THE EFFECT OF DEFECTS ON THE DURABILITY OF EPOXY-COATED REINFORCEMENT

Malcolm McKenzie*

The effect of defects in commercially produced UK epoxy-coated reinforcement is being assessed using concrete test specimens. Conditions being studied include uncoated ends, repaired ends, holes in the coating, and bent bars. The experiment involves both salt ponded specimens and specimens with salt added to the concrete mix. Corrosion currents are being measured between bars connected with a resistor. After 2 years the experiment has shown that corrosion does spread from the defects under the epoxy coating in salt contaminated concrete. Corrosion was also detected beneath repaired coating and beneath the coating on bent bars. Corrosion of the epoxy-coated reinforcement was light surface rusting without loss in bar section, or peeling or blistering of the coating, and less than that of uncoated steel. Half-cell potential measurements on epoxy-coated reinforcement were more variable than on uncoated steel. Due to this variability, periodic readings should be made to detect significant changes in potential. Testing is continuing at the Transport Research Laboratory in the UK.

INTRODUCTION

The ingress of chlorides into bridge concrete can lead to corrosion of the reinforcement. One approach to preventing such corrosion is to coat the reinforcement with a fusion bonded layer of epoxy resin. This provides a continuous barrier with low permeability to oxygen, water and chloride ions. Tests (*1*) have shown that epoxy coatings on reinforcement can reduce the rate of deterioration of concrete specimens containing high levels of chloride. However, corrosion did develop at faults in the rebar coating.

In practice, there will be some defects in epoxy-coated bridge reinforcement, i.e., pinholes in the coating when it leaves the factory, and damage during transport to the site, placement of the reinforcement, and pouring and vibrating the concrete (*2*). Such damage should be repaired, but locating all of the faults is difficult and very time consuming. The after-production cut-ends and damaged areas are coated with repair-epoxy rather than the fusion bonded material. In addition, bent bars, although visually undamaged might have lower corrosion resistance than straight bars (*3*). The long term durability of structures employing epoxy-coated reinforcement will depend on the progress of corrosion at defects. If the number of defects is limited and corrosion does not spread beneath the coating, then long term performance should be possible.

The Transport Research Laboratory (TRL) in the United Kingdom (UK) set up an exposure test to study the effect of defects and potential areas of reduced corrosion resistance on the performance of epoxy-coated reinforcement. The factors considered were repaired and unrepaired coating damage, and bent bars. The corrosion performance of epoxy-coated reinforcement with such defects was compared with uncoated reinforcement using test specimens exposed in an outdoor rural environment. To encourage corrosion salt was added to the concrete mix during casting of some specimens. Others were ponded with salt solution after exposure. The epoxy-coated reinforcement used was produced commercially and in compliance with the recently developed British Standard (*4*). Although epoxy-coated reinforcement has been used in bridges in North America since 1973, it has seen little use so far in bridges in the UK. The first UK manufacturer commenced production in 1987 which encouraged the development of the British Standard.

This report deals with the results after the first 2 years of the exposure tests. Additional specimens remain on exposure for future examination.

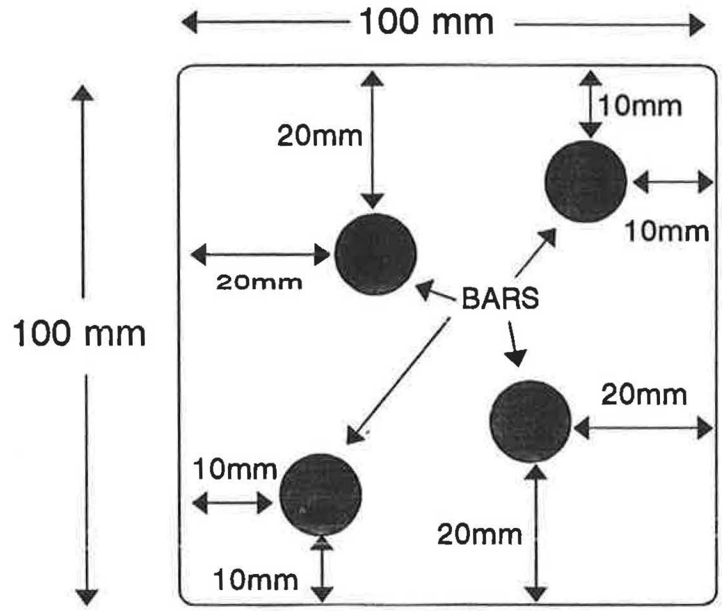
EXPOSURE TESTS

Concrete Test Specimens

Two shapes of concrete test specimen were used - beams and slabs, see Figure 1. The beam samples were for visual assessment of performance and the slab specimens to allow for electrochemical measurements, such as half-cell potential and galvanic currents. The concrete mix used for all specimens consisted of 330 kg (728 lbs) of Portland Cement, 980 kg (2,161 lbs) of Thames Valley Aggregate and 802 kg (1,768 lbs) of medium sand. The water/cement ratio was 0.58. The mean 28 day cube strength was 42 MPa (6,100 psi). Chloride additions,

* Malcolm McKenzie, Bridge Division, Transport Research Laboratory, Old Wokingham Road, Crowthorne, Berkshire RG11 6AU, United Kingdom, TEL: +0344-773131, FAX: +0344-770356.

