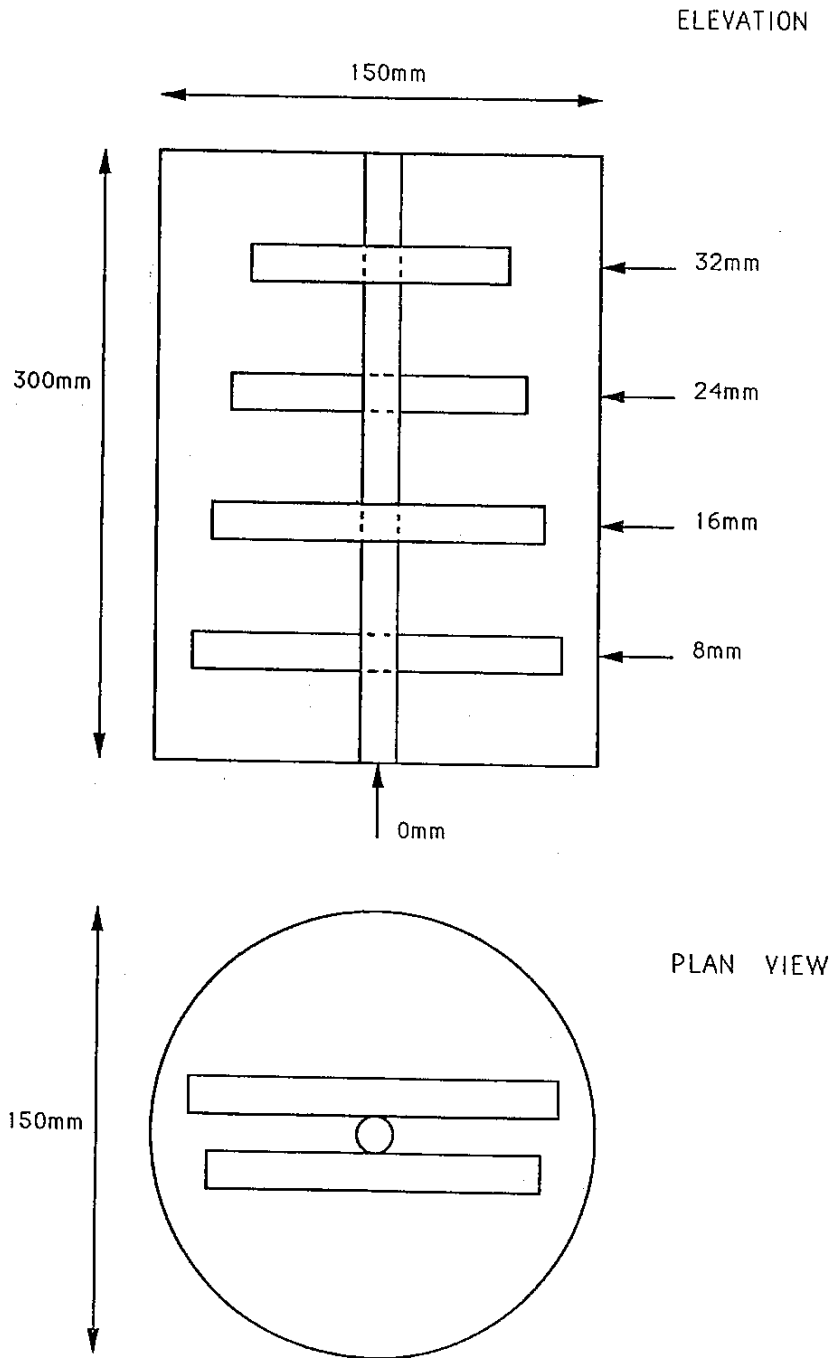


Figure 1: Details of reinforcement frame in accelerated corrosion samples.

The black steel reinforcement was moderately sand blasted to a uniformly clean (rust and mill scale free) condition prior to being wired into the frames. There was, of course, no repair treatments necessary in this case.

When casting the concrete specimens, it was necessary that the reinforcement frame remain centrally located within the cylinder so as to provide similar cover to the treated and untreated ends of the steel sections. Axial positioning was achieved with the use of cardboard stencils which were placed within the cylinders prior to casting the specimens. During vibration, the frames were temporarily secured in order to maintain centrality.

The test specimens were labelled (as below) then fog room cured for 7 days. At the completion of this time, the samples were placed into the accelerated corrosion environments. Two accelerated corrosion environments were used namely:

**Wet & Dry** - alternate wetting for 3 days in a 3.5% salt solution at 40°C and drying for 4 days at 60°C.

**Salt Fog** - continuous exposure in a salt fog chamber at 40°C.

In addition, some companion specimens were exposed to the natural environment in a local urban situation. The specimens were identified with a prefix letter as follows:

**B** - for salt fog exposure;  
**O** - for wet and dry cycling;  
**R or G** - for natural atmospheric exposure.

At the completion of the curing period, the B and O specimens were dried for 7 days at 40°C prior to the commencement of accelerated exposure testing. The purpose of this was to hasten the early ingress of chlorides from the exposure regimes.

Regular visual inspection of the specimens was carried out, and specimens were removed from the exposure regimes at intervals of 41, 98 and 132 days. At these times chloride analysis of the concrete was done and the specimens were broken open for a detailed visual examination.

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 three 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. Care was taken to ensure that the reinforcement itself did not interfere with the drilling procedure and thus the samples were drilled at approximately 90° to the plane of the reinforcement. The chloride content was determined by the potentiometric titration of chloride with silver nitrate following the method described in ASTM C114.



## 2.2 Pullout Testing

A series of pullout tests were done using 16 mm diameter (R16) plain reinforcement to AS 1302 Grade 230S. The plain bar was coated by either epoxy coating or galvanizing. The galvanized coating was to the same specification as that used in the accelerated corrosion testing, namely 85 micron specified minimum coating thickness to AS 1650. For epoxy coating of the plain reinforcement two powders were used: INTERPON HD33 manufactured by Taubmans - coloured yellow; and an experimental powder manufactured by Dulux - coloured green.

Lengths of each type of reinforcement (black, epoxy coated, and galvanized) were cast centrally into 100 mm cubes with an embedment length of 100 mm. The details of the concrete mix used are given in Table 1. The reinforcement used for the pullout specimens was in a variety of conditions as follows:

- Black Steel** - as received with light mill scale and very slight surface rusting;
- Epoxy Coated** - surface wiped down with a dampened cloth and allowed to dry in air;
- Galvanized** - as received and naturally weathered bar,

Chromate additions to the concrete mix water were in the proportions 15, 35, 70 and 150 ppm of hexavalent chromate ion ( $\text{Cr}^{6+}$ ) by weight of cement. These proportions were based on a standard addition of 103 g of pure sodium dichromate per tonne of cement for 70 ppm chromate concentration (CIA, 1984).

All pullout specimens were fog room cured for 14 days then dried in air at room temperature for approximately 3 hours prior to testing. The testing involved placing the specimens in a jig and tensile loading (at constant rate) via the exposed 200 mm length of exposed reinforcement bar. The pullout tests were done in a Shimadzu UMH-30t Universal Testing Machine. The load was applied at a constant rate of 25 N/min over a 60 kN range, and a continuous load time chart recording was made. In addition, dial gauge deflection readings were obtained at intervals of 0.5 N until failure of the specimen occurred.

While it was recognized that pullout testing in this manner would only provide comparative data because the concrete at the pullout end of the specimen is subject to compression while the load is applied, this was sufficient for the purpose intended here, which was to investigate the effects of different coatings and conditions on the bond between the reinforcement and the concrete. Further, the use of plain bars rather than deformed (i.e. ribbed) bars was to avoid the overshadowing effect of mechanical interlock between the concrete and the rib pattern. In this way it was anticipated that the pullout strength determined would more closely indicate the actual bond between the reinforcement or its coating and the concrete itself.

