SELECTION AND PERFORMANCE EVALUATION OF CATHODIC PROTECTION SYSTEMS FOR REINFORCED CONCRETE PARKING STRUCTURES

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INTRODUCTION

The possibility that cathodic protection (CP) could successfully reduce corrosion on reinforced concrete structures exposed to the atmosphere was postulated by Finley [1] in 1961 and later attempted on bridge decks by Stratfull [2] and Fromm [3] during the 1970's. Much of the research work into the types and operating characteristics of CP systems has been funded by the U.S. Federal Highways Administration which as a result issued a memorandum on December 31, 1981 that concluded "Research and field experiences with cathodic protection (CP) on the other hand, show that corrosion damage can be halted regardless of the salt content of the concrete".[4] Although bridge structures are particularily susceptible to corrosion arising from the combined presence of air, moisture and chlorides from de–icing salts so also are reinforced concrete parking facilities. The earliest developed CP systems used a conductive asphalt overlay electronically connected to high silicon iron anodes but this type of system is not feasible for parking structures because of the inability of the parking reinforced structural slabs to support the substantial weight of the overlay.

As CP is probably the most cost effective corrosion control option for existing facilities, a number of alternative systems have been developed over the last decade which now make CP systems routinely applicable to parking structures. Presently it is estimated in Canada alone that CP has been applied to over 500 thousand square meters of reinforced concrete parking decks. Most of these systems have utilized a conductive coating applied to the soffit as the primary anode instead of the overlay on the top surface. Other systems, applied to the top surface have utilized anode materials such as conductive polymer cable, and rare metal oxide coated titanium in a mesh configuration or platinum clad niobium wires implanted in sawed slots surrounded by a conductive grout. Regardless, before CP is applied to a reinforced concrete parking structure several factors must be considered.

ELECTRICAL CONTINUITY

The electrical continuity of embedded metallic components in a reinforced concrete structure, must be assured before CP is applied. This is usually determined by an electrical continuity test which involves measuring and comparing the potential difference between the various steel components and a reference electrode placed at a fixed location. Should any component potential vary ±5mV compared to the steel potential recorded at the stationary reference electrode location then an electrical discontinuity is suspected. Potentials on a representative sample of all metallic components such as top and bottom reinforcing steel, drains, electrical conduit and expansion joints must be measured as shown in Figure 1. Typically for reinforced structural slabs

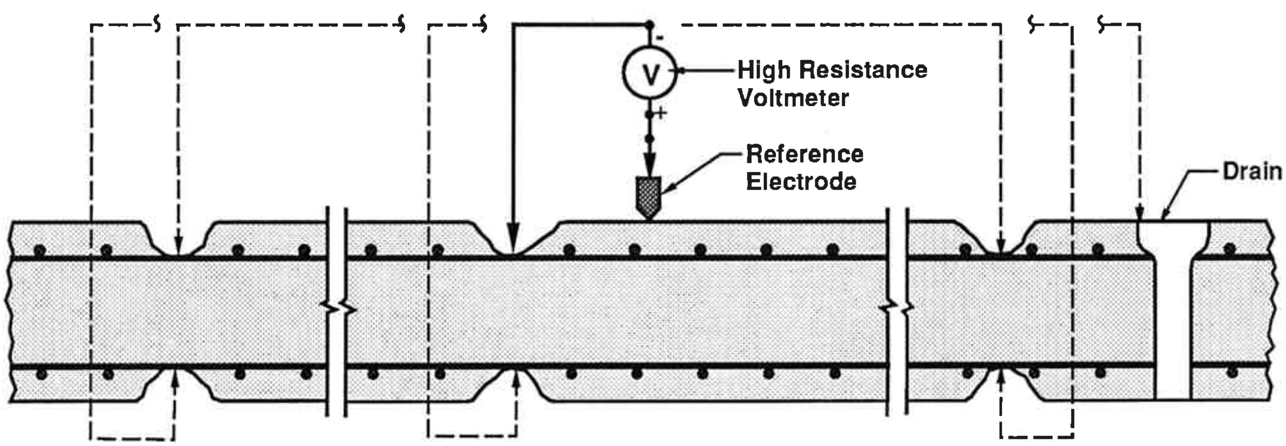


FIGURE 1

in parking structures both top and bottom reinforcing steel is exposed and contacted for measurement purposes at least once for every $100m^2$ of structure surface area. Review of structural drawings is indispensable procedure in determining which components and what locations are to be tested. Should there be doubt about the electrical continuity of any metallic component then a subsequent polarization continuity test must be conducted. This involves impressing a DC current onto the reinforcing steel at the reference electrode position in order to change the potential by polarization. After recording the new potential at the reference location the metallic component suspected of being discontinuous is then contacted. If the potential change differs by more than $\pm$5mV of the change at the reference electrode location then the component being tested by this method is considered to be electrically discontinuous.