CROSS SECTION OF BEAM



PLAN VIEW OF SLAB

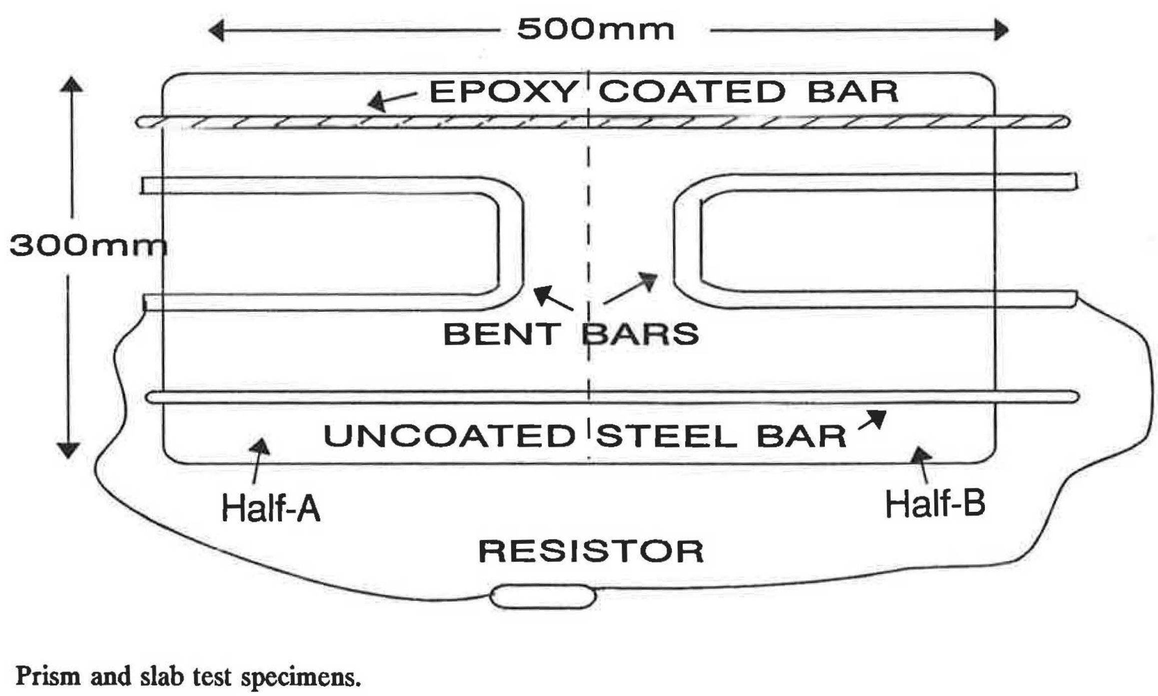


Figure 1 Prism and slab test specimens.

where made, were 3.2% by weight of cement. All the epoxy-coated reinforcement was commercially produced in the UK.

Beam specimens. Each concrete beam was 400 x 100 x 100 mm (15.75 x 3.93 x 3.93 in) and contained four 10 mm (0.39 in) diameter reinforcing bars. The bars were positioned and electrically isolated using plastic spacers with two bars having a minimum of 10 mm (0.39 in) cover and two bars having 20 mm (0.79 in) cover. Bars in a given beam were either epoxy-coated or uncoated. Where bars were epoxy-coated, one bar at each cover depth was damaged at four specific positions using an Ericsohn Paint Borer to make a small hole of about 1 mm (0.04 in) diameter in the coating. In addition, one of the cut-ends of the epoxy bar was left bare. The other bar of each pair was embedded with both cut-ends coated with standard twin pack epoxy repair material supplied by the coating manufacturer. Sets of beam specimens were cast both with and without salt added to the concrete mix. The numbers of each type of specimen are given in Table I.

Slab specimens. Each slab specimen was 500 x 300 x 60 mm (19.69 x 11.81 x 2.36 in) and contained one straight epoxy-coated bar, one straight uncoated bar, and two bent bars either coated, uncoated or one of each. The minimum concrete cover was 20 mm (0.79 in). Some specimens had salt added to the concrete mix. Others were cast in two halves so one of the bent bars was in chloride contaminated concrete while the other was in chloride free concrete. A lip was cast in the top of all the slab specimens to allow half of some initially chloride free slabs to be ponded with salt solution. The number of specimens for each combination of bent bar, cast-in chloride or ponded chloride is given in Table II. All bars protruded from the edge of the specimens for electrochemical measurement connections. The protruding sections of bar and the concrete edges were coated to prevent corrosion of the exposed steel. The bent bars within each specimen were permanently connected through an external resistor, see Figure 1. Any current flow that developed between the two bars could be measured from the potential drop across the resistor. The resistors used varied between 0.1 and 10k Ω (Ohms) and were chosen to be low when compared with the internal resistance of the galvanic cell created by combining the two bent bars.

Table I NUMBER OF BEAM SPECIMENS FOR EACH CHLORIDE CONTENT AND BAR TYPE

Chloride Content, % (Cl^- by weight cement)	Number of Specimens	
	Uncoated Bars	Coated Bars
0	10	10
3.2	10	20

Exposure Conditions and Routine Monitoring

Both beam and slab specimens were placed outdoors at TRL, a rural site in Southern England with low levels of atmospheric sulphur compounds and chlorides. Half-A of four out of the original five slab specimens from each chloride free set were ponded with a 3% solution of sodium chloride weekly. The salt solution was contained on Half-A of each specimen by a ponding lip. No attempt was made to maintain the chloride solution on the surface during the week. Depending on the weather conditions the solution evaporated leaving salt crystals on the surface or was diluted by rain. Water present in the ponding depression was removed before the chloride solution was poured in each week. Slab specimens with cast-in chlorides and the beam specimens were not ponded with chloride solution.

