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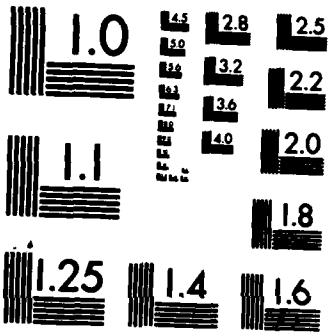

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CORROSION CONTROL FOR REINFORCED CONCRETE

BY

RANDALL M. TORIGOE

A REPORT PRESENTED TO THE GRADUATE COMMITTEE
OF THE DEPARTMENT OF CIVIL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

FALL 1983

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CHAPTER ONE

INTRODUCTION

1.1 Background

The National Bureau of Standards has reported that in 1975 the national cost of corrosion was estimated at $70 billion. Approximately 40 percent of that total was attributed to the corrosion of steel reinforcements in concrete, which continues to drain the financial resources of both public and private sectors. Due to the popularity of concrete, this cost is expected to rise as the volume of concrete in-place continues to steadily increase. Though concrete is generally perceived as a permanent construction material, cracking and spalling can occur when corrosion of steel reinforcements progresses to an advanced stage. This problem frequently occurs in reinforced concrete highway bridge decks, wharves, piers, and other structures in marine and snowbelt environments. ~~Since the Navy maintains~~ waterfront facilities throughout the world, it experiences its share of corrosion problems.

As the former Staff Civil Engineer of the U. S. Naval Ship Repair Facility, Yokosuka, Japan, the author estimates that over 70 percent of the activity's $5.5 million facilities maintenance budget was spent to correct deficiencies, which were either directly or indirectly caused by corrosion. In

the six drydocks, the items most notably experiencing corrosion problems were the huge dewatering pumps, the drydock caissons, the gratings, and the culverts' gates and valves. Along the waterfront, the support columns of the reinforced concrete wharves and the steel fender systems, also, required periodic repairs. Another major problem area was the old utility systems, in which, pipes and valves for potable water and steam routinely experienced corrosion related leakage.

1.2 Overview of Report

These problems warrant examination of the Navy's corrosion control program for shore facilities to determine its adequacy and to provide suggestions to improve its success at all levels of the Navy organization. At first, this report's scope was to have covered all types of corrosion problems. However, it was quickly learned that the Air Force has prepared a very comprehensive design manual[1] for cathodic protection of steel framed structures and pipeline systems. Since the Navy is in the process of revising its own manual on cathodic protection, it is suggested that the Air Force manual be used as a source of reference for the revised edition. Therefore, it was decided to concentrate efforts for this report on corrosion problems of reinforced concrete structures. This topic is of great

concern to the Navy due to its requirements for waterfront facilities.

The two succeeding chapters will provide a brief introduction to the principles and mechanisms of the corrosion process. In Chapter Four, current materials and methods used to prevent and arrest the corrosion process are discussed.

With information to better understand the subject of rebar corrosion, Chapter Five reviews the Navy's current corrosion control program for shore facilities. The investigation examines the command responsibilities at various echelons and the adequacy of the current design manuals and provides suggestions to improve the overall success of the program.

CHAPTER TWO

CORROSION MODEL

2.1 Reinforced Concrete

During construction, the steel reinforcing bars are completely embedded in the concrete mix, which is composed of the cement paste, aggregates, and admixtures. However, since the model will primarily focus upon the process at the steel-concrete interface, the steel reinforcements and cement paste will be examined without initial consideration for the aggregates and admixtures present in the concrete mix. These considerations will be considered later in the report.

2.2 Components

2.2.1 Steel Reinforcing Bars

Reinforcing bars are usually made of low-carbon steel, because of its high strength and ductile properties. Generally specified for reinforced concrete construction are billet steel of Grades 40, 60, and 75, which have minimum yield strengths of 40,000, 60,000, and 75,000 psi, respectively. Because the Grade 60 steel costs just slightly more than the Grade 40 steel, it is now the most predominate type of steel used in concrete beam and slab construction.

The Grade 75 steel is mostly used for the construction of columns.

Reinforcing bars of the deformed type are hot-rolled in air and consequently have various types and amounts of mill scale on their surfaces. The mill scale does not form a continuous coating and bare areas of exposed steel are found where the scale has flaked off. Mill scale, being more noble than steel, can act as the cathode of a couple whose anode is the base steel. Thus, the corrosion of the steel may be accelerated by the presence of mill scale.