Before CP can be installed permanently on a reinforced concrete structure, all components must be determined by measurement to be electrically interconnected or must be made continuous.

EMBRITTLEMENT

An operating CP system causes a reduction reaction to occur at the metal/concrete interface such as

$$2H_2O \rightarrow H_2\uparrow + 2OH^-$$

that results in the production of hydrogen which can produce structural embrittlement in some high strength steels. Post tensioned structures, where the tensioning steel strands have a martensitic crystal structure as opposed to a pearlitic crystal structure are particularly susceptible to embrittlement [5]. Most existing tensioned structures contain pearlite structural strands since it has been common practice to "lead patent" (eg. control cooling in liquid lead) the steel strands since World War II.

As a precaution when considering the protection of a post–tensioned or pre–stressed structure, a sample of the stressed member must be retrieved and analyzed metallographically to determine the type of crystal structure prior to proceeding with a CP design.

SYSTEM SELECTION

Existing parking decks can seldom support the added weight of a conductive asphalt overlay which has led to the development of numerous systems composed of lightweight anode materials.

CONDUCTIVE COATING

Conductive coatings were first evaluated as a means of introducing CP current into reinforced concrete by the U.S. Department of Transportation - Federal Highways Administration which tested several commercially available coatings in the early 80's [6,7].

Today there are several coating materials that have been used extensively. In all cases the conducting medium in the coating is graphite or carbon which must be added in large proportion to ensure that these particles touch in order to obtain electronic conduction. This high carbon loading makes the coating relatively porous and brittle and therefore unsuitable for application on the top side without a top wear coat to protect the conductive coating from damage by vehicular traffic. Accordingly, conductive coatings have been applied primarily to the soffit side as shown in Figure 2 where a wear coat is unnecessary.

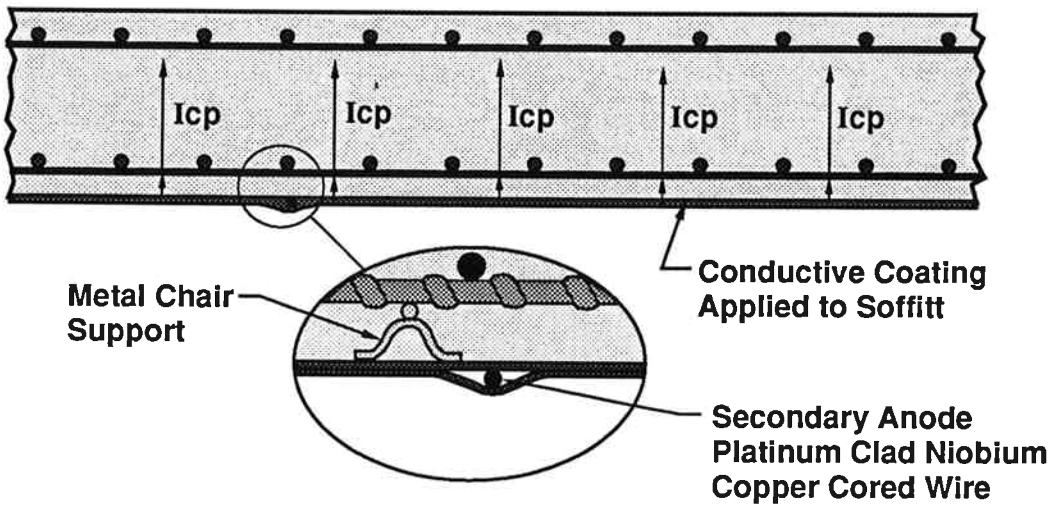


FIGURE 2 - SOFFIT SIDE CONDUCTIVE COATING CP SYSTEM

Although the carbonaceous material affords relatively good conductance, wires consisting of a copper cored, niobium and platinum composite are embedded in the coating to provide primary current distribution and to bridge cracks which may ultimately appear in the coating. These wires, typically positioned at 3m intervals, connect directly to the positive header cable.