Both slab and beam specimens were visually inspected every three months for signs of cracking and rust staining. On the slab specimens, measurements of half-cell potential were made on the straight bars using a silver/silver chloride reference cell positioned over Half-A (the chloride contaminated or ponded section). Current flow between the bent bars was also measured.

Destructive Examination

At 1 and 2 years, some beam and slab specimens from each of the individual sets were opened and the reinforcing bars removed for detailed examination. Ten beam specimens (four from the set with epoxy coatings and cast-in chloride and two from each of the other three combinations, see Table I) were destructively examined along with one slab specimen from each of the sets given in Table II. The bars were examined for the type and extent of corrosion present. In some cases the epoxy coating was stripped from sections of the bar to check for underfilm corrosion. Stripping was carried out either mechanically or by soaking the bars in methylene chloride.

Table II NUMBER OF SLAB SPECIMENS FOR EACH COMBINATION OF CHLORIDE CONTENT AND BENT BAR COMBINATION

Location of Cast-In Chloride[a]	Number of Specimens For Each Bent Bar Combination (combination shown as Half A - Half B)			
	Epoxy-Epoxy	Steel-Steel	Epoxy-Steel	Steel-Epoxy
None[b]	5	5	5	5
Half-A	5	5	5	5
Both Half- A & B	5	5	5	-

[a] 3.2% by weight of cement.
[b] Four specimens from each set were ponded with salt solution on Half-A, see Figure 1.

RESULTS

Cracking and Rust Staining

During the first two years outward signs of deterioration on the beams containing epoxy-coated reinforcement were apparent on only one chloride contaminated specimen with a single fine crack and minor rust staining. In contrast, the chloride contaminated beam specimens with uncoated bar rapidly developed rust staining and significant levels of cracking. After one year, this was apparent above bars with 10 mm (0.39 in) cover and after two years was present above bars with 20 mm (0.79 in) cover. At two years, all 10 specimens with cast-in chloride were showing rust staining and fine cracking. More extensive cracking was present in six of these specimens. After two years, there was very little outward sign of deterioration on any of the beams containing uncoated bar without chloride in the mix.

For the slab specimens rust staining and cracking developed above some uncoated steel in specimens with cast-in chloride within one year. No staining or cracking was apparent above the epoxy-coated steel during the first two years.

Electrical Measurements On Slab Specimens

Half-cell potential measurements on chloride free slabs were between +50 mV and -300 mV (Ag/AgCl reference cell) for both coated and uncoated bars. On slabs with cast-in chloride, potentials were more negative for uncoated bars and showed wide variation with time for coated bars. For slabs ponded with chloride, potentials of both coated and uncoated straight bars became more negative as time passed but, as in the specimens with cast-in chloride, there was more variation in the potentials measured on the coated bars. Typical results from single slabs are shown in Figure 2.

Current measurements between the connected bent bars were made at three month intervals. Current was termed positive if the direction of flow agreed with expectations, i.e., if the bar expected to act as the anode did so. The largest currents were found in uncoated-uncoated bar combinations where only one bar was in chloride contaminated concrete. Where both bars were in chloride contaminated concrete currents were lower and in some cases changed direction as time passed. For coated bars where the coated bar was acting as the anode, the highest currents were measured for coated-uncoated bar combinations where the coated bar was in chloride contaminated concrete and the uncoated bar was in chloride free concrete. However, the magnitude of the current was lower than for the equivalent uncoated-uncoated combination. Average currents for all slabs in the uncoated-uncoated and coated-uncoated sets with cast-in chloride in one side only are shown in Figure 3. The maximum current measured for coated-uncoated bar combinations was about 1 µA, some 50 times lower than the maximum measured on uncoated-uncoated bar combinations.

Condition of the Reinforcement from Visual Inspection Before Removing the Epoxy Coating

Beam specimens. After removing the bars from the concrete, the extent of visible corrosion was assessed. Only the bars from the chloride contaminated beams showed signs of significant corrosion. At one year, up to 10% of the bar surface was corroded for uncoated bars with both 10 mm (0.39 in) and 20 mm (0.79 in) cover. At two years, the area of corrosion had increased for the 10 mm (0.39 in) cover bars, see Figure 4.