By examining the microstructure of the steel reinforcing bar, we discover an unfortunate property which may lend itself to the dissolution of the material. The atom of an element is in its most stable state when the outer energy shell is either filled or half-filled with electrons. Therefore, to achieve stability, the atom will perform one of the following procedures: (1) receive extra available electrons to fill its outer energy shell, (2) release electrons to empty or half-fill the outer energy shell, or (3) share electrons with another atom.[2]

In the case of steel, it is composed of about 99% iron and each iron atom has a total of twenty-six electrons orbiting its nucleus. The orbital arrangement of an iron atom is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$. Since the iron atom has just two

valence electrons in its outer energy shell, it has a strong tendency to lose these two valence electrons to the stronger pull of another atom. This atom is then referred to as a ferrous iron ion, Fe^{+2}, with a positive two charge. Next, since the Fe^{+2} ion has six electrons in the 3d energy shell, which may hold up to ten electrons, an additional loss of one electron will half-fill the 3d energy shell and even further stabilize the iron atom. This ferric ion, Fe^{+3}, is the basic composition of rust.

2.2.2 Cement Paste

The process of producing portland cement consists of firing $CaCO_3$ (limestone) and SiO_2 (clay) at temperatures around 2700°F. The reaction of this process, shown in Figure 2.1, forms anhydrous minerals such as tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF).* Besides the above oxides, traces of $(MgO)SO_3$, MnO, TiO_2, and alkali elements can be detected in the cement.[3]

Presently, there are five main types of portland cement, each differing in the proportions of anhydrous minerals and in the fineness of the grounded product.

*Cement chemistry notation is used to denote mineral phases. C=CaO, S=SiO_2, A=Al_2O_3, F=Fe_2O_3, H=H_2O.

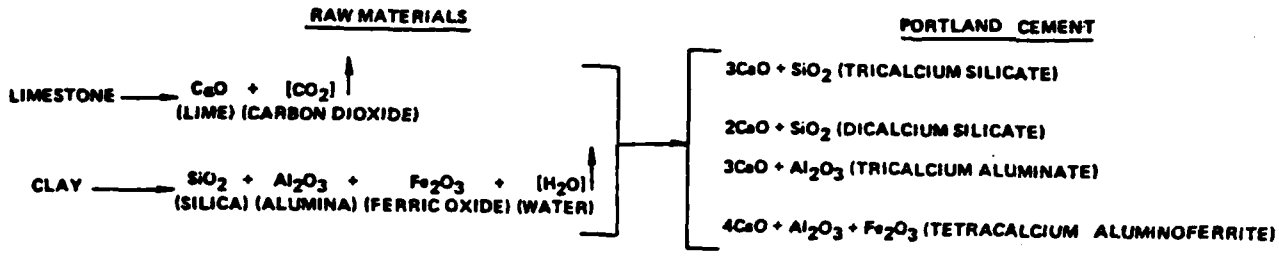


Figure 2.1 The formation of portland cement from limestone [3] and clay in the cement kiln.

$2(3CaO \cdot SiO_2)$ (TRICALCIUM SILICATE)	+	$6H_2O$ (WATER)	=	$3CaO \cdot 2SiO_2 \cdot 3H_2O$ (TOBERMORITE GEL)	+	$3Ca(OH)_2$ (CALCIUM HYDROXIDE)
$2(2CaO \cdot SiO_2)$ (DICALCIUM SILICATE)	+	$4H_2O$ (WATER)	=	$3CaO \cdot 2SiO_2 \cdot 3H_2O$ (TOBERMORITE GEL)	+	$Ca(OH)_2$ (CALCIUM HYDROXIDE)
$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ (TETRACALCIUM ALUMINOFERRITE)	+	$10H_2O$ (WATER)	+	$2Ca(OH)_2$ (CALCIUM HYDROXIDE)	=	$6CaO \cdot Al_2O_3 \cdot Fe_2O_3 \cdot 12H_2O$ (CALCIUM ALUMINOFERRITE HYDRATE)
$3CaO \cdot Al_2O_3$ (TRICALCIUM ALUMINATE)	+	$12H_2O$ (WATER)	+	$Ca(OH)_2$ (CALCIUM HYDROXIDE)	=	$3CaO \cdot Al_2O_3 \cdot Ca(OH)_2 \cdot 12H_2O$ (TETRACALCIUM ALUMINATE HYDRATE)
$3CaO \cdot Al_2O_3$ (TRICALCIUM ALUMINATE)	+	$10H_2O$ (WATER)	+	$CaSO_4 \cdot 2H_2O$ (GYPSUM)	=	$3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$ (CALCIUM MONOSULFOALUMINATE)

Figure 2.2 The reactions occurring when water is added to [3] portland cement.

When water is added to portland cement, the above anhydrous minerals react with water to produce the results shown in Figure 2.2. The resulting reaction products include calcium silicate hydrate (termed tobermorite gel), calcium hydroxide, and other hydrate phases. It is this tobermorite gel which provides the primary cementing action in concrete. After setting, the gel begins to dry and to crystallize in the forms of fibers and sheets.

During hydration, the cement paste develops a very high alkaline characteristic with pH levels in the range between 12 to 14. Previously, it was assumed that the alkalinity was due to the large quantity of calcium hydroxide present in the cement paste. Though the calcium hydroxide contributes to the alkalinity, it is now believed that the potassium hydroxide and sodium hydroxide produced in the cement paste are responsible for elevating the pH up to the 12 to 14 region.