### **3. RESULTS**

#### **3.1 Accelerated Corrosion Testing**

The purpose of the accelerated corrosion tests was to promote the degradation of steel reinforcement contained within the concrete due to chloride ingress. With this in mind, a number of parameters were considered during the investigation, namely:

- a) variation in depth of cover of concrete;
- b) the exposure environment; and
- c) the protection offered from repairs to the cut ends.

As previously indicated, repair compounds were applied to one cut end of the galvanized and epoxy coated pieces. The opposite end remained in the as-cut state. The repair compounds were applied with a paint brush so as to simulate the method of application that would be common practice on the construction site. The black reinforcement had no need for repairs to be done. The exposure environment consisted of two types; salt fog and intermittent salt water immersion. The latter was to provide the bulk of the effects to the concrete-reinforcement samples, though the salt fog provided a more realistic exposure.

Following the appropriate exposure, the cylinders were split open and visual examination of the reinforcement was conducted, the observations being summarized below. Chloride ingress into the concrete was determined in order to associate possible corrosion effects on the presence of the chloride ion.

##### **3.1.1 Assessment Reports - 41 Day Exposure**

###### **3.1.1.1 Black Steel**

###### **a) Atmospheric Exposure (Sample RB4)**

The black steel reinforcement was protected by the concrete mass though some corrosion did occur on the exposed bar (0 mm cover). This attack with red rust formation was restricted to the very end of the exposed bar and there was no corrosion on any of the other reinforcement pieces at depth from the concrete surface.

###### **b) Salt Fog (Sample RB10)**

There was increased corrosion activity on the exposed bar (0 mm cover) and this had progressed to a maximum of some 15 mm from the free surface (see Plate 1). Similar attack had initiated at the ends of the section with 10 mm cover where localized points of red rust corrosion were present.

###### **c) Wet and Dry (Sample OB7)**

The black steel reinforcement subjected to the periodic salt water immersion was affected to a much greater extent than was the case for the other exposure regimes. Corrosion was well progressed at

both exposed faces with 0 mm cover, and had progressed some 20 mm from the free surface (see Plate 2). Surprisingly, there was little or no attack on the reinforcement sections at depth, even that with only 10 mm cover.

### **3.1.1.2 Galvanized Steel**

#### **a) Atmospheric Exposure (Sample RG4)**

The galvanized steel sample exposed to the atmosphere showed no evidence of corrosion. There was a slight amount of white zinc reaction product present at the concrete-reinforcement interface on the unrepaired end of the exposed bar (0 mm cover). There was no evidence of corrosion below the concrete surface.

#### **b) Salt Fog (Sample BG10)**

There was only a small amount of white zinc reaction product evident at the unrepaired end of the exposed (0 mm cover) reinforcement. The repaired end with 0 mm cover showed no attack as was the case for all the reinforcement at depth in the concrete.

#### **c) Wet and Dry (Sample OG7)**

The formation of a small quantity of white zinc reaction product at the unrepaired exposed end (0 mm cover) was the only evidence of attack at this exposure.

### **3.1.1.3 Epoxy Coated Steel**

#### **a) Atmospheric Exposure (Sample RE4)**

The epoxy coated steel showed general attack at the exposed (0 mm cover) unrepaired end, and also exhibited localized pitting attack at some 7 locations of failure of the repair compound at the opposite end of the exposed bar (see Plate 3). Apart from this there was no sign of corrosion at any location of reinforcement within the concrete mass, including those sites where the cut ends were not repaired.

#### **b) Salt Fog (Sample BE10)**

Surface corrosion was well developed at the exposed (0 mm cover) cut end of the epoxy coated bar and some slight corrosion was evident at a unrepaired end of a bar with 30 mm cover. Apart from this there was no other evidence of corrosion within the cylinders.

#### **c) Wet and Dry (Sample OE7)**

The epoxy coated steel was severely corroded at the exposed unrepaired end, and there was some evidence that corrosion was progressing along the bar beneath the coating. At the exposed (0 mm cover) repaired end of the bar, there were some 13 locations

where localized corrosion was evident (see Plate 4). On bars with concrete cover of 15-20 mm, rusting of the cut end was evident and the opposite repaired end was showing distress to the coating. Elsewhere at greater depth in the concrete, the reinforcement was intact including cut ends which had not been repaired.

### **3.1.2 Assessment Reports - 98 Day Exposure**

#### **3.1.2.1 Black Steel**

##### **a) Salt Fog (Sample BB11)**

There was extensive corrosion of the exposed ends of the black steel bars in the salt fog regime, this attack extending some 15 mm along the bar below the concrete surface (see Plate 5). On bars with approximately 25 mm cover to the cut ends, some slight red rust corrosion was also in evidence.

##### **b) Wet and Dry (Sample OB8)**

The exposed bar had extensive corrosion at both ends, which had progressed some 15-20 mm along the bar. Corrosion was also well progressed on bars with 10 mm cover to the cut ends and this attack had spread a further 5 mm along those bars. On bars with up to 30 mm cover corrosion was also in evidence.

#### **3.1.2.2 Galvanized Steel**

##### **a) Salt Fog (Sample BG11)**

White zinc reaction product was evident at both ends of the exposed bar and there was one small area of red rust staining on the unrepaired end. Apart from some small areas of corrosion at the unrepaired end of the bar with about 10 mm cover, there was little evidence of attack of any form on the remainder of the reinforcement.

##### **b) Wet and Dry (Sample OG8)**

The galvanized bars showed both white reaction product and red rust corrosion on both ends of the exposed section (0 mm cover). The reaction product extended some 40 mm along the bar from the concrete interface. Throughout the specimen there was evidence of attack on the zinc but no substantial regions of exposure of the underlying steel leading to red rust corrosion.

#### **3.1.2.3 Epoxy Coated Steel**

##### **a) Salt Fog (Sample BE11)**

Corrosion was well progressed at the unrepaired end of the exposed bar. At the repaired end, two points of rust corrosion were evident at the bar edges where it was apparent that the epoxy

coating was quite thin. On the bar with about 20 mm cover corrosion was evident at both ends.

**b) Wet and Dry (Sample OES)**

Corrosion was well progressed on both ends of the exposed bar (see Plate 6), and was also evident at both ends (repaired and unrepaired) of bars with covers in the 10-20 mm range (see Plate 7). On the bars at depth in the concrete, the corrosion was localized in this early stage of attack,

**3.1.3 Assessment Reports - 132 Day Exposure**

**3.1.3.1 Black Steel**

**a) Salt Fog (Sample BB12)**

The exposed reinforcement was extensively corroded with attack occurring to a depth of 8-15 mm along the length of the bar. The reinforcement within the cylinder was in good condition.

**b) Wet and Dry (Sample OB9)**

The exposed reinforcement was again extensively corroded with the corrosion extending some 10-25 mm from the surface of the concrete. At the ends of most of the embedded pieces of bar to a depth of about 30 mm, corrosion to varying extents was evident. In some cases the corrosion had progressed up to 20 mm along the bars further into the concrete mass.

**3.1.3.2 Galvanized Steel**

**a) Salt Fog (Sample BG12)**

Very little attack on the reinforcement was evident, even at the repaired end of the exposed (0 mm cover) bars. Some minor white zinc reaction product was evident around and along the bars nearest to the concrete surface. Elsewhere, the reinforcement was unaffected.

**b) Wet and Dry (Sample OG9)**

The unrepaired end of the exposed bar was corroded (see Plate 8) though elsewhere no red rust corrosion was evident. White zinc reaction product was evident around both ends of the exposed bars. All the bars at depth in the concrete showed varying degrees of white product at their surface. Bars with 10 mm cover showed white product up to 55 mm from the unrepaired end and 30 mm from the repaired end. Bars with 30 mm cover also showed some white zinc reaction product over a significant portion of their length (see Plate 9). No red rust was present at any site on the reinforcement frame.