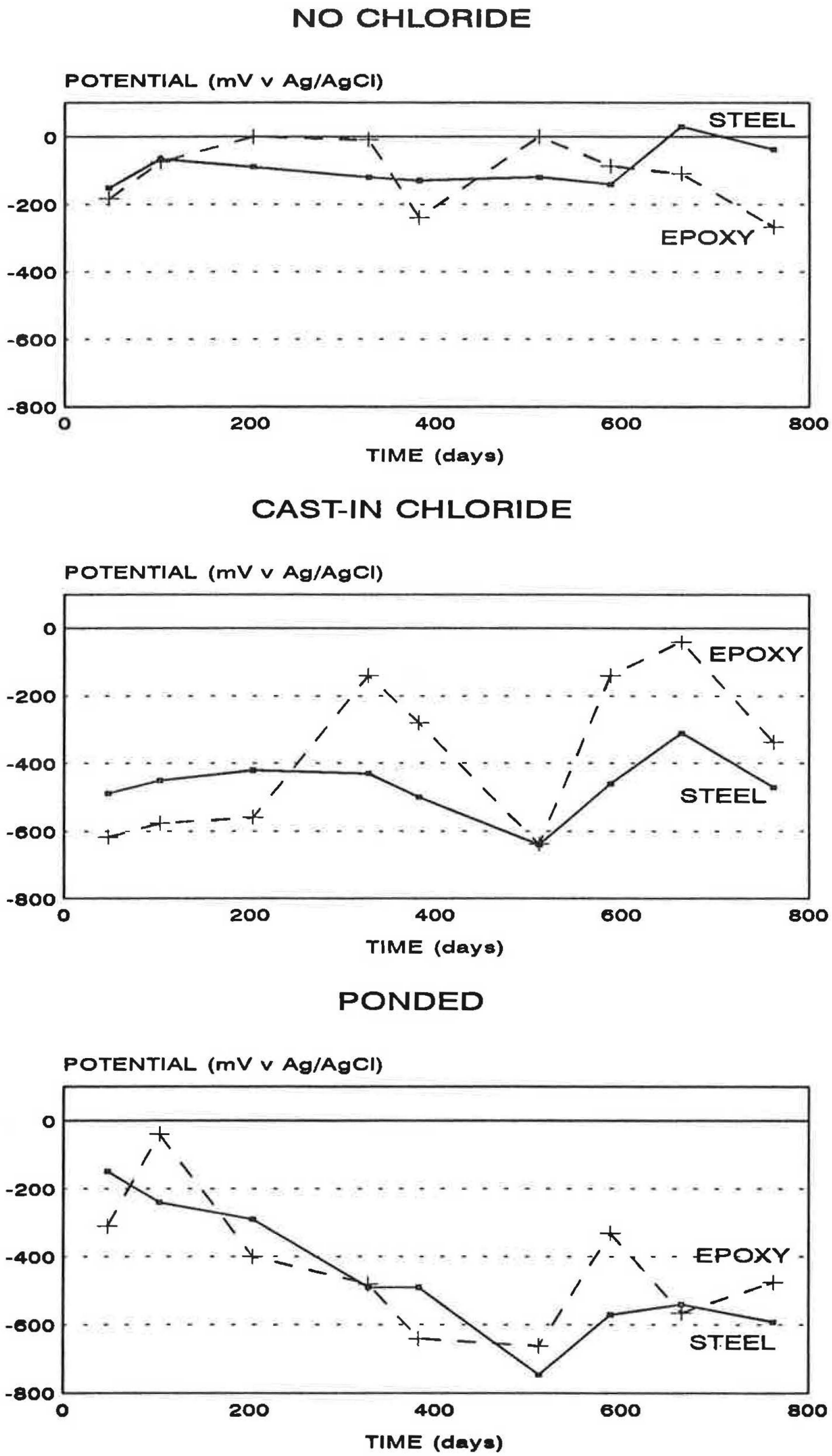


Figure 2 Typical half cell potential measurements on single slab specimens.