CHAPTER THREE

CORROSION PROCESS

3. Thermodynamics

The tendency of a chemical reaction to proceed in a spontaneous direction, when it is subjected to a specific environment, is measured by a free energy change, ΔG. For a given reaction, the sign of the free energy change is the most important factor, since it indicates whether or not the reaction is spontaneous. If the change in free energy is negative, the reaction does have a tendency to proceed spontaneously. However, due to the complexity of the corrosion process, it is not known whether the reaction will indeed react spontaneously and if it does, the rate of reaction will be uncertain. On the other hand, it is stated with certainty that a positive free energy change will not cause the reaction to proceed at all under the particular conditions specified.

The change in free energy accompanying an electrochemical or corrosion reaction may be determined by the understanding of the reaction's cell potential. Depending upon the nature of the metal and the nature of the solution of the cell, the reaction possesses a certain potential. As the production of ions increases or decreases, the potential changes accordingly. A standard hydrogen electrode is used as a

reference to measure the electrode potential (and therefore the corroding tendencies) of the metal. If the spontaneous direction of the reaction indicates metal oxidation, corrosion is expected to occur.[4]

Before proceeding further, it is necessary to define a galvanic cell and to identify its components. Two electrical conductors (electrodes), connected by a low resistant wire, are immersed in a conductive solution, called an electrolyte. The galvanic cell converts chemical energy to electrical energy. Electrons flow through the metallic path from the negative electrode to the positive electrode. Within the electrolyte, the current is carried by both negative and positive ions. The electrode at which chemical reduction occurs is called the cathode and the electrode at which the chemical oxidation occurs is called the anode. Typically in a corrosion reaction, the metal electrodes are of a dissimilar nature. The electrodes may be of different metals or the same metal species with differing characteristics. For corrosion of steel reinforcements, a single rebar can have an anodic and cathodic area adjacent to each other which forms a corrosion producing cell. The anodic and cathodic areas may differ in potential due to metal defects or impurities, differing concentrations of electrolytes (chlorides or sulphates) and varying oxygen availability. Adjacent reinforcements and metal utility conduits embedded in the concrete may also act as electrodes.[5]

The use of the Evans or polarization diagram (Figure 3.1) is very helpful in determining the current density of the corrosion rate with respct to the changing potential. For the model, the reactions, with their respective oxidation-reduction (redox) potentials, are expected to occur:

$Fe \longrightarrow Fe^{+2} + 2e^-$	-0.440 volts
$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$	+0.401 volts
$2H^+ + 2e^- \longrightarrow H_2$	0.000 volts*

The reactions of iron and water have different open-circuit potentials. As water comes in contact with iron, the production of iron ions changes the potential of both reactions. The only potential, where the total rate of oxidation equals the total rate of reduction, is at the intersection represented by a "mixed" or corrosion potential, E_{corr}. At this point, the rate of iron dissolution is equal to the rate of hydroxyl formation. The current density associated with this point is called the corrosion current density, i_{corr}.

*Due to the high initial pH of the cement paste, the scarse availability of hydrogen ions will limit the evolution of hydrogen gas.

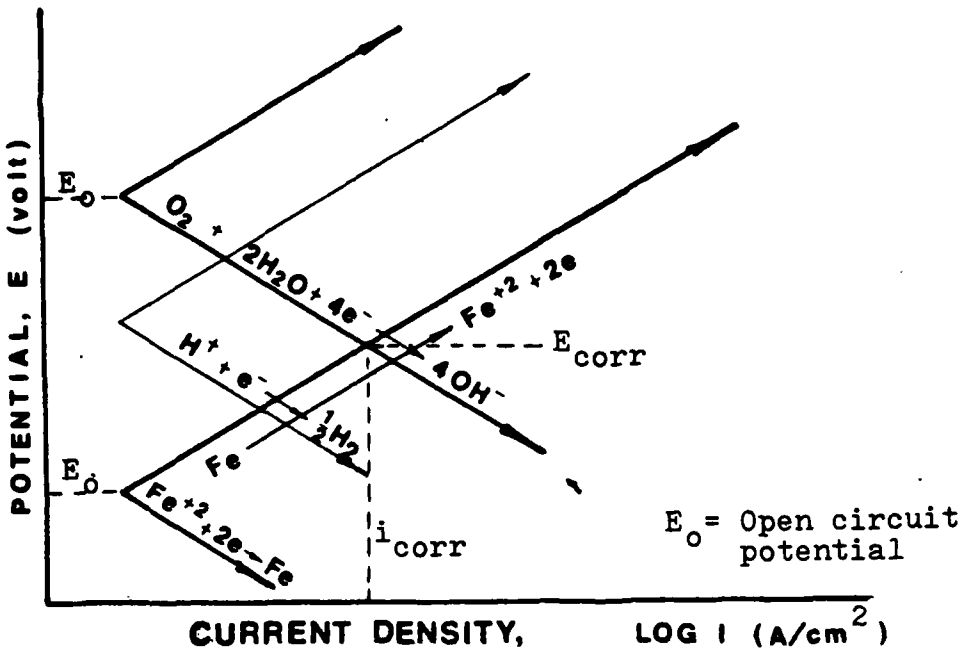


Figure 3.1 Electrode kinetic behavior of pure iron in solution. (Evans or polarization diagram)