Soffit conductive coating CP systems have some distinct advantages over top side and embedded anode systems as follows:

- delamination repairs on the top side are not required thereby delaying repair and restoration expenditures until actual spalling occurs.
- the anode being close to bottom reinforcing results in preferential elimination of any macro-corrosion cells involving the bottom steel functioning as a cathode with respect to the top side steel.
- least expensive of all CP systems
- provides better current distribution

There are two types of resins which are used as a vehicles for the graphite particles, namely solvent based acrylic and water based acrylic. The water based acrylics are more tolerant of high moisture content in the concrete whereas the solvent based acrylics are more resistant to acid attack. The latter feature is important in decks severely contaminated with chlorides since the following oxidation reaction at the coating/concrete interface often produces a localized acid condition and hypochorites which are strong oxidizers.

$$2H_2O + 2Cl^- \rightarrow 2OCl^- + 4H^+ + 4e^-$$

Acid production occurs readily if the curent density exceeds 100mA/m^2. Not only can the acid readily attack water based acrylic type coatings but it can also etch the concrete causing disbondment of the anode coating. This illustrates the most important of the disadvantages of the conductive coating CP system which are summarized below;

- Acid production at concrete/coating interface can cause concrete etching and coating disbondment.

- In buildings where the relative humidity falls below 50 or 60%, the surface of the concrete can dry out resulting in a high circuit resistance which compounded by electro-osmosis can severely limit the CP current density. Under these conditions some performance criteria cannot be achieved.

- Contact between the conductive coating and reinforcing steel chairs, normally used to raise the reinforcing steel from the bottom form, results in a CP system short circuit. (See Figure 2) Not only do the short circuits affect the functioning of the CP system but if they are not located and removed a galvanic corrosion cell can result between the reinforcing steel and the conductive coating that could accelerate rebar corrosion. Short detection and removal is a very difficult and time consuming procedure because of the typically high density of contacts that can range up to 30 per square meter. Furthermore, if only one short circuit contact remains, the effectiveness of the CP system will be significantly impaired.

Despite the limitations of soffit conductive coating systems they represent the vast majority of parking deck CP systems and continue to find favour, mainly because of their lower cost and the minimal facility disruption during installation.

LIGHTWEIGHT EMBEDDED ANODES

The development of lightweight anode materials in the late 70's and early 80's was coincident with a need to have a light, easily handled anode for embedding in reinforced concrete. These materials generally range from wires composed of platinum cladding over a passive metal substrate such as titanium, niobium and tantalum, carbon filled polymer over a stranded tinned copper conductor, and rare metal oxides of ruthenium and iridium coated on a titanium substrate. All these materials have been fabricated into mesh form to provide an expansive low profile anode material that can be placed within the concrete or on its surface. In the latter case a cementitious cover is applied over the mesh after it has been fastened to the concrete. This system is illustrated in Figure 3.