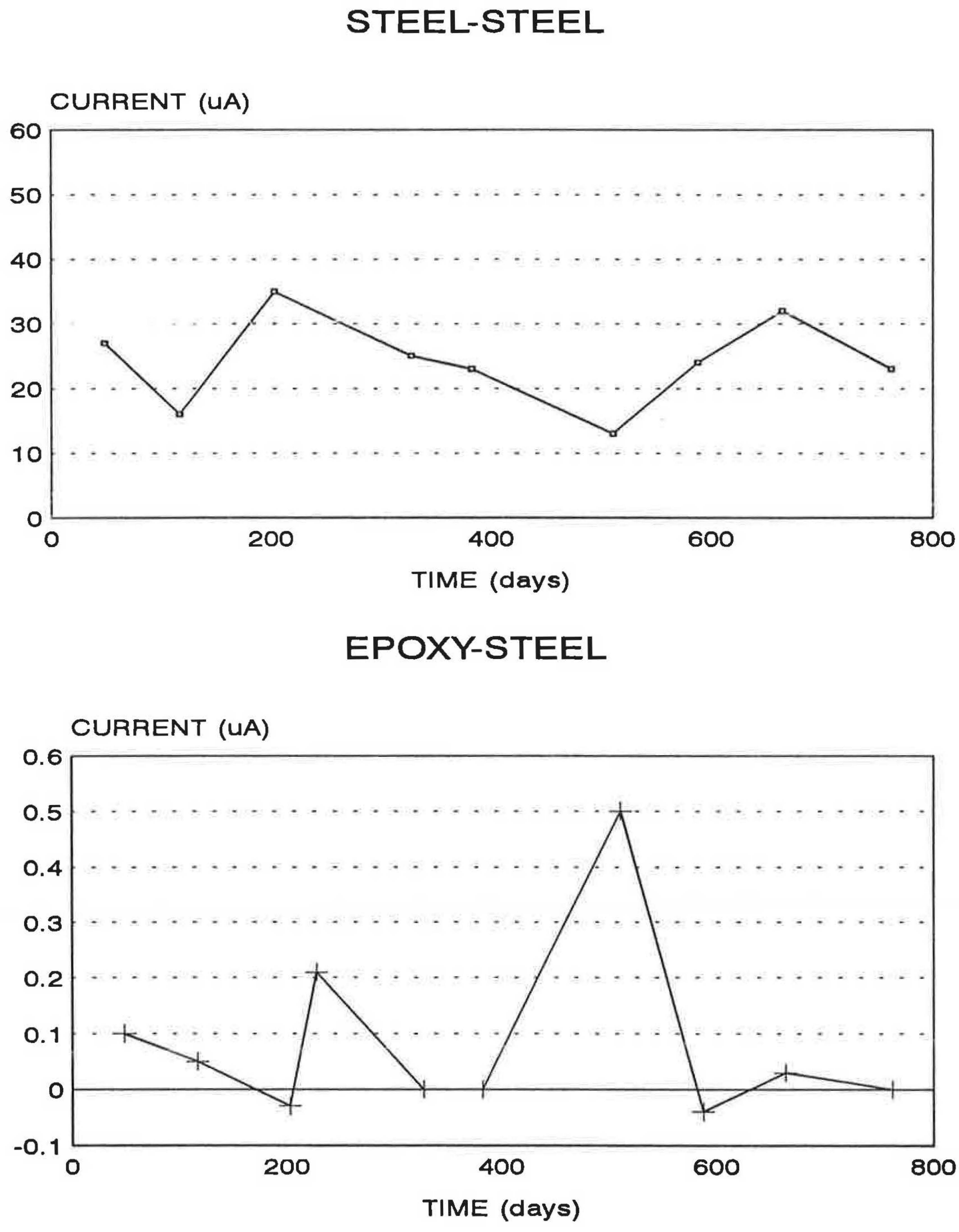


Figure 3 Average corrosion current measured between bent bars in slab specimens containing cast-in chloride in one side only. [First named bar is in the chloride side].

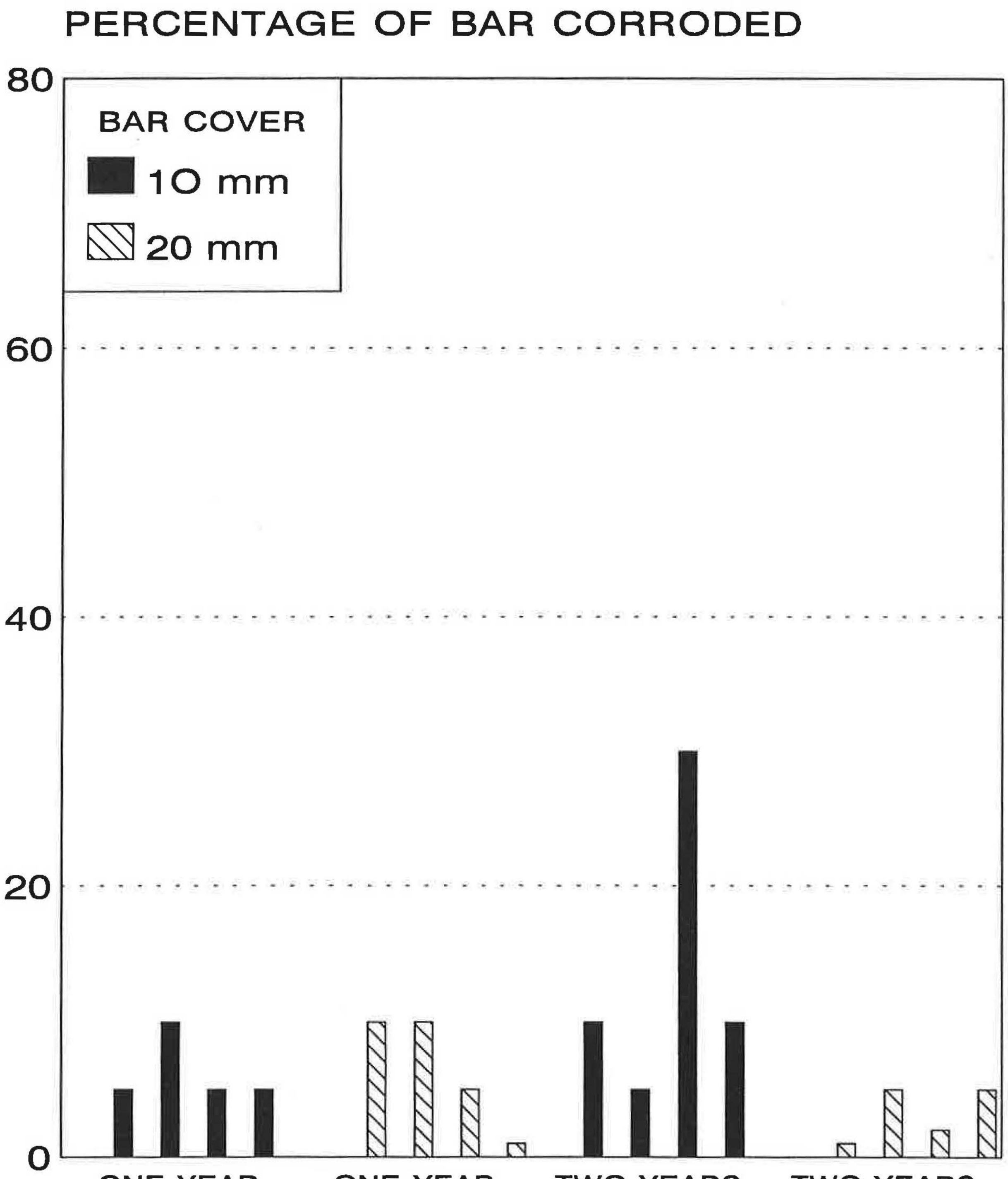


Figure 4 Percentage of surface corroded for uncoated bars removed from chloride contaminated beam specimens after one and two years exposure.

Epoxy-coated bars showed little sign of corrosion. There was rust spotting at some introduced holes after one year and after two years rust spotting at other positions was visible. However, this was all very slight and the unrepaired cut-ends remained rust free.

Slab specimens. The straight epoxy-coated bars used in the slab specimens were all visually undamaged when cast into the concrete. On removal after one and two years they appeared to have undergone very little deterioration. The maximum area of bar corroded was about 1% and this was found on only two of the 11 bars examined each year. The corrosion was light surface rusting with no loss in section of the bars. The uncoated bars however showed extensive corrosion, 50% of the bar in one case, see Figure 5.