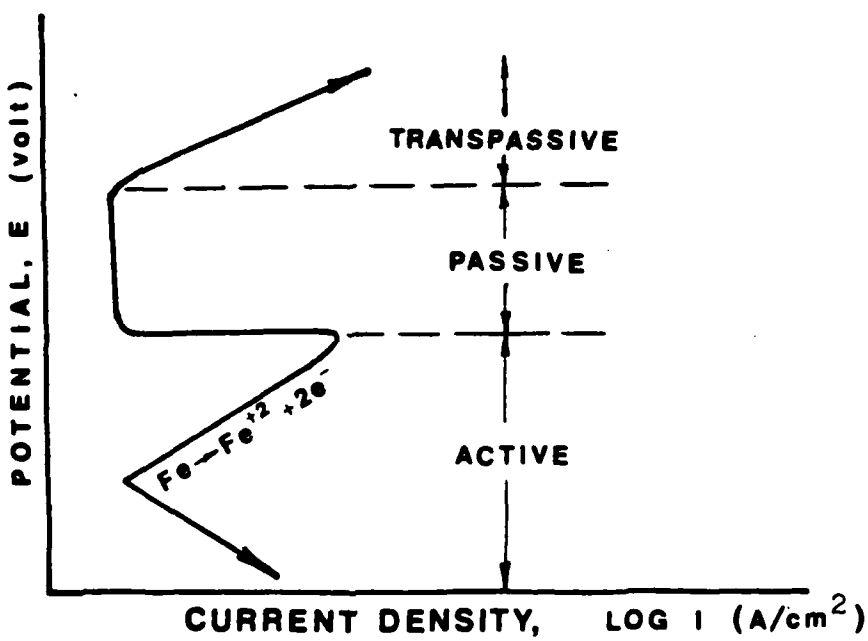


Figure 3.2 Typical anodic dissolution behavior of an active-passive metal.

During the corrosion of certain metals and alloys, including iron, a phenomenon known as passivity can occur (refer to Figure 3.2), in which, there is a loss of chemical reactivity under certain environmental conditions. As the model corrodes, the corrosion product forms a thin uniform film over the surface of the iron. The film will continue to increase its thickness until the resistive property of the film becomes high enough to reduce the current flow and halt the corrosion process. Therefore, this protective barrier between the metal and the solution prevents further transfer of electrons and ferrous iron ions from diffusing into solution. If this passive state remains unchanged the steel reinforcing bar will not corrode any further. Unfortunately, this passive state is relatively unstable and is subject to changes caused by physical damage and chemical attack.

Thermodynamic data is conveniently summarized in potential-pH diagrams, known as Pourbaix diagrams, which relate to the electrochemical and corrosion behavior of metals in water. Figures 3.3 and 3.4 are Pourbaix diagrams of iron in water. By glancing at the diagrams, the potential and pH conditions under which the iron either does not react (immunity) or can react to form specific oxides or complex ions may be determined. However, the Pourbaix diagram does have its limitations, in that, it does not provide information on reaction rates; that is, whether the reaction occurs slowly or rapidly when the energy changes are

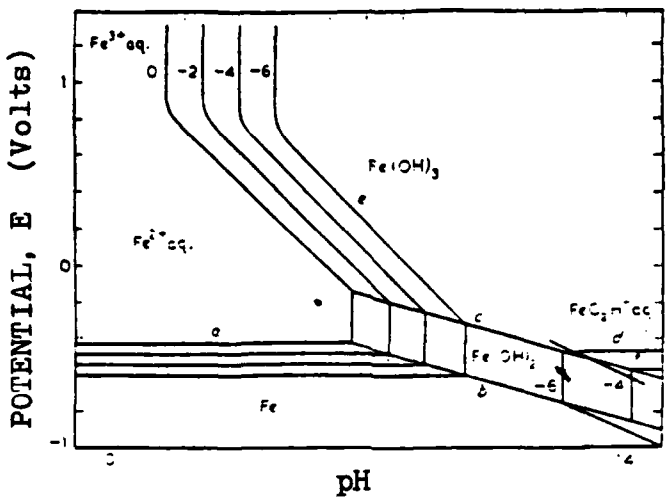


Figure 3.3 Simplified potential/pH diagrams for the Fe/H_2O [6] system showing the zones of thermodynamic stability of cations, anions, and hydroxides of iron (Deltombe and Pourbaix).