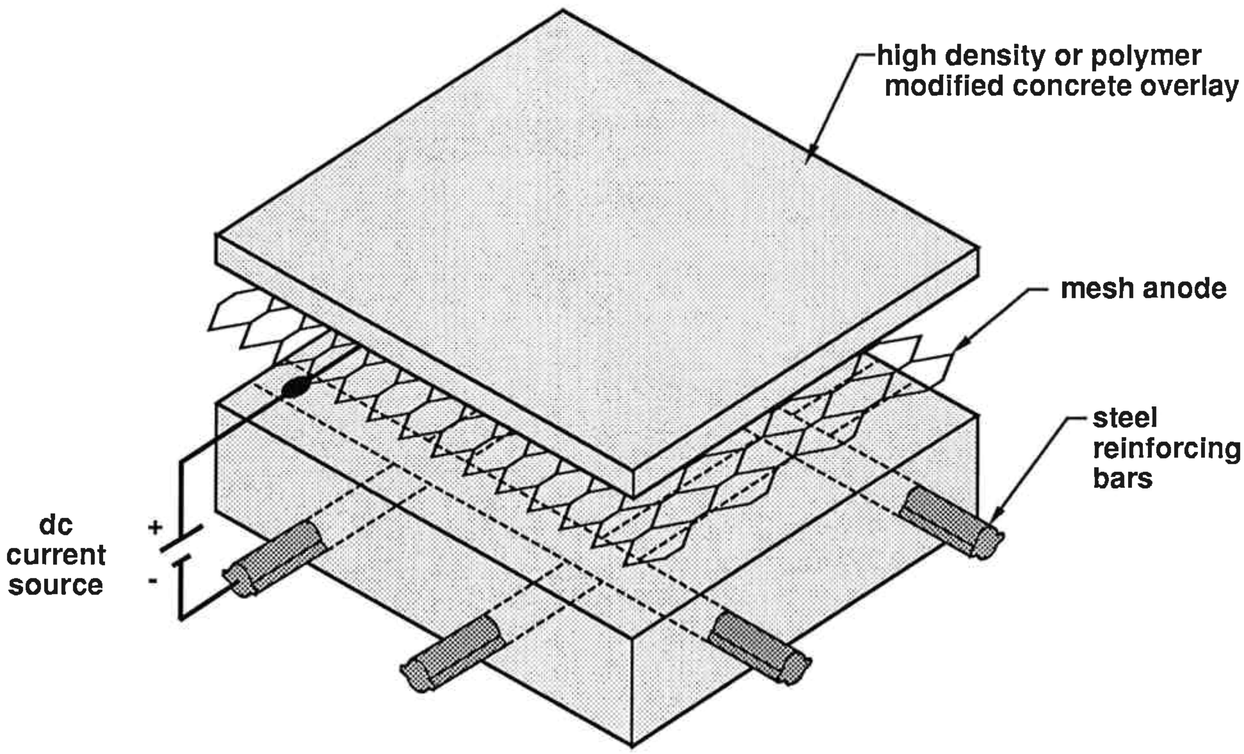
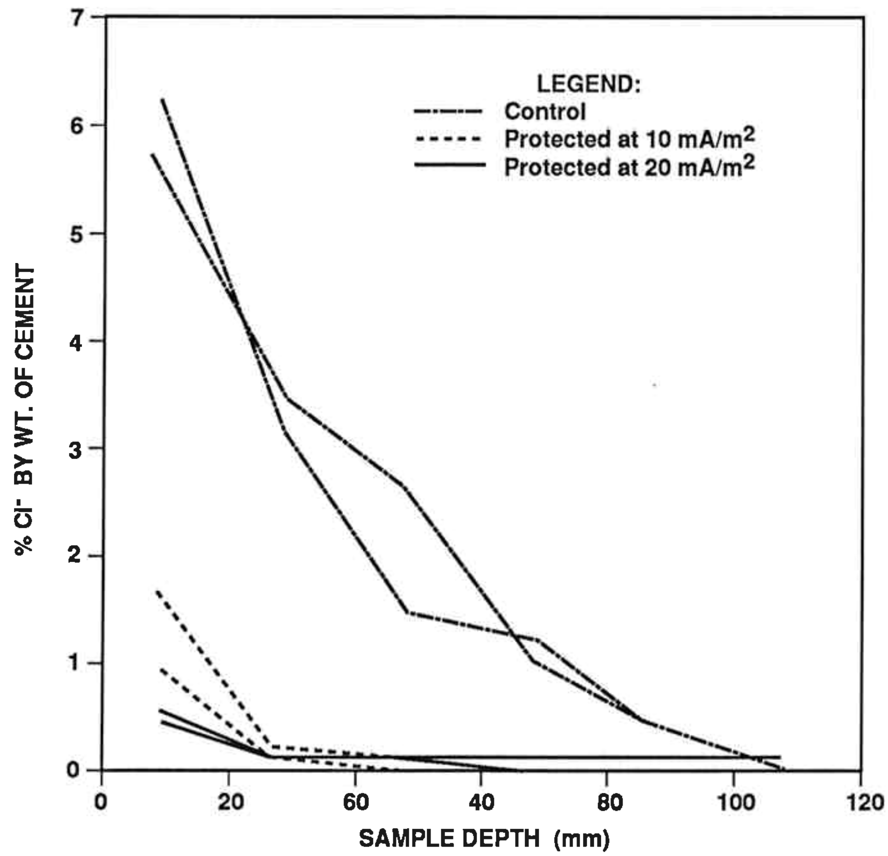


FIGURE 3 - TOP SURFACE MESH ANODE SYSTEM

The placement of these impressed current anode materials on the top surface has several advantages over the soffit conductive coating as follows:

- The possibility of a short between the anode and reinforcing steel is substantially reduced.
- The anode materials are more resistant to acid conditions and do not depend on the anode-to-concrete bond in order to continue to function.
- An operating top side system will retard chloride ion penetration as indicated in Figure 4.[8]



EFFECT OF CATHODIC PROTECTION ON THE PENETRATION OF CHLORIDE IONS INTO CONCRETE

FIGURE 4 - CHLORIDE PENETRATION WITH AND WITHOUT CP

- CP current will be distributed more evenly to the wet chloride contaminated areas than with a soffit system because most wetting occurs on the top surface. For this same reason the effect of building humidity changes will have less effect on the CP current output than with conductive coating systems applied to the soffit.