### **3.1.3.3 Epoxy Coated Steel**

#### **a) Salt Fog (Sample BE12)**

Both the repaired and unrepaired ends of the exposed (0 mm cover) epoxy coated bar were corroded (Plates 10 and 11). The general condition of the reinforcement within the concrete was good, except for the repaired end of the bar with about 30 mm cover (see Plate 12).

#### **b) Wet and Dry (Sample OE9)**

Both ends of the exposed bar were corroded, the unrepaired end quite severely so with corrosion occurring under the coating along the bar. The repaired end showed some eight points where the coating had broken down and initiated corrosion. At depth in the concrete, corrosion was well progressed at the unrepaired ends of bars with covers of 8 mm, 16 mm and 24 mm (see Plate 13). For some of these, localized corrosion was evident at distances 5-10 mm from the end of the bars (see Plate 14) and it was obvious that corrosion of the steel was occurring beneath the epoxy coating and causing the coating to detach. The repairs to the cut ends for bars at depths in excess of 15 mm showed little or no sign of corrosion at this time.

### **3.2 Chloride Analysis.**

The results of the chloride analysis of drilled samples taken from certain of the exposure cylinders are given in Table 2. The variation of chloride content with depth from the concrete surface is shown graphically in Figures 2-4.

### **3.3 Pullout Testing**

A summary of the results of the pullout testing of plain bars is given in Tables 3 and 4. The bond stress is calculated as the failure or maximum load divided by the contact area of length of the embedded reinforcement. The mean value and the standard deviation are calculated from the three individual results given. In Table 3, the comparative pullout performance of black, epoxy coated, and galvanized plain steel bars is given. The effect of various levels of chromate ion additions to the concrete mix water on the pullout strength of galvanized plain steel reinforcement is given in Table 4.

The mode of failure of the pullout specimens was dependent on the nature of the reinforcement itself. While there was no difference in the failure of specimens with different surface coatings, there was an effect depending on whether or not deformed or plain bar was used. All of the plain reinforced specimens failed by slippage of the bar with little or no disturbance to the concrete mass. In contrast, deformed (i.e. ribbed) bar specimens from previous work all failed by splitting of the concrete. These differences are shown by the representative specimens in Plates 15 and 16.

A summary of the pullout data is given in Figures 5 and 6, in which the mean bond strength of the various bar types is plotted.

Table 2: Chloride penetration data determined by the method given in ASTM C114-85.

Exposure Samples	Depth (mm)	Chloride Content (%) <sup>(a)</sup>		
		41 Days	98 Days	132 Days
Atmosphere	0-10	0.02		
RB4 (41 days)	10-20	0	Not Determined <sup>(c)</sup>	
BB10 (98 days)	20-30	0.01		
OB7 (132 days)	30-40	0		
	40-50	0 <sup>(b)</sup>		
Salt Fog	0-10	0.07	0.15	0.15
BB11 (98 days)	10-20	0.04	0.09	0.10
OB8 (132 days)	20-30	0.03	0.07	0.07
	30-40	0.01	0.04	0.07
	40-50	0.01	0.04	0.04
Wet and Dry	0-10	0.12	0.17	0.18
BB12 (98 days)	10-20	0.07	0.14	0.17
OB9 (132 days)	20-30	0.06	0.11	0.11
	30-40	0.04	0.09	0.10
	40-50	0.03	0.05	0.08

- Notes:
- (a) Expressed as weight percent chloride ions by weight of cement;
  - (b) Zero values indicate result of less than 0.01%;
  - (c) These determinations were not made.

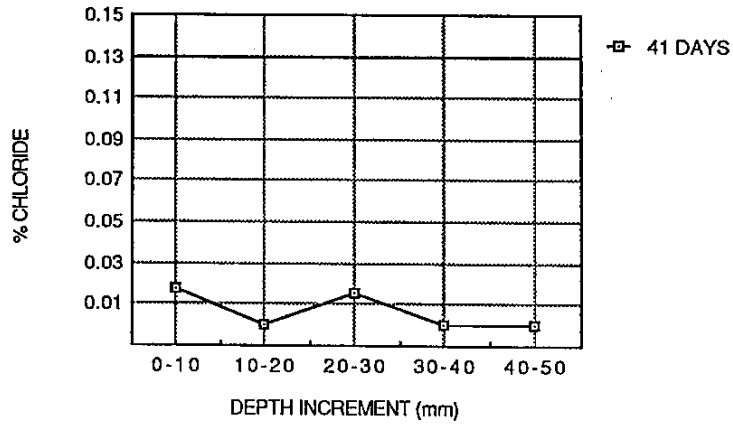


Figure 2: Chloride penetration profile for 41 day atmospheric exposure (Sample RB4).

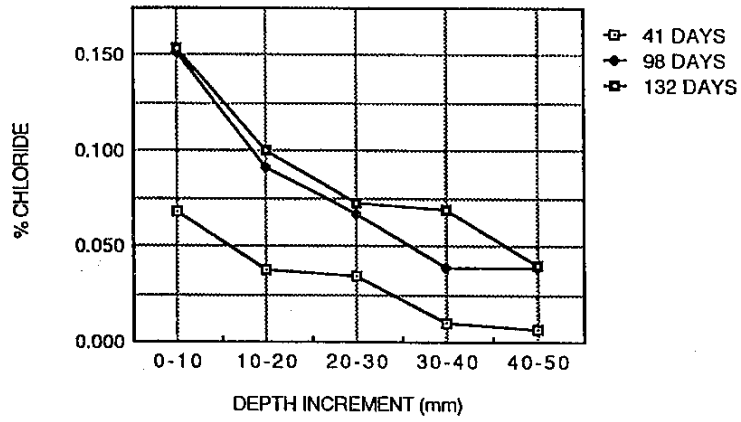


Figure 3: Chloride penetration profiles from salt fog exposure for 41, 98 and 132 days (Samples BB10, BB11 and BB12 respectively).

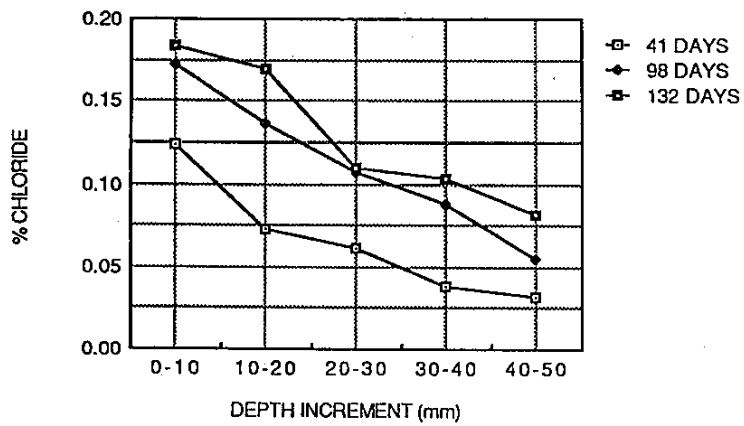


Figure 4: Chloride penetration profiles from wet and dry salt water exposure for 41, 98 and 132 days (Samples OB7, OB8 and OB9 respectively).



Table 3: Ultimate bond strength of specimens with plain bars.

Specimen	Bond Stress (MPa)	Mean (MPa)	Standard Deviation
Black Steel B1 - B3	4.45 3.60 3.34	3.80	0.58
Galvanized G1 - G3 G01 - G03	5.07, 4.94 5.09, 4.40 5.15, 5.29	4.99	0.31
Epoxy - Yellow EY1 - EY3	3.02 3.28 3.22	3.17	0.14
Epoxy - Green EG1 - EG3	3.99 3.80 2.33	3.37	0.86

Note: All bar types embedded in the as-received condition.