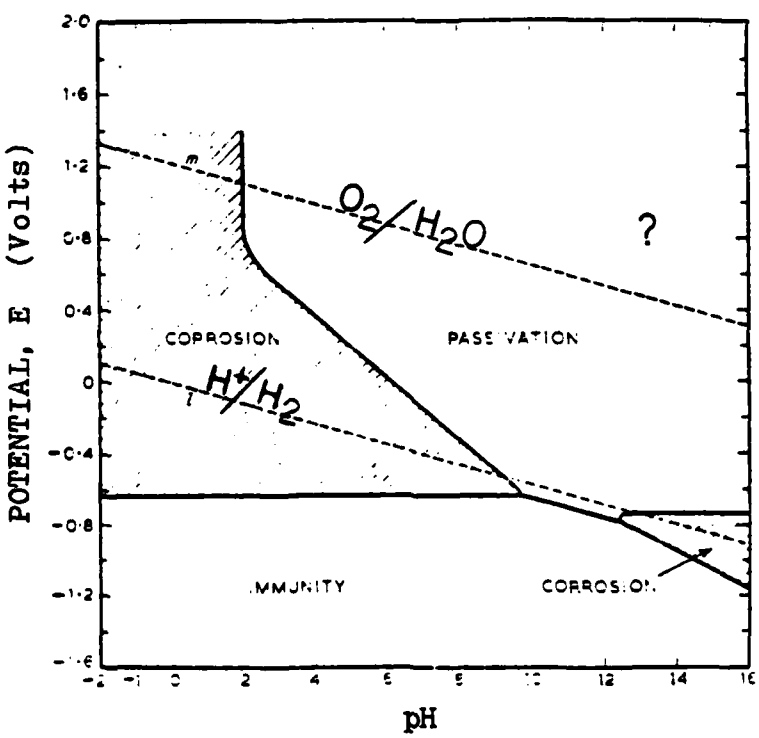


Figure 3.4 Simplified potential/pH diagram showing the [6] zones of corrosion, immunity, and passivation.

favorable. Though the diagrams may indicate conditions which produce passive film on the metal surface, it does not provide information on the film's effectiveness in the presence of specific anions, such as chloride ions.

3.2 Electrochemical Aspect

At the metal-surface interface of the model, the following reactions occur:

Oxidation (anodic reaction) $Fe \longrightarrow Fe^{+2} + 2e^-$

Reduction (cathodic reaction) $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

The oxidation of iron or anodic reaction is indicated by an increase in valence charge or the release of electrons from the outer energy shell of the iron atom. On the other hand, the decrease in valence charge or the capturing of electrons by the oxygen atom to fill its outer energy shell signifies a reduction or cathodic reaction. It is very important to understand that both reactions occur naturally in order to form more stable elements. Rust is produced because it is a more stable species of iron than processed steel.

The iron atom at the metal surface releases its two valence electrons and the resulting Fe^{+2} ion breaks away from the metal surface and goes into solution as illustrated in Figure 3.5. Since there is a high concentration of OH^- ions in the cement paste at the metal surface, the Fe^{+2} ion will

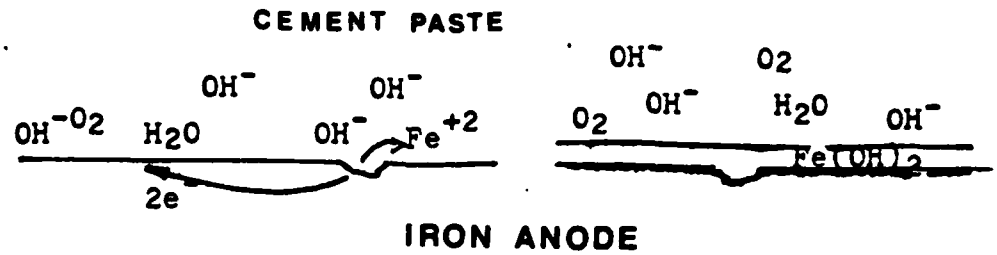


Figure 3.5 Corrosion process at the metal surface.