- All these anode materials have a longer CP anode performance history than conductive coatings.

With all the foregoing advantages, it may at first seem surprising that these anodes are not more often used in parking structures. The major disadvantage however is the most important one — price. It and a number of other disadvantages as follows has resulted in limited use:

- Owing to the high material cost and the need for a cementitious top coat, the total costs are typically double that for conductive coating systems. The high cost is further compounded by the practical necessity of repairing all top surface delaminations before installation.

- The anode surface area for most of these open mesh anodes is usually a fraction of the reinforcing steel surface area and when operating an average of 10mA/m^2 of concrete surface the current density on the anode surface will be several times greater which can produce a highly localized acid condition that will result in concrete deterioration at the anode.

- Unlike a conductive coating CP system the lightweight anode materials are not as easily repaired and if repairs are needed it usually results in traffic disruption.

Generally the use of lightweight anode meshes for embedding in the top surface can only be justified when it has been decided that a substantial depth of concrete must be removed from the surface during restoration. When this is done the choice of this type of system is the best option.

OPERATING CHARACTERISTICS AND PERFORMANCE EVALUATION

There is no currently available published standard by which to judge the performance of reinforcing steel CP systems. NACE technical committee T-3K-2 has however approved a standard for publication.[9] Unfortunately, the criteria contained in the NACE document differs from that of the British Joint Venture Committee E4–9.[10] Herein lies a major difficulty in consensus seeking since comparable groups of interested industry representatives do not fully agree on criteria. Fortunately there are several research studies that are investigating many of the proposed criteria which will no doubt clarify this situation.

Presently, the only criterion that practitioners seem even close to agreement on, is the -100mV potential shift. To satisfy this value a minimum of 100mV of cathodic polarization must be achieved on the reinforcing steel surface. Normally the degree of polarization is determined by measuring with respect to a surface mounted reference electrode as indicated in Figure 5 imme-

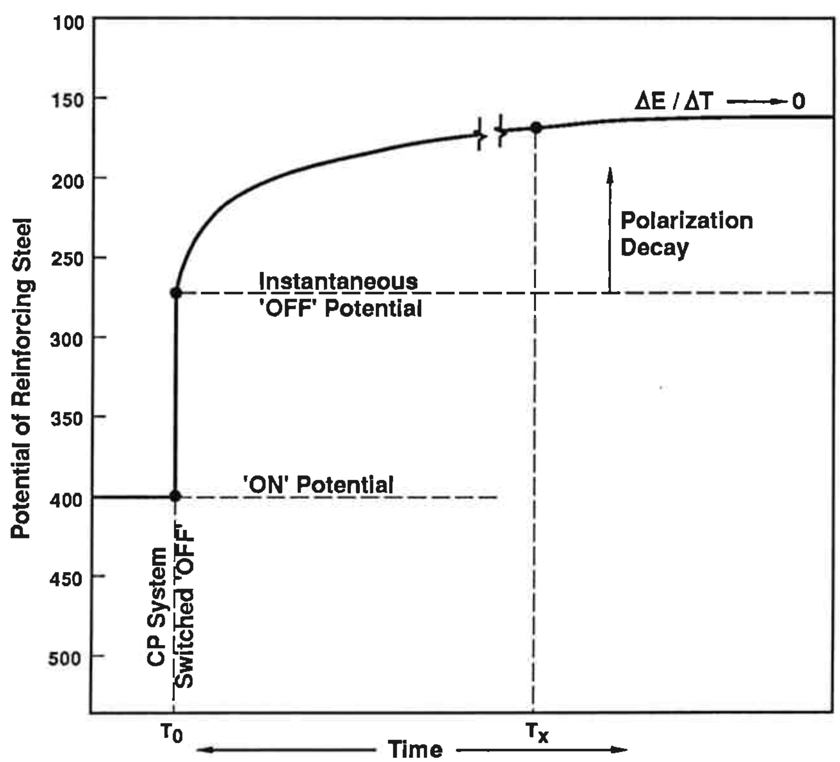


FIGURE 5

diately after the CP current is turned off and comparing this potential to the potential after the polarization has decayed for 4 hours or until the change in potential with time approaches zero.