Table 4: Ultimate bond strength of galvanized reinforced specimens with different chromate levels in the concrete.

Specimen	Bond Stress (MPa)	Mean (MPa)	Standard Deviation
Galvanized G1 - G3 G01 - G03	5.07, 4.94 5.09, 4.40 5.15, 5.29	4.99	0.31
Galvanized 15 ppm Cr <sup>6+</sup> G11 - G13	5.53 4.87 5.66	5.35	0.42
Galvanized 30 ppm Cr <sup>6+</sup> G21 - G23	5.22 6.98 5.77	5.99	0.90
Galvanized 75 ppm Cr <sup>6+</sup> G31 - G33	6.18 5.21 4.45	5.28	0.87
Galvanized 150 ppm Cr <sup>6+</sup> G41 - G43	4.91 5.47 5.72	5.37	0.41

Note: All bars embedded in the as-received condition.

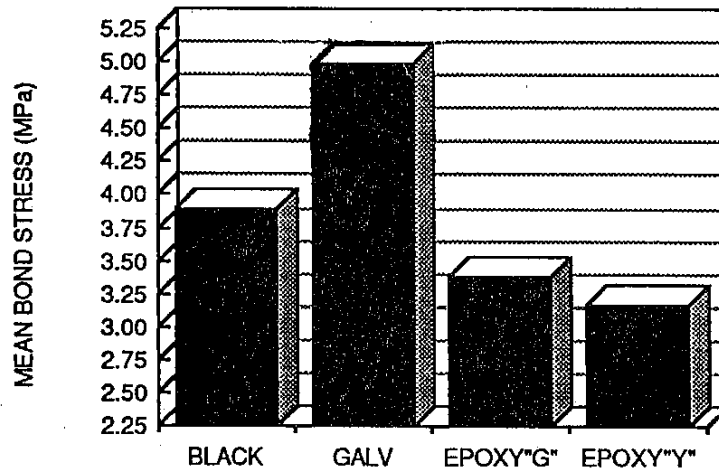


Figure 5: Comparison of ultimate bond stress of black steel and coated plain steel reinforcement.

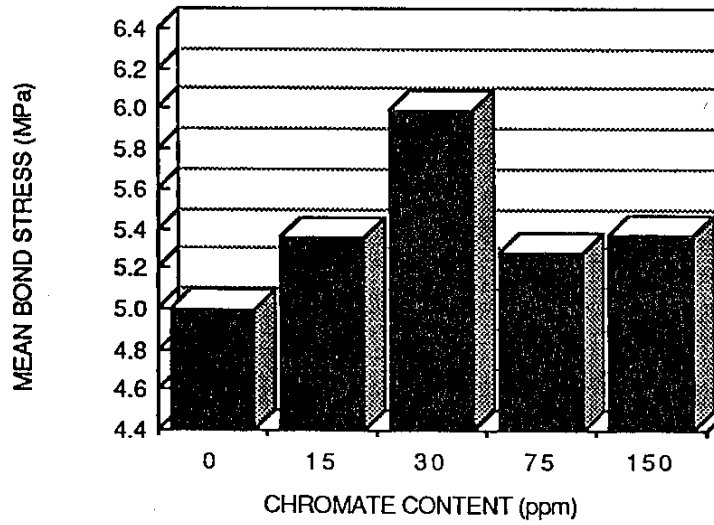


Figure 6: Showing the effect of chromate additions on the ultimate bond stress of galvanized plain steel reinforcement.

## **4. DISCUSSION OF RESULTS**

### **4.1 Accelerated Corrosion Testing**

#### **4.1.1 Summary of Observations**

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 environment, 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 multiple 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 many locations on 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 accelerated regimes, corrosion of cut ends of the epoxy coated bars 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. After 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.

#### **4.1.2 Commentary**

These tests on the black and coated steel have demonstrated the beneficial effect of zinc in protecting steel in exposure situations where black steel corrodes. Zinc can clearly resist chloride levels somewhat higher than black steel, and the sacrificial effect of zinc protects cut ends for some considerable time. The presence of the white product on the zinc is evidence that some reaction is occurring, but it is likely that it is only the pure outer zinc layer that is being removed in the early stages, thereby exposing the more corrosion resistant underlying iron-zinc 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, premature and localized corrosion often occurred even at depth within the concrete mass.

These effects are indicative of the care that is necessary when handling and fabricating epoxy coated reinforcement. Small breaks in the coating (in addition to the natural holidays which will exist) allow access of species from the environment to the steel which will initiate localized corrosion. At cut ends where the coating was not repaired, very rapid attack occurred once the passivity of the steel was destroyed by the chloride ingress.

In other regions where the epoxy coating was repaired, the repair itself had varying degrees of success. The quality of the surface and its preparation, and the method of application all seemed to have a significant effect. Where the steel surface was not clean and dry, adhesion of the coating was quite poor and several instances of large scale detachment of the repair patch and hence unexpected corrosion of the underlying steel did occur. These instances were not included in the corrosion survey reports given before. Also, where the repair patch was quite thin, certainly around the edges where surface tension effects draw the coating away, there was a tendency for the repair to break down at these regions leading to the onset of localized corrosion.

What was also quite apparent was that once the epoxy coating or the repair had perforated and allowed corrosion to commence, the spread of corrosion was quite rapid with underfilm corrosion occurring and detachment of the adjacent coating.

In contrast, the zinc coating of the galvanized reinforcement sacrificially protected the bare cut ends of the reinforcement throughout much of this exposure program. Further, the galvanizing repair paint performed well and its effectiveness did not appear to be as strongly

influenced by the surface preparation and application methods as well the case for the epoxy coating repairs.

The variation in chloride ion content with depth from the free surface of the specimens given in Table 2 reveals that for the atmospheric exposure specimens, an exposure period of 41 days gave concentrations at the surface less than 0.02% chloride by weight of cement and less than 0.01% at depth (see Figure 2). 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.

As an example of this, the ACI (Committee 201) 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  $0.8 \text{ kg/m}^3$ , which for a concrete containing say  $280 \text{ kg/m}^3$  cement equates to 0.28% chloride.

There was a significant difference in both the rate and extent of corrosion for the wet and dry exposure compared to the salt fog regime, due largely to the very high 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 attack, whereas the zinc coating showed only slight signs of reaction, and no red rust corrosion.

This higher tolerance of zinc to the effect of chlorides is in agreement with work by Cornet (1966) who found that galvanized steel could withstand chloride contents in concrete some 10 times higher than that tolerated by black steel before corrosion occurred. More recently, studies by Tonini (1976), ILZRO (1981) and others, have shown that the threshold chloride concentrations for depassivation of galvanized reinforcing bar is 4-5 times the level required for the same attack on black steel.

#### **4.2 Pullout Testing**

The approach to the pullout tests using plain reinforcement was an attempt to eliminate the effects of mechanical interlock which, under ordinary circumstances, overshadows the adhesion developed between the reinforcement and concrete itself. Bond failure is assumed to be a result of shearing failure in this adhesion, though frictional resistance may further increase the bond strength following the break in adhesion. The frictional resistance was not eliminated in these tests and therefore remains as a component of the ultimate bond strength.

#### 4.2.1 Plain Reinforcement

The ultimate bond stress data (mean and standard deviation) for the black and coated plain reinforcement specimens (from Table 3) were:

Black Steel (as-received)	3.80 (0.58) MPa
Galvanized Steel (weathered)	4.99 (0.31) MPa
Epoxy (Yellow) Coated Steel	3.17 (0.14) MPa
Epoxy (Green) Coated Steel	3.37 (0.86) MPa

Statistical analysis of these results using the Null Hypothesis method indicates that at a 5% significance level there is a statistically significant difference between the data for the black steel and the galvanized steel specimens. On the same basis, the two epoxy coated samples (EY and EG) cannot be said to be different to each other, and when considered as a single population, the data for the epoxy coated steel is not significantly different to that for the black steel.