The bent epoxy-coated bars were visually in good condition with no signs of corrosion after one year. Uncoated bent bars had up to 70% of the bar corroded after the same period, see Figure 6. After two years, four coated bars showed signs of corrosion over 1 to 2% of the bar. Uncoated bars showed higher levels of corrosion, see Figure 7. In some cases uncoated bent bars in non-chloride zones in the ponded and half chloride specimens had corroded. This might have resulted from diffusion of the chloride from the ponded or chloride half. The level of corrosion found on uncoated bars was more severe than on coated bar with noticeable loss in section in some bars.

Examination Of Epoxy-Coated Bars after Removal of the Coating

The epoxy coating was removed from around both repaired and unrepaired cut-ends on some epoxy-coated bars extracted from the beam specimens after two years. A scalpel blade was used to remove the coating. Although there was no visible signs of corrosion before the coating was removed, corrosion was found beneath one repaired cut-end. Underfilm corrosion was also found in regions adjacent to unrepaired cut-ends. Crevice corrosion was taking place with the uncoated cut-end acting as a cathode in the corrosion cell. In one case the corrosion had spread some 15 mm (0.59 in) from the cut-end. The corrosion consisted of light surface rust with no loss in bar section.

To enable more of bar to be examined chemical stripping of the epoxy coating was carried out on a selection of bars from both beam and slab specimens. This was done by soaking the bars overnight in methylene chloride. On straight bars with signs of corrosion at defects, underfilm corrosion was spreading from the defects. The extent of the spread was small - only a few millimeters (0.08 in) - and formed a light surface rust coating with no loss in bar section. There was an area of corrosion on a bent bar where there had been little sign of corrosion before the coating was removed. The corrosion covered some 15% of the bar surface, similar to that found on some uncoated bars. However, the corrosion beneath the coating was light surface rusting only.

Only a few bars were examined at this stage of the experiment and it is not appropriate to identify the underfilm corrosion as significant. More detailed assessments need to be conducted at the next destructive examination.

DISCUSSION

The main objective of this experiment was to assess the effect of defects on the corrosion performance of epoxy-coated reinforcement. The results have shown that corrosion starting at defects in the coating can spread beneath the epoxy coating. Corrosion can be active beneath repaired coating and beneath visually undamaged coating. It must be emphasized that the severity of such corrosion was much less than that found on uncoated bar. The underfilm corrosion was light surface rusting with no loss in section of the reinforcing bar while corrosion on the uncoated bar had led to loss in bar section. The measurements of corrosion current indicate that the rate of underfilm corrosion over the first 2 years was low and there was no peeling or blistering of the epoxy coating.

The results obtained to date highlight some difficulties in assessing the performance of epoxy-coated reinforcement. Concrete specimens containing epoxy-coated reinforcement have shown less cracking than those containing uncoated bars, and corrosion on the coated bars has been less severe than on uncoated bar. Epoxy-coated reinforcement can reduce the deterioration caused by corrosion in chloride contaminated concrete. However, will the low rate of corrosion continue as time passes? Future destructive examinations of the specimens should provide the answer. If the coating debonds, the corrosion rate might rise to the levels found on uncoated bar. The consequences of this will depend on the extent of the disbondment and how this influenced the serviceability and strength of the structure.

The question also arises as to how the extent and severity of corrosion in epoxy-coated reinforcement can be detected in in-service structures since corrosion is initially likely to be localized without signs of stain, cracking or spalling. Half-cell potential mapping is one