Quite often 100mV of polarization can be difficult or impossible to obtain which in some cirumstances is not particularily serious. For instance, where the decayed-off potential is more positive than -350mV/CSE then according to ASTM Standard C-876 [11] it is unlikely that the steel is actively corroding. Accordingly a minimum -100mV potential shift would only seem to be important when the decayed–off potential is more electronegative than -350mV/CSE.

A further complication in evaluating system performance using a potential shift criterion arises from the depletion of Cl^- ion concentration as a result of the continued application of CP current. It has been shown [12] that reinforcing steel potentials are affected by Cl^- concentration as illustrated in Figure 6. Here it can be seen that the steel reinforcing potential becomes more electro

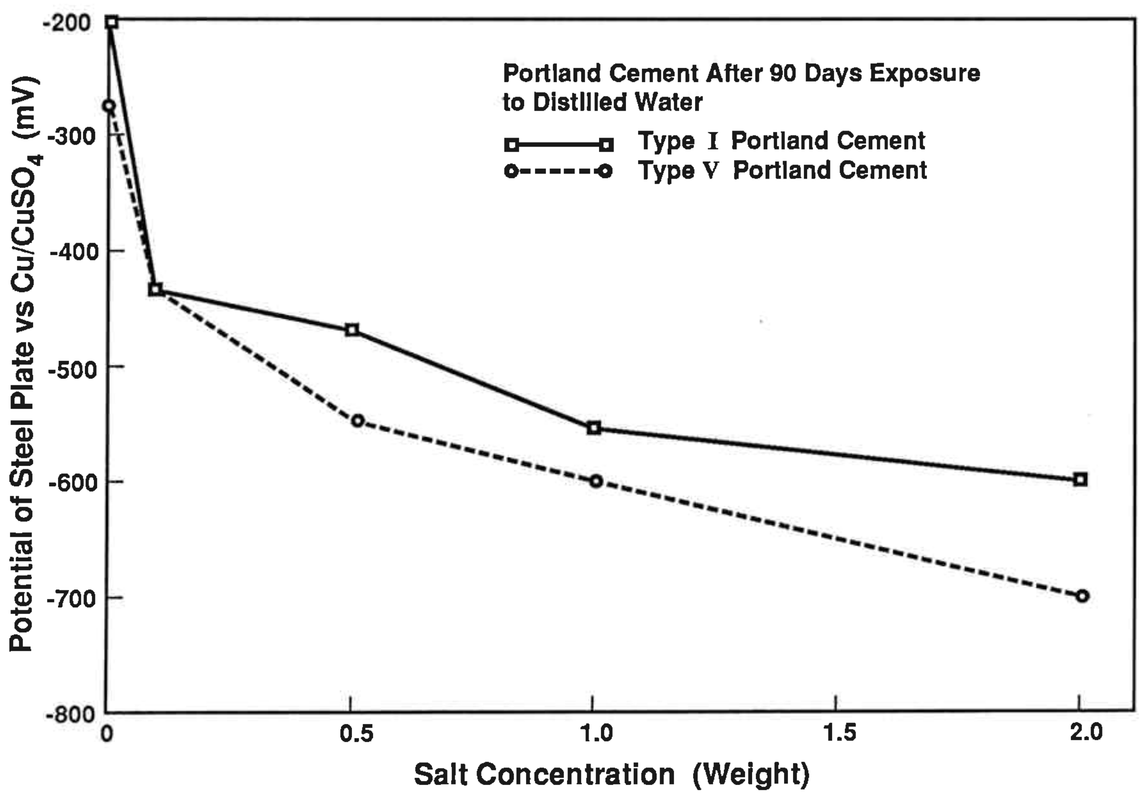


FIGURE 6

negative with increased Cl^- ion concentration which is consistent with the theory that the Cl^- ion attacks the otherwise stable passive film on the surface of the steel. When a CP electric field is superimposed on a chloride contaminated deck, the Cl^- will tend to migrate away from the rebar and also the pH at the rebar surface will change in the basic direction as charges are transferred by the following reduction reaction which predominates in concrete.