On the other hand, the data for the galvanized steel is significantly different to that for both types of epoxy coatings (EY and EG) and also to the single population of data for the epoxy coated steels. In summary, the statistical analysis of this data reveals that:

- a) the ultimate bond strength of galvanized plain reinforcement is some 31% higher than that for equivalent black steel reinforcement;
- b) the ultimate bond strength of epoxy coated plain reinforcement (when taken as a single population of data) is some 17% less than that for equivalent black steel reinforcement; and
- c) the ultimate bond strength of galvanized plain reinforcement is some 57% higher than that for equivalent epoxy coated steel reinforcement (when taken as a single population of data).

These results are in good agreement with much published bond strength data for plain bars. For example, early work by Bresler and Cornet (1964) reported that for plain bars the bond strength of galvanized bars was between 30% and 50% greater than that for similar black bars. Other work by Roberts (1977) showed that galvanized bars had equal or better performance than equivalent black steel bars, provided the zinc/alkali reaction was inhibited by passivation.

As for the epoxy coated bars, the smooth surface of the coating reduced the bond strength (i.e. 17% below that of plain black steel bars) in line with results obtained by Rajkumari (1986) and Treece (1987). This reduction is recognised and taken into account in a number of Standards (ASTM A775, JSCE 1986) in which there are requirements to the effect that the main critical bond strength for coated bars shall not be less than 80% of the main strength for uncoated bar.

#### 4.2.2 Comparison with Deformed Reinforcement

The results obtained in this study on plain reinforcement could be compared with earlier work involving pullout testing using deformed bars (Yeomans, 1988). The previous results for deformed reinforcement were:

Black Steel	5.90 (0.57) MPa
Epoxy Coated Steel	6.04 (1.11) MPa
Galvanized Steel (Weathered)	5.68 (1.21) MPa

Statistical analysis of this data indicates that there is no significant difference between the ultimate bond strength of deformed black, epoxy coated and galvanized reinforcement. This result is consistent with other published data which often reports that there is little or no difference in the bond of deformed black steels and coated (both epoxy and galvanized) steels. This is what would be expected for deformed reinforcement where the mechanical interlock provided by the rib patterns overshadows effects due to chemical bonding at the reinforcement interface.

In this context it is interesting to note however, that the thickness of epoxy coatings has an adverse effect on bond, the reduction in bond being more pronounced in larger diameter bars than smaller ones (Al-Sulaimani, 1989). The reason for this is that as the epoxy thickness is increased, the mechanical interlock is reduced because the coating tends to smooth the sharp edges and the fillet at the deformation marks (i.e. bar lugs), and also reduces their effective height. Since quite thick epoxy coatings can be placed onto the steel (in excess of 300 microns), the reduction in bond could be significant particularly for the smaller (say 12 and 16 mm) bar sizes.

Since the thickness of the galvanized coating on steel is limited by the extent of the metallurgical reaction that occurs, it is most unlikely that a similar reduction in bond will be observed due to slight variations in zinc coating thickness.

When comparing the same types of plain and deformed reinforcement (i.e. plain black to deformed black bars), it is quite clear from these results that the ultimate bond strength of deformed bars for each type of reinforcement is statistically different to that for the equivalent plain bars. This comparison of ultimate bond strength (MPa) can be summarized as follows:

	Plain Bars	Deformed Bars
Black Steel	3.80 (0.58)	5.90 (0.57)
Epoxy Coated	3.27 (0.59)	6.04 (1.11)
Galvanized	4.99 (0.31)	5.68 (1.21)

In each case, the bond of the deformed bars is substantially higher than that for plain bars, the extent of this increase ranging from 12-48%, which is also in general agreement with much published data.

### 4.2.3 Chromate Additions

The pullout testing using weathered galvanized plain bars with various chromate ion additions to the concrete mix (see Table 4) can be summarized as follows:

Nil added chromate	4.99 (0.31) MPa
15 ppm chromates	5.35 (0.42) MPa
30 ppm chromates	5.99 (0.90) MPa
75 ppm chromates	5.28 (0.87) MPa
150 ppm chromates	5.37 (0.41) MPa

This data (shown graphically in Figure 6) does seem to indicate that the addition of chromates to the concrete mix results in an overall improvement in the bond strength, and there may be some maximum to this effect at about the 30 ppm level of added chromates. However, even though a trend is indicated, it has not been possible to demonstrate that there is a statistically significant difference between these data, mainly because of the restricted population size in each group and a fairly large coefficient of variation of the data. This applies to comparisons both between the groups of specimens to which chromates had been added, as well as between these specimen groups and that for which no chromates had been added.

Other work (e.g. Hofsoy 1969) has demonstrated the importance of passivation of galvanized reinforcement in concrete; the same bond strength was obtained for galvanized and black steel deformed bars using cement with high chromate content, though where the bars had been quench passivated the bond strengths for galvanized bars were greater. Also, the results of recent testing on bond strengths have confirmed these results by indicating that galvanized reinforcement without passivation is comparable to black steel for bond strength, whilst passivation has an apparent positive effect on bond strength (SAHDGA, 1988).

Thus, despite the published data, it is not possible at this stage to confirm from this work whether or not passivation by chromates has a significant effect on bond, and if this is the case then what minimum level of chromates is required. Further data will be needed to verify this.

An interesting point to note is that cement itself contains varying levels of naturally occurring chromates. In this work, chemical analysis of the cement used for mixing and the concrete produced was done to confirm the presence of chromates. The analysis indicated that the cement powder contained 62.5 ppm of chromates expressed in terms of  $\text{Cr}_2\text{O}_3$  (i.e. 44.1 ppm in terms of  $\text{CrO}_3$ ). This amount of natural chromate thus contributes of the order of 5 to 7 ppm chromates to the concrete mix. Ideally this should be taken into account in determining the levels of added chromates required.



## **5. CONCLUSIONS**

- 5.1** 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 an initial 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.
- 5.2** Galvanizing provides positive protection to steel when 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.
- 5.3** Epoxy coating provided excellent protection to the steel, providing 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 the coating offers.
- 5.4** There is no significant difference between the ultimate bond strengths of black, galvanized, and fusion bonded epoxy coated deformed reinforcement. The ultimate bond strength of deformed bars is thus independent of the presence of surface coatings, and is some 12-48% higher than for equivalent coated plain bars.
- 5.5** 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.
- 5.6** Chromate passivation of galvanized plain bars could not be shown to produce a statistically significant change in ultimate bond strength. Further work needs to be done to confirm this however.

## **6. FUTURE WORK**

This work, which is part of a continuing program, has highlighted some areas where further investigation is warranted. In particular, the question of the use of chromates for the passivation of galvanized bar and the elimination of the hydrogen evolution problem and its (presumed) effects on bond, need to be resolved. What is required is to test larger populations of plain bar specimens to which different levels of chromates have been added, so as to compare passivated bars with non-passivated bars and also to determine the minimum level of chromates required.

Further, the question of whether in fact deformed galvanized bars need to be passivated is also relevant. Data to hand suggests that the effects of hydrogen evolution on the bond of deformed bars is slight (if at all measurable) because the bond with concrete is primarily determined by mechanical interlock rather than chemical adhesion. Since virtually all reinforced concrete construction uses deformed bars and not plain bars, then the whole issue of the need to prevent hydrogen evolution at the interface is open to debate.

One other area which could be a most interesting and useful investigation, is to confirm the use of half-cell potential measurements to follow the stages in the functioning of the zinc coating when protecting the underlying steel. Information to hand suggests that the zinc exhibits its maximum potential of about -1100 mV after it has been activated by depassivation, and that as the zinc coating is consumed its potential gradually shifts to about -600 mV. This is the potential at which black steel is actively corroding with the formation of red rust.