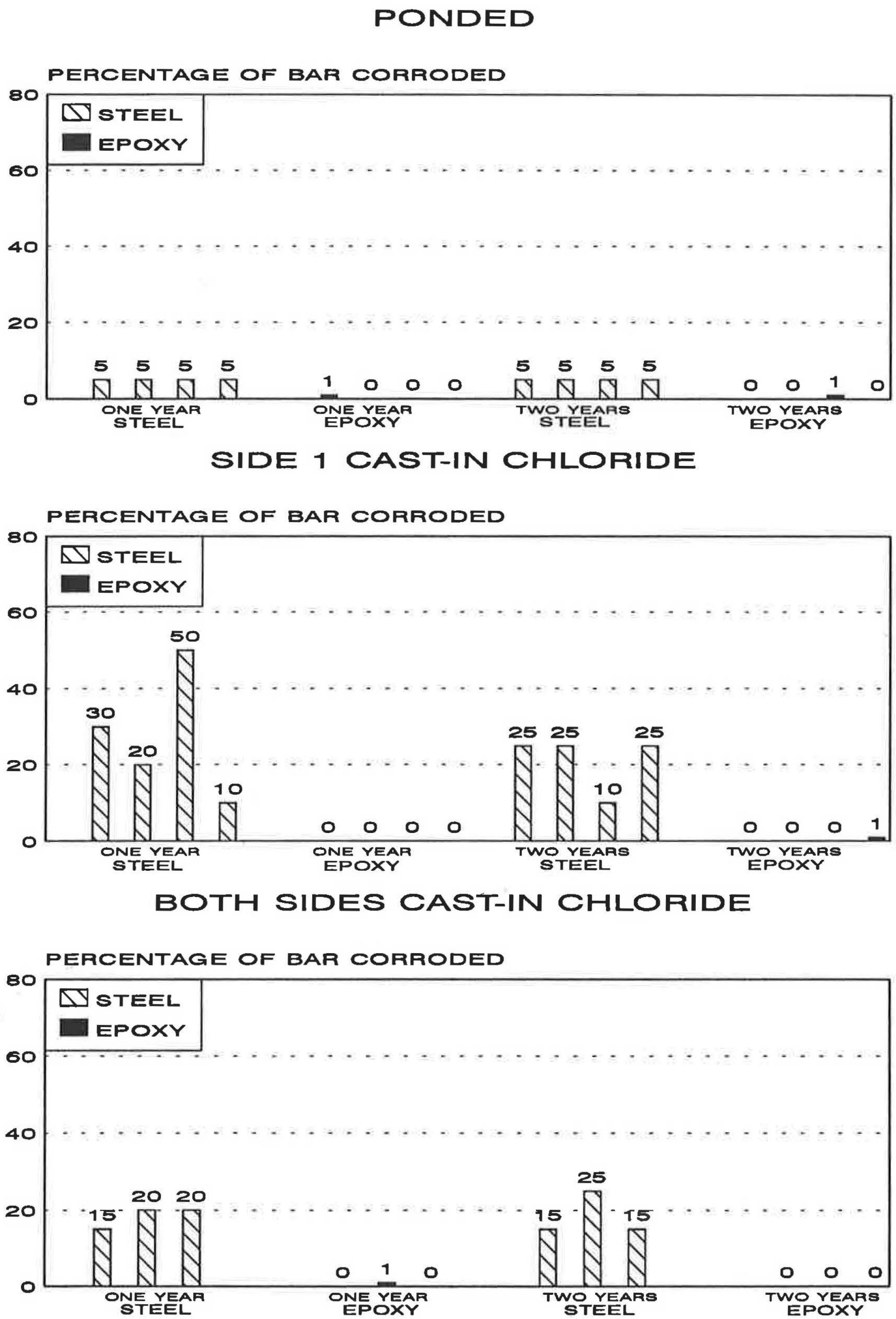


Figure 5 Percentage of surface corroded for straight bars removed from slab specimens after one and two years. [Numbers within each figure show the actual value].

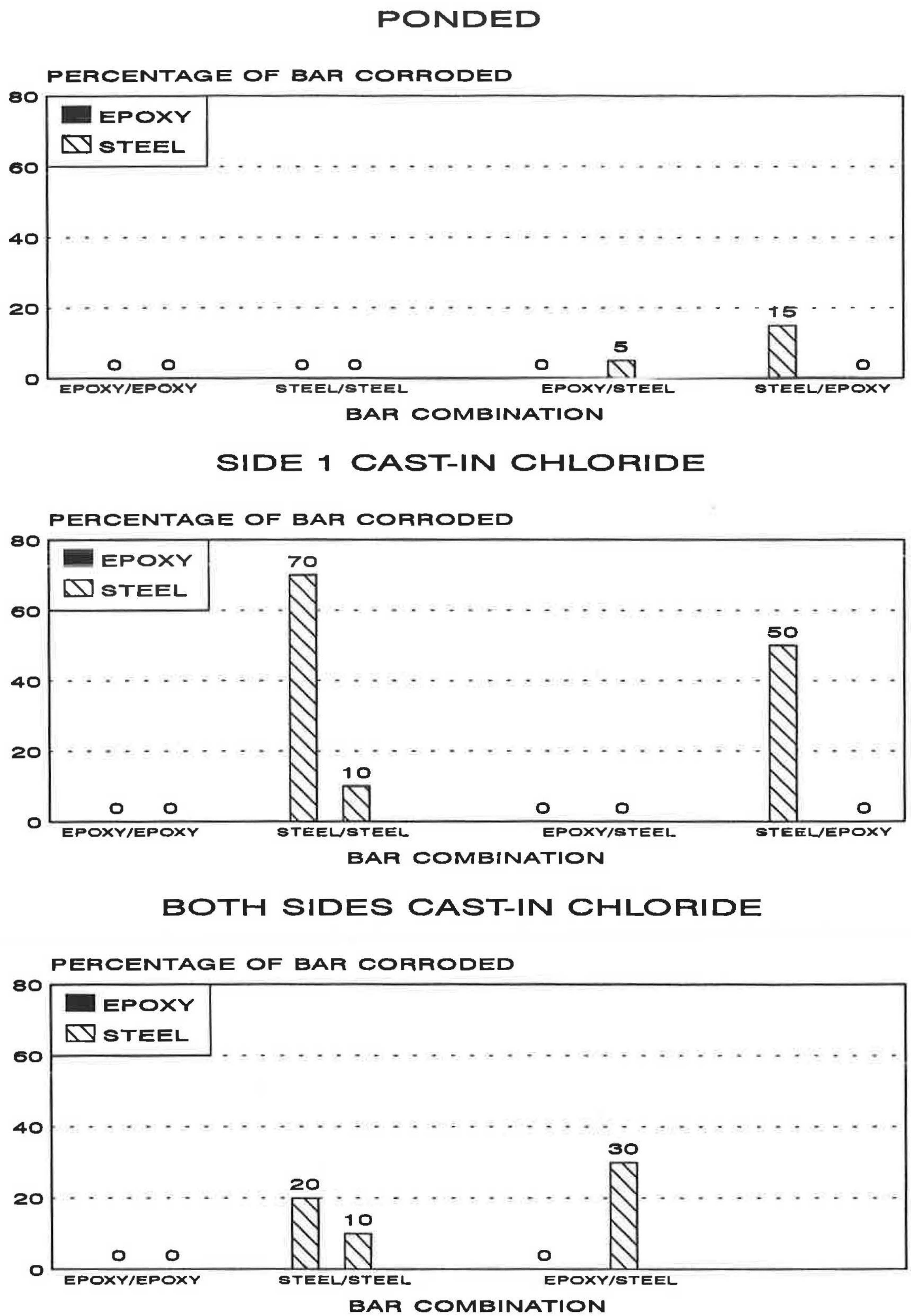


Figure 6 Percentage of surface corroded on bent bars removed from slab specimens after one year. [Where appropriate, the first named bar of the combination was in the chloride side].