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$

With increasing pH and decreasing Cl- concentration the rebar pH/potential denoted by point C could, according to the Pourbaix diagram shown in Figure 7 move into the passive region via path ① or into the immunity zone as in path ② or anywhere in between.

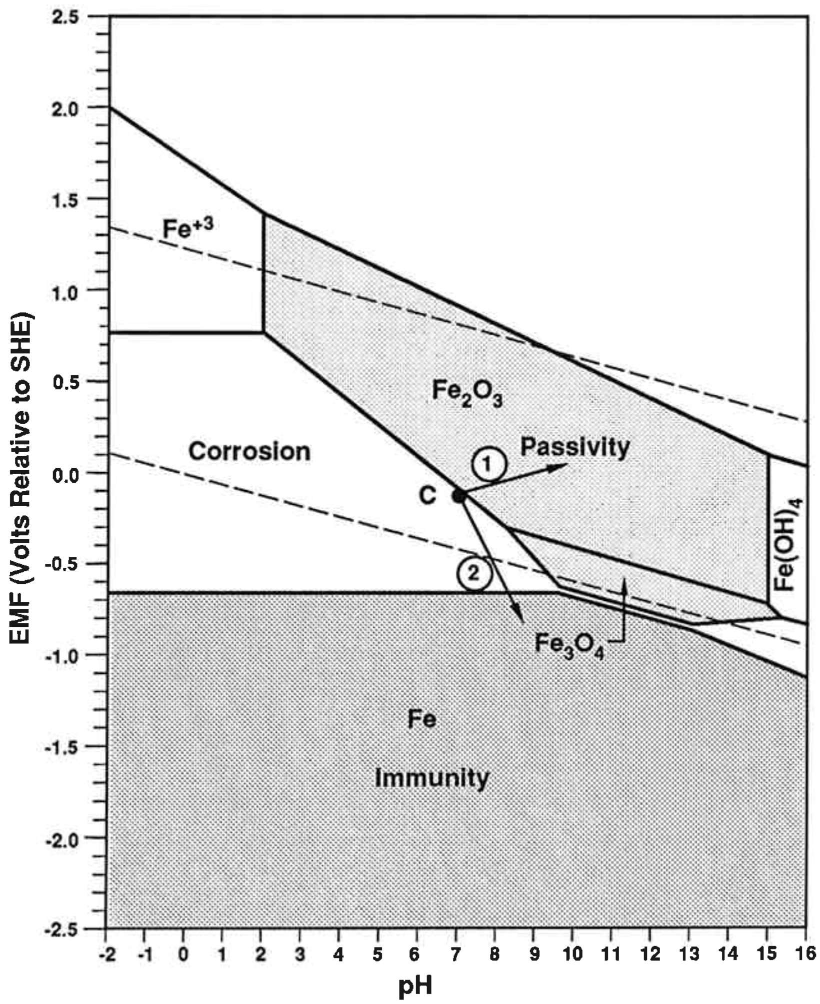


FIGURE 7

Furthermore if the CP system is turned off for a period of time and the Cl^- ions migrate back to the reinforcing steel the potential change with time will be in the electronegative direction rather than in the electropositive direction as required by the -100mV shift standard. Because reinforcing steel exhibits active-passive behaviour a potential shift criterion may be both impractical and indeterminate in denoting an adequate level of CP.

A more practical yet longer term indicator of adequate corrosion protection is whether or not delamination growth has been brought under control. The major advantage of this factor is that reduced delamination growth can be directly related to reduced corrosion activity. In addition the assessment of system performance is often left up to the structural engineer who has a better appreciation for delamination survey results than for electrochemical potential measurements.

A third performance evaluation method involves measuring the corrosion rate directly. Presently there are corrosion probes and linear polarization (LP) probes which can be installed at pre-selected locations. By monitoring these probes with time the effect of cathodic protection can be evaluated directly as indicated in Figure 8. [12] The flattening of the probe corrosion value denotes a cessation of corrosion activity. The typical high cost of these probes unfortunately prohibits their use in large numbers as would ideally be required to monitor a large surface area. Other experimental techniques such as AC impedance and acoustic emission show promise for determining reinforcing steel corrosion rates accurately but much development is still required before this instrumentation can be used routinely with confidence in the field.