If this behaviour can be confirmed, it would define a time span over which zinc protects steel in concrete. The delaying effect on corrosion due to the zinc is recognised as one of the main advantages of galvanizing, but there has not previously been an ability to quantify the delay period. It is intended to pursue this by measuring the time dependence of the half-cell potentials of galvanized bar (with black steel as a bench mark) at various chloride levels, and to follow this with actual measurements of the rate of zinc coating thickness loss.

## **7. ACKNOWLEDGEMENTS**

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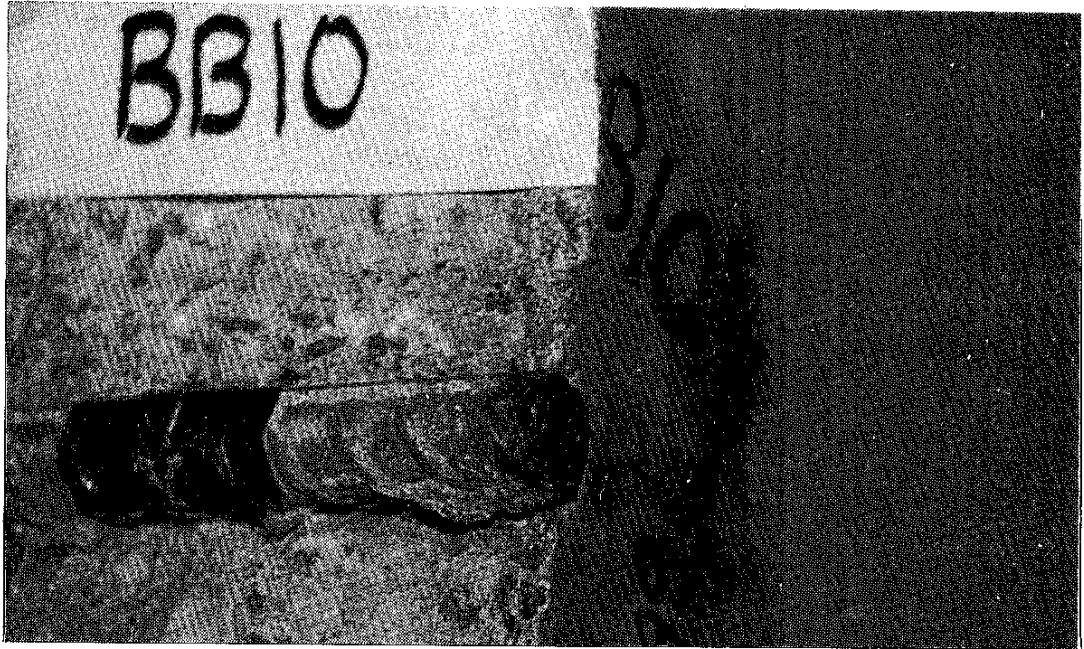


Plate 1: Sample BB10: Black Steel - Salt Fog - 41 Days.  
Corrosion activity on exposed end (0 mm cover) of longitudinal bar.

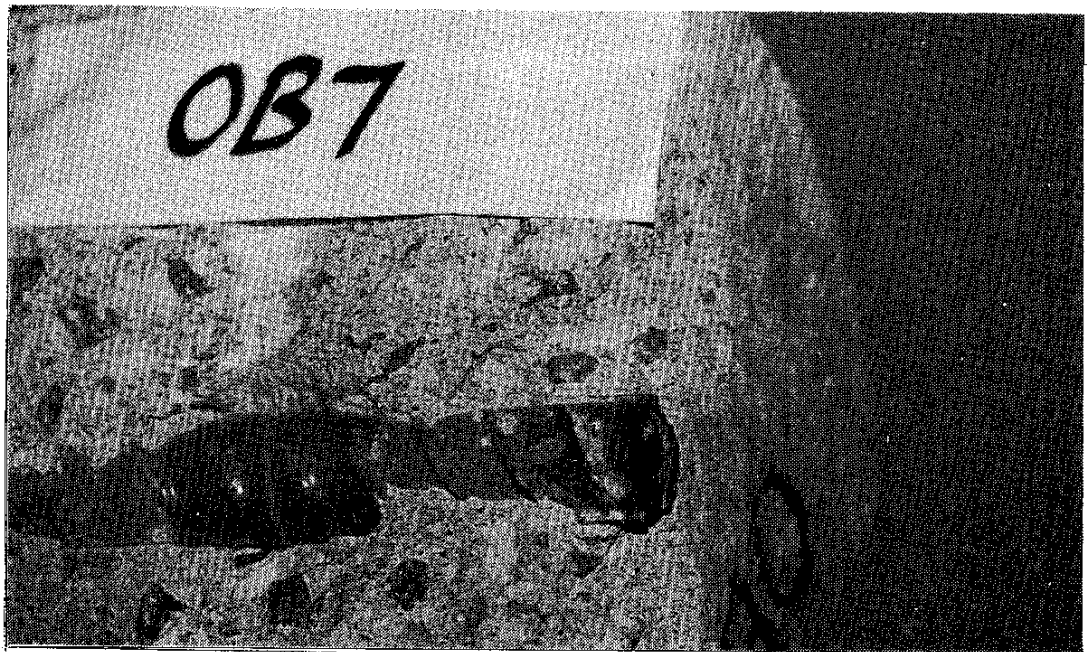


Plate 2: Sample OB7: Black Steel - Wet and Dry - 41 days.  
Corrosion activity progressing some 13 mm from the exposed end of the longitudinal bar.



Plate 3: Sample RE4: Epoxy Coated Steel - Atmosphere - 41 Days. Localized corrosion at repaired exposed end of longitudinal bar.