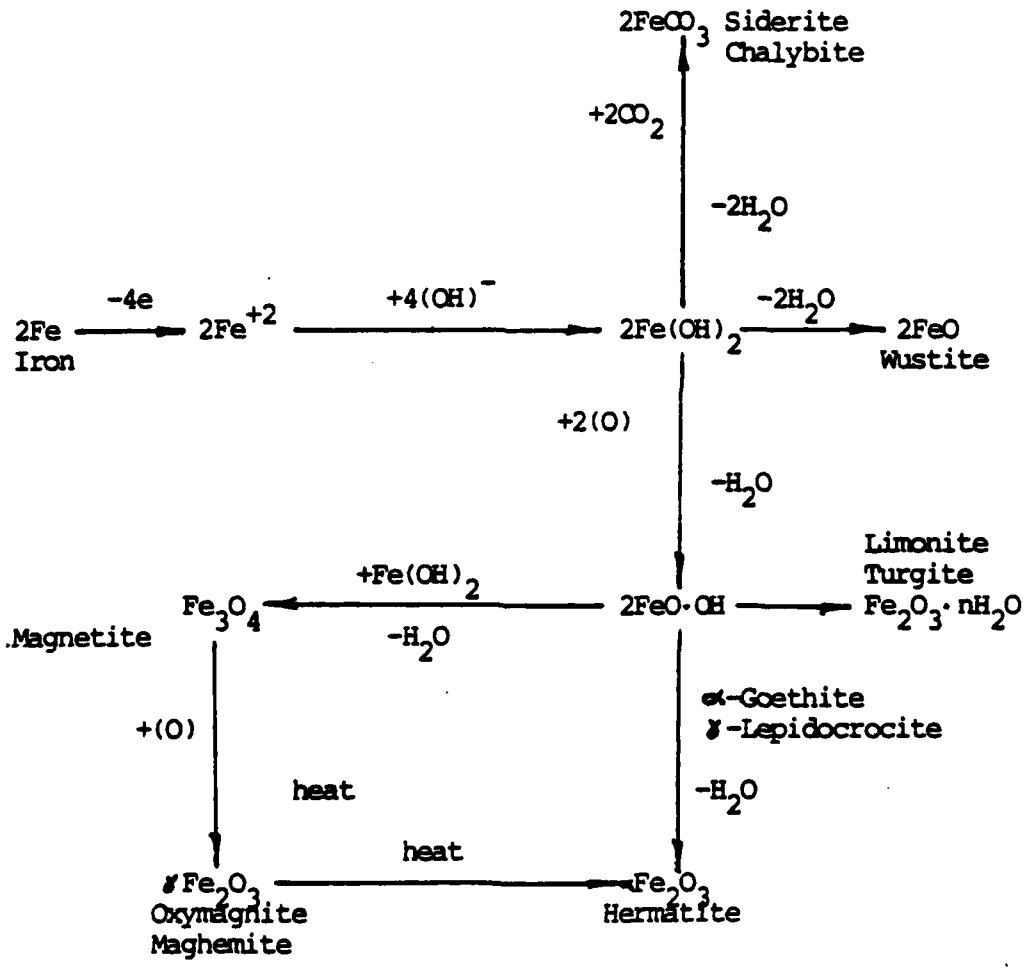


Figure 3.6 Notational reactions in the formation of rust.[7]

immediately bond with the OH^- ions to form ferrous hydroxide, $Fe(OH)_2$, on the metal surface. The overall reaction is obtained by adding the two specific reactions:

$$Fe + H_2O + O_2 \longrightarrow Fe^{+2} + 2OH^- \longrightarrow Fe(OH)_2$$

Though $Fe(OH)_2$ is one of the most common types of passive film, there are other species of ferrous hydroxides and oxides which also form diffusion barriers. The various species and how they evolve are shown in Figure 3.6. Pure $Fe(OH)_2$ is a white corrosion product, but when exposed to oxygen, it turns into a black corrosion product, Fe_3O_4. After further exposure to air, the corrosion product turns into an orange to reddish-brown color, which comprises most of the ordinary rust.

3.3 Corrosion of Steel Reinforcements

When steel reinforcements are embedded in a concrete mix, several reactions may occur, but the most probable reaction is the formation of a thin passive film of $Fe(OH)_2$. This is a direct result of the high pH concentration of the cement paste. In this alkaline solution, the $Fe(OH)_2$ covered reinforcements are expected to remain in a passive state. However, it is known that the passive film eventually dissolves and rebar corrosion occurs, especially in waterfront structures and bridge decks. Many factors which

contribute to the corrosion process have been identified, but still the answers as to how and why corrosion occurs in this environment are not completely understood. Chloride and oxygen concentrations are two very important factors contributing to the corrosion process and their effects are briefly explained in the following discussions.

3.3.1 Effects of Chloride Ions

As previously stated, chloride ions (Cl^-) are introduced into the system, usually as seawater or deicing salts. Though there are uncertainties as to exactly what part the chloride ions play in the corrosion process, information gathered through research and inspections of existing structures clearly indicates that chloride ions do contribute to the corrosion of steel reinforcements.

One explanation as to how the chloride ions contribute to the corrosion of the rebar states the following anodic reactions:[8]

$$Fe + 2Cl^- \longrightarrow (Fe^{+2} + 2Cl^-) + 2e^-$$

followed by

$$Fe^{+2}(Cl_2) + 2H_2O \longrightarrow Fe(OH)_2 + 2H^+ + 2Cl^-$$

This theory implies that chloride ions are able to diffuse through the $Fe(OH)_2$ layer and bond with the iron atoms. Whether this process can physically occur has not been

proven and requires further research. However, if this iron chloride complexing was to occur, it would satisfy other known conditions which occur. Hydrogen ions (H^+) would be formed as a by-product of this reaction and lower the pH concentration of the cement paste. As the pH is reduced, the concentration of available OH^- would decrease, which in turn, would reduce the rate of formation of $Fe(OH)_2$. Eventually, the pH level would fall below the pH level required to produce $Fe(OH)_2$ as shown in the Pourbaix diagram. Once the passive film is dissolved and unable to reform, the corrosion rate increases as the reinforcements are now in an acidic environment. The corrosion products examined were yellowish-green to green-blue in color indicating an iron chloride complex. Also, white products found were undoubtedly $Fe(OH)_2$.