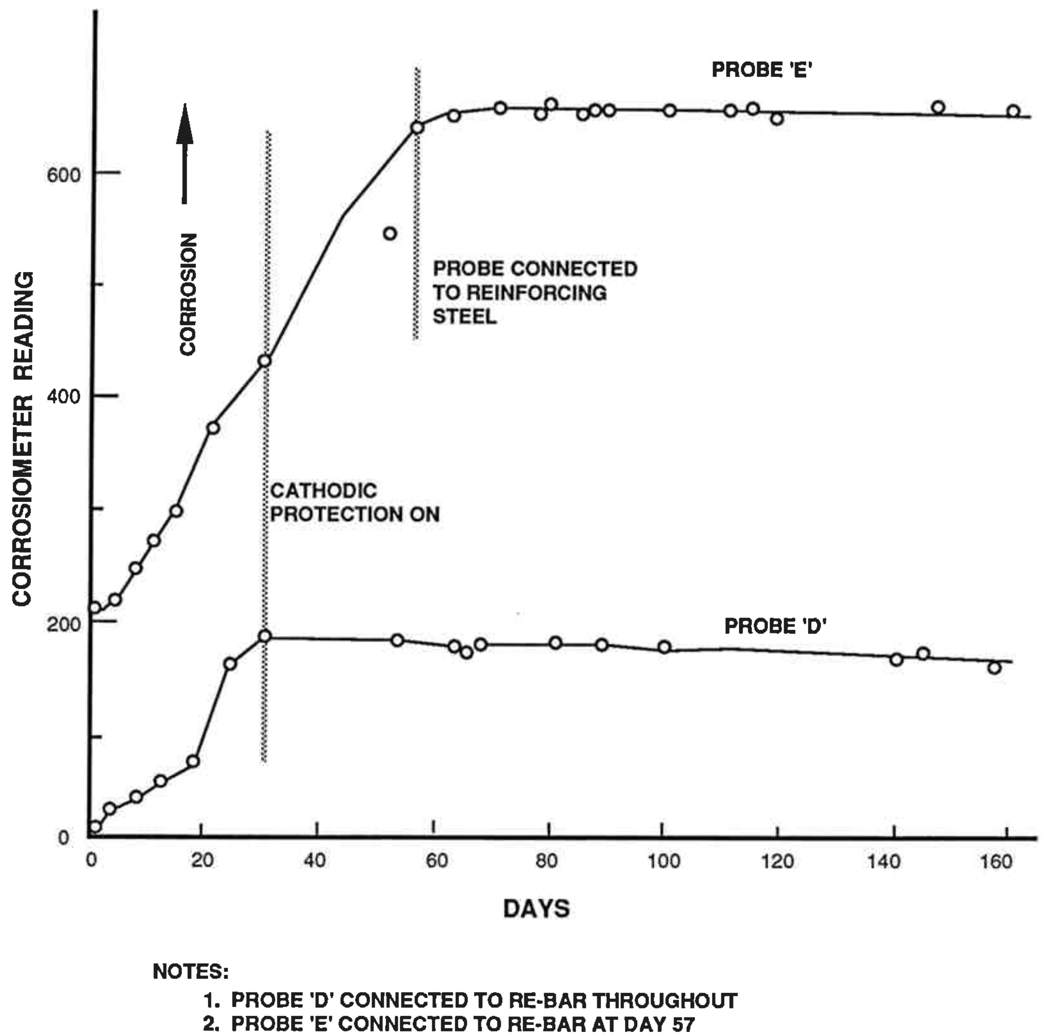


FIGURE 8 – CORROSION ACTIVITY AFTER THE APPLICATION OF CP

FUTURE DEVELOPMENTS

As CP systems stand the 'test–of–time' as durable and reliable and as the important practical feedback from delamination surveys verify their effectiveness, cathodic protection will become a more frequently chosen option to reduce corrosion thereby minimizing future parking structure rehabilitation and restoration expenditures. Even with proven reliability, however, CP systems primarily provide corrosion protection rather than leak protection in the slabs themselves, yet leak protection albeit a nuisance more than a structural dilemma is a very important rehabilitation factor.

Recently attempts have been made to combine the conductive coating with an elastomeric membrane top coat to provide a top surface protection system which would address both the leaking and corrosion problem. Unfortunately, most of the early trial installations have failed dramatically. Nevertheless, the restoration industry's need is so great and the technological challenge so compelling that the ultimate development of a successful corrosion and leak proof hybrid system is inevitable.

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