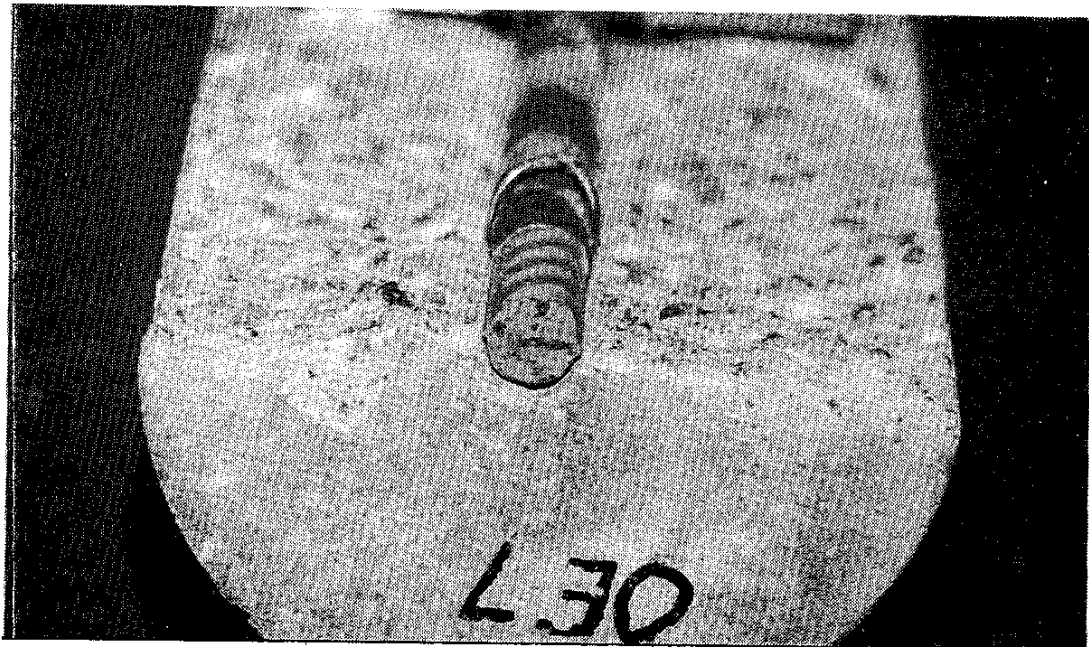
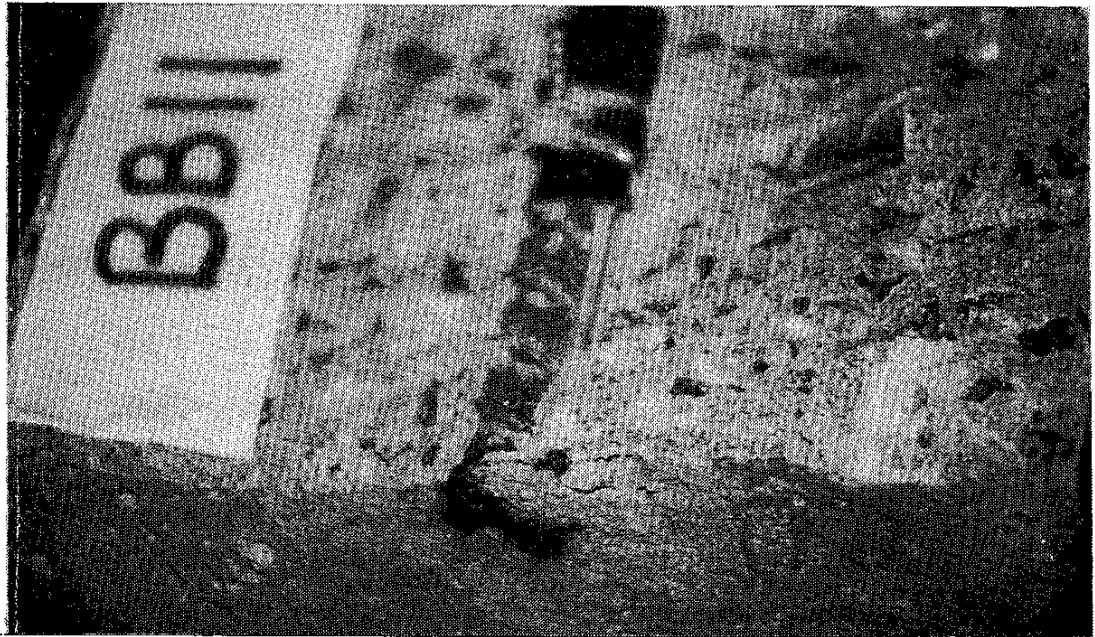


Plate 4: Sample OE7: Epoxy Coated Steel - Wet and Dry - 41 Days. Localized corrosion at repaired exposed end of longitudinal bar.



**Plate 5:** Sample BB11: Black Steel - Salt Fog - 41 Days.  
Corrosion progressing along the bar from the exposed end of longitudinal bar.



**Plate 6:** Sample OE8: Epoxy Coated Steel - Wet and Dry - 98 Days.  
Corrosion at unrepaired exposed end of longitudinal bar.

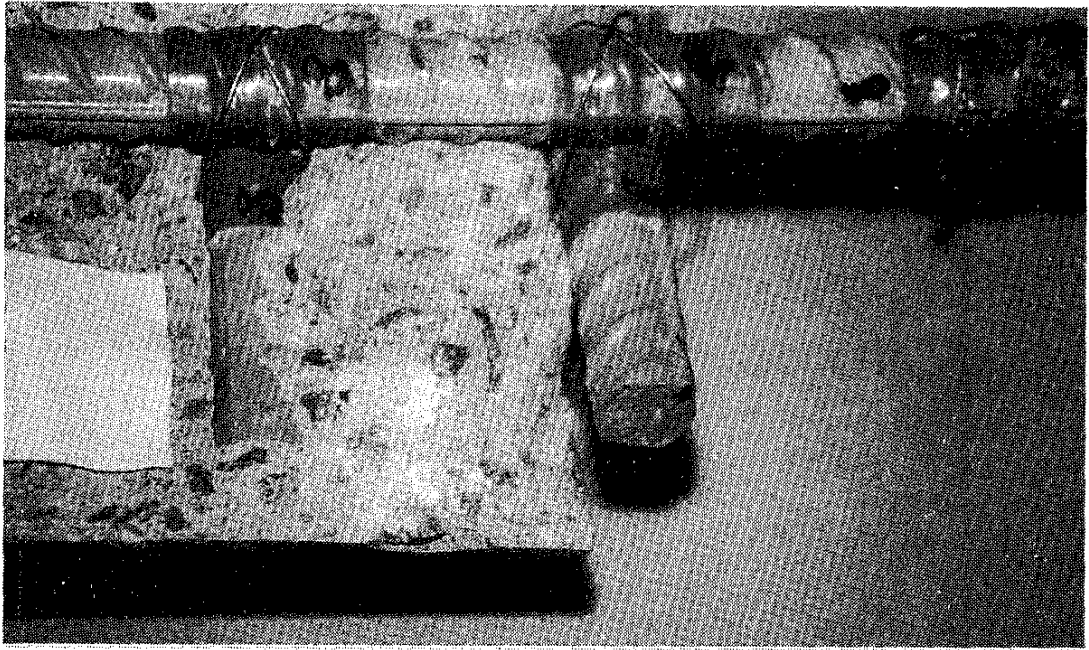


Plate 7: Sample OE8: Epoxy Coated Steel - Wet and Dry - 98 Days. Localized corrosion activity at repaired end of the bar with 8 mm cover.

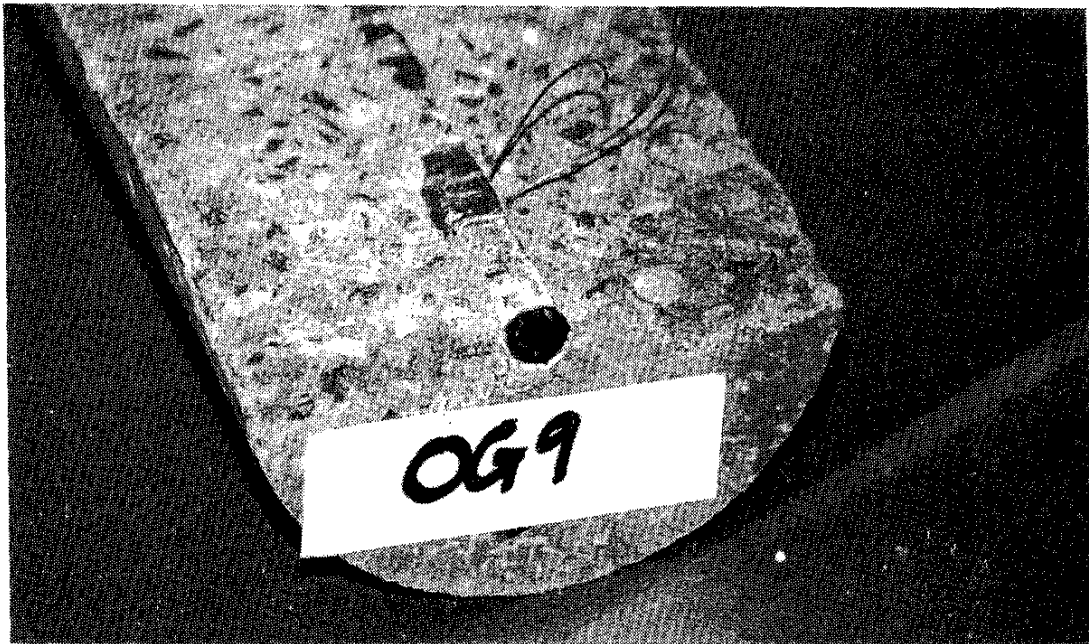


Plate 8: Sample OG9: Galvanized Steel - Wet and Dry - 132 Days. General corrosion at unrepaired exposed end of longitudinal bar also showing white zinc reaction product.