For the same reactions, the following equations are suggested:[9]

$$Fe^{+2} + Cl^- \longrightarrow (FeCl^- \cdot complex)^+$$

$$(FeCl \cdot complex)^+ + 2OH^- \longrightarrow FeO \cdot xH_2O + Cl^-$$

Again, without fully explaining the reactions, it is proposed that the iron complex causes the dissolution of the steel.

3.3.2 Effects of Oxygen

Since the reaction rate at the anode must equal the reaction rate at the cathode, the presence of oxygen is equally as important as the intrusion of chloride ions. Fortunately and unlike chloride ions, the role of oxygen in the corrosion process is better understood. In the cathodic reaction, the oxygen and water molecules accept the free electrons released by the iron atoms; thus allowing corrosion to occur. Since a metal in solution cannot spontaneously accumulate an electrical charge, the corrosion process will stop if either oxygen gas or water is not available to accept the electrons. As an example, a reinforced concrete pile partially submerged in seawater will experience relatively small amounts of corrosion at the submerged end of the pile. Though the pile is saturated with chloride ions, the seawater is not fully aerated to produce substantial corrosion problems. In contrast, the rebar corrosion increases in areas closer to the water surface and is highest in the splash zone just above the high tide level, due to the availability of both chloride and oxygen. Therefore, both the anodic and cathodic reactions occur unimpeded. In addition, the cathodic reaction produces addditional OH^- ions, which maintains the solution around the cathode at a very high pH level and, at least, protects the cathode from corroding. This adds to the protection of the rebar at the submerged end of the pile.

3.4 Failure of Reinforced Concrete

Since concrete has a very low tensile strength, steel reinforcements are added to carry the tensile load of the composite member. Corrosion reduces the effective diameter of the reinforcements and, therefore, decreases the load carrying capability of the member. Though the corrosion process may occur in various forms and may be caused by different sources, the ultimate result is still the failure of the reinforced concrete.

When rebar corrosion occurs, the corrosion product occupies a greater volume of space than the original metal which has corroded. This volumetric expansion caused by the corrosion product creates internal pressures which, if high enough, will produce a crack in the concrete. This fissure will first develop near the corroding reinforcement and will steadily advance outward to the concrete's surface. The crack provides an easier access to the corroding reinforcement for further intrusion by chloride ions and oxygen molecules. As the concentrations of chloride ions and oxygen increases, the corrosion rate accelerates and the corrosion product increases in volume. This destructive cycle perpetuates until the reinforcement fails or repair efforts are undertaken to arrest the corrosion process. Corrosion at the metal surface may also affect the bonding between the rebar and the concrete. Debonding and possible

increased volume accompanying the formation of Fe_3O_4 to the increased volume accompanying the formation of ZnO (per mole of parent metal consumed) is only 1.46. Tests were conducted by embedding regular and galvanized (zinc-coated) reinforcing steel into concrete cylinders. The results of internal pressure measured in the concrete cylinders indicate that the corrosion product of the regular steel reinforcement produced much greater internal stresses than the corrosion product of the galvanized reinforcement. In addition, the failure of the concrete cylinder with the regular reinforcement occurred within a much shorter period of time. Interestingly, the ratio of internal pressures measured was much greater than the 1.46 ratio of volumetric expansion. This may be explained by the second factor.

The solubility of the corrosion product affects the development of internal pressure in the concrete. The resulting Fe_3O_4 layer was characterized as continuous and adherent, while the ZnO layer was less adherent and more soluble. The Fe_3O_4 layer simply expanded outward radially during the corrosion process, whereas the more soluble ZnO was able to fill cracks and pores in the mortar and effectively migrate away from the steel-cement paste interface. This mobility of diffusing into the concrete displayed by the more soluble product produced far less internal pressure than that which had been expected to be caused by the corrosion product.[10] The initial findings

subsequent slippage problems will reduce the effective transfer of load from the concrete to the rebar.

At first, the development of hairline cracks at the surface of the concrete may not present any significant problems. Since the concrete in the tensile section is not designed to carry a load and cracks often occur due to shrinkage there may not be a great concern for the structural integrity of the member. However, the corrosion products, Fe^{+3} and Fe^{+2}, also exist in a soluble state. Upon reaching the concrete surface, the soluble products are exposed to air and turn into the familiar reddish-brown color of rust. Though the rust coloring presents an appearance problem, more importantly, it indicates that the rebar corrosion has already progressed to an advanced stage. Failure of the corroding reinforcement is assured unless measures are taken to arrest the corrosion process.