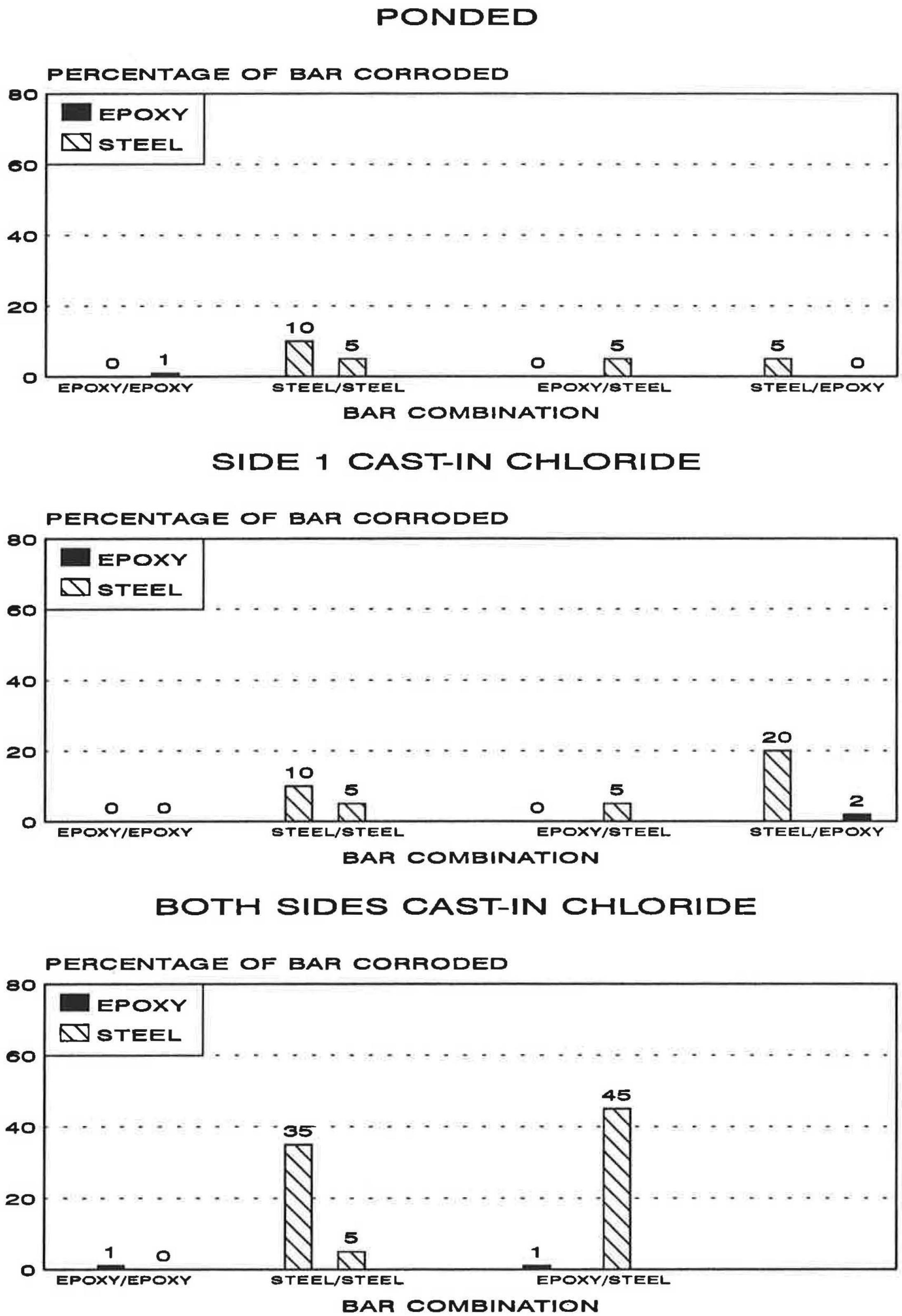


Figure 7 Percentage of surface corroded on bent bars removed from slab specimens after two years. [Where appropriate, the first named bar of the combination was in the chloride side].

of the standard methods of testing in-situ reinforcement for early signs of corrosion. There are practical difficulties in using this technique on epoxy-coated reinforcement because a separate electrical connection needs to be made to each bar of interest. For in-service structures, it is worth considering making electrical connections to bars in critical areas during construction to facilitate the use of this or other electrical techniques. Measurements of half-cell potential made during this test showed that results on epoxy-coated reinforcement can be more variable than on uncoated steel. This makes interpretation difficult from a single set of measurements. If this technique is to be used, it is necessary to conduct periodic surveys to detect significant changes in potential.

CONCLUSIONS

The extent of concrete cracking and the severity of reinforcement corrosion were reduced for epoxy-coated reinforcement in chloride contaminated test specimens in comparison with specimens containing uncoated reinforcement over a two year period. However, corrosion did spread under the coating from defects in the epoxy. Corrosion was also detected beneath repaired coating and beneath the coating on bent bars. The corrosion found beneath the epoxy coating was light surface rusting without loss in bar section, or peeling or blistering of the coating. During the same period, there was noticeable loss in bar section due to corrosion of the uncoated bar. Half-cell potential measurements on epoxy-coated reinforcement were more variable than on uncoated steel.

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