Plate 9: Sample OG9: Galvanized Steel - Wet and Dry - 132 Days. White zinc reaction products on bar with minimum cover at ends of 32 mm.



Plate 10: Sample BB12: Epoxy Coated - Salt Fog - 132 Days. Localized corrosion at repaired exposed end of longitudinal bar.





Plate 11: Sample BE12: Epoxy Coated - Salt Fog - 132 Days.  
General corrosion at unrepaired exposed end of longitudinal bar.



Plate 12: Sample BE12: Epoxy Coated - Salt Fog - 132 Days.  
Corrosion activity at repaired end of bar with 32 mm cover.

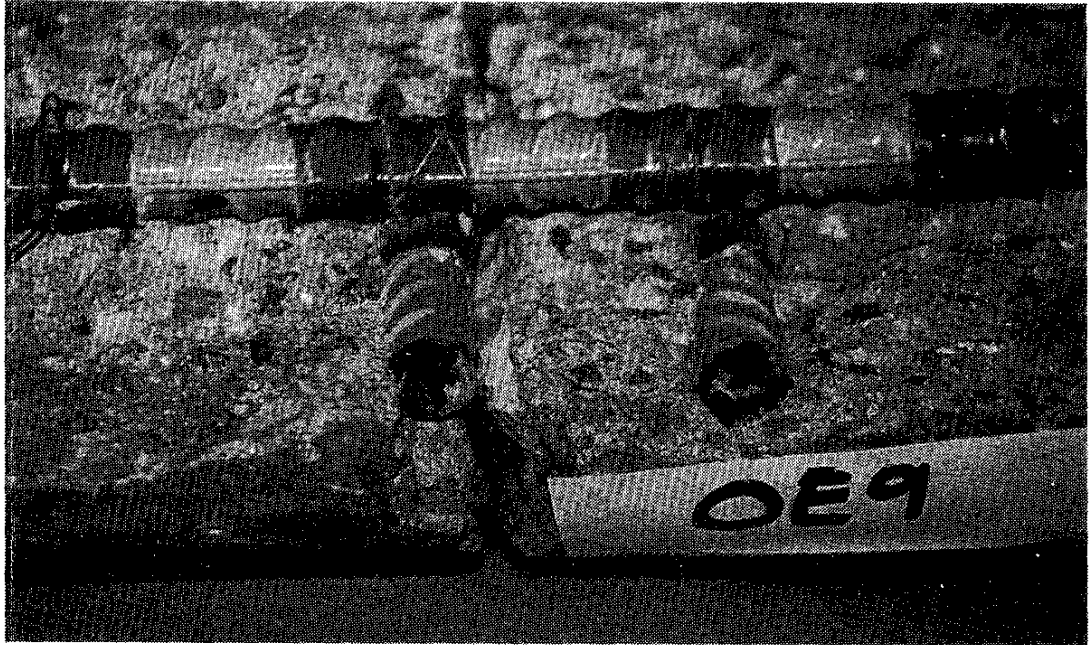


Plate 13: Sample OE9: Epoxy Coated - Wet and Dry - 132 Days.  
Corrosion at unrepaired ends of bars with covers of 16 mm  
and 22 mm.



Plate 14: Sample OE9: Epoxy Coated - Wet and Dry - 132 Days.  
Corrosion at unrepaired end of bar with 32 mm cover also  
showing localized attack along the bar away from cut edge.

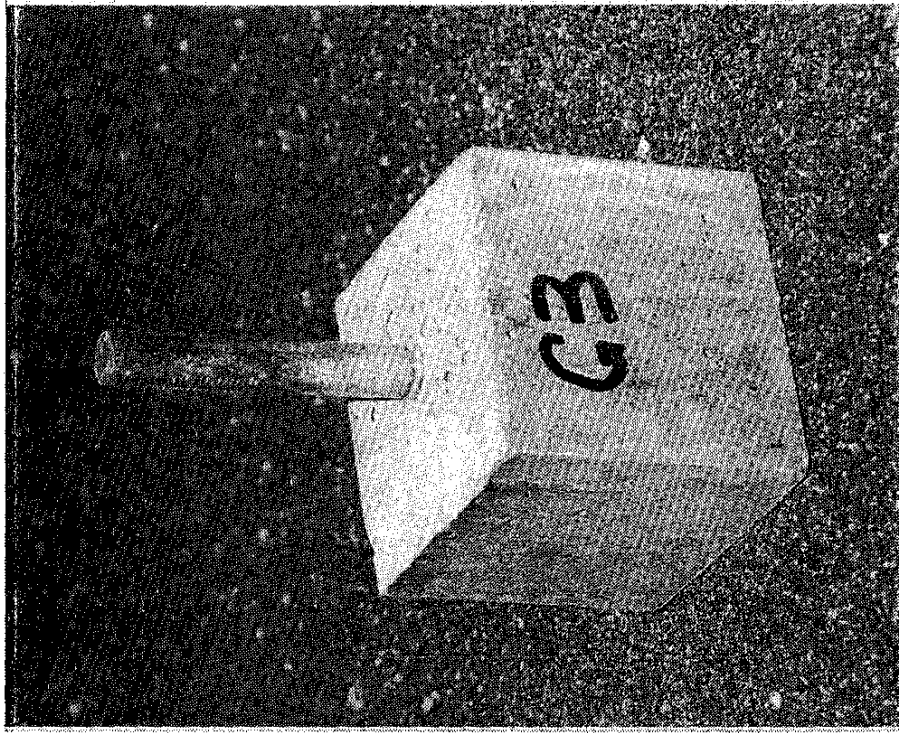


Plate 16: Slippage of bars in pullout testing with plain bars.

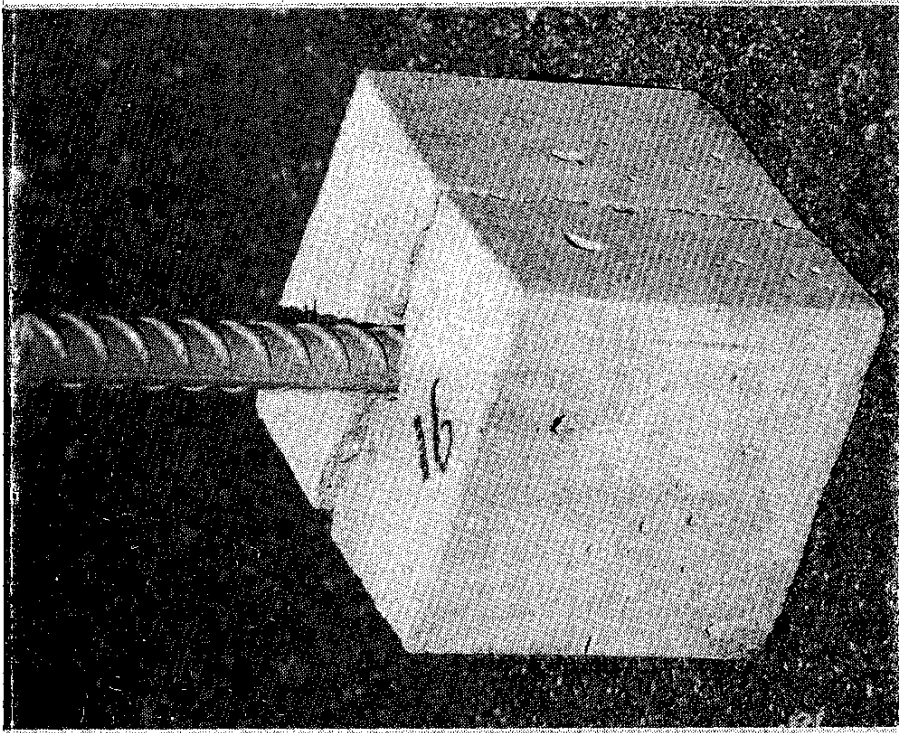


Plate 15: Splitting failure of pullout specimens with deformed bars.