It may be apparent now that the characteristics of the corrosion product greatly influences the cracking of the concrete. From preliminary investigations, two important characteristics of the corrosion product have been determined. First is the magnitude of the volumetric expansion associated with the parent metal. For example, the corrosion products of Fe_3O_4 and ZnO in laboratory tests experienced increases in volume of 7.80 and 5.36 cc per mole of parent metal consumed, respectively. The ratio of

imply that the use of galvanized reinforcing steel is preferred over regular rebars, because its corrosion product produces less internal stress in the concrete. However, the above is still speculative since a complete and thorough research on the topic has not been undertaken.

CHAPTER FOUR

METHODS OF PREVENTING OR ARRESTING THE CORROSION PROCESS

4.1 Reducing Chloride Intrusion

The corrosion process may be limited by restricting the flow of chloride ions within the concrete. This may be accomplished by establishing barriers or by developing the properties of concrete which inhibit the intrusion of chloride ions.

4.1.1 Designing Quality Concrete Mix

Usually, the most important consideration in concrete mix design is its strength. Then, upon considering the local conditions, construction method, and functional use of the structure, the design of the concrete mix is properly proportioned to reflect these conditions. For facilities with potential rebar corrosion problems due to the continued presence of water and chloride ions, the following should be considered in the designing of a quality concrete mix.

4.1.1.1 Cement

Currently in the United States, there are five types of portland cement in use (refer to Table A), which

are specified in the American Society for Testing and Materials (ASTM) Specification C150.

TYPE	I	II	III	IV	V
Tricalcium Silicate	51	46	58	26	39
Dicalcium Silicate	25	32	16	54	43
Tricalcium Aluminate	9	4	8	2	2
Tetracalcium Aluminoferrite	8	12	8	12	8
Other phases	7	6	10	6	8

Table A. Typical proportions of primary anhydrous mineral phases in the 5 major types of portland cement.[3]

Type I is the most commonly used cement due to its properties and availability. It contains a high percentage of tricalcium silicate, frequently referred to as alite, which is rapid hardening, acquires early high strength, and displays excellent hydraulic characteristics. Type II cement contains a higher percentage of dicalcium silicate, also known as belite, which provides additional resistance to disintegration by aggressive chemicals, most notably the sulfates, found in soils and water. However, the reduced percentage of alite causes the concrete to harden at an appreciably slower rate and have a lower heat of hydration than Type I. Of the five different types of portland cement, Type III has the highest percentage of alite, which allows the concrete to rapidly gain strength. For this reason, the Type III cement is heavily used in cold weather regions,

where high early strength is required, and also in the production of prestressed and precast structural members. On the other hand, Types IV and V concrete have the lowest content of alite and the highest content of belite. Therefore, setting occurs at a much slower rate than the other types, but provides the greatest amount of protection against concrete deterioration by aggresive chemicals. Due to their special nature, Types IV and V are not readily stocked and usually must be specially ordered.[11]

The use of fly ash (the combustion product of pulverized coal) to replace up to 20 percent of the portland cement will generally develop favorable qualities in the concrete. This fly-ash cement concrete has a denser and more watertight structure than portland cement without fly ash. Due to this fact, it is necessary to add more air-entraining agents to fly-ash cement concrete to allow for expansion and contraction, especially in cold regions. Also, it develops less heat on hydration and minimizes shrinkage. Concrete with fly ash hardens at a slower rate, but after a year in service, it will have higher compressive and tensile strengths than portland cement without fly ash. Experimental tests have shown that the addition of fly ash to the concrete mix improves the corrosion resistive properties of the concrete. Rebar corrosion may be significantly delayed, but once the corrosion process is initiated, the fly ash cement offers no additional protection.

The composition and structure of fly ash depends on such factors as the mineral composition of the pulverized coal, the temperature of combustion, the period in which it passes through the combustion chamber, and the rate of cooling. The quality of fly ash cement concrete is governed by the fineness of the ash, the sulphur and carbon content of the ash, and the $Ca(OH)_2$ content liberated during the hydration process.[12]

4.1.1.2 Aggregates

In a quality concrete mix, the proportions of coarse (gravel or crushed stone) and fine (sand) aggregates are carefully selected to yield a minimum of voids in the mixture. By doing so, the ingress of chloride ions into the concrete is greatly reduced. Particle size gradation and shape are also important as angular shapes or coarse textures may preclude the use of low water/cement ratios.

However, aggregates may contribute to corrosion if corrosive substances are harbored in the interior pore system or coat the exterior surface of the aggregate. Chloride and sulfate salts may be present in native aggregate sources or may contaminate open stock piles. If these aggregates are introduced into the concrete mix, the chloride ions will be able to roam freely in the cement paste medium and eventually attack the steel reinforcements.

In freezing conditions, aggregates may cause cracking of the concrete due to a condition termed "unsoundness". This poor resistance to the freeze-thaw cycle is generally caused by a high proportion of aggregate which does not allow for sufficient cement paste and air voids to bond the aggregate. Thus, cracks develop since the concrete does not have sufficient elastic properties to handle the contracting and expanding conditions.[13]

Lastly, the economic factor predominates. The selection of the aggregate depends upon the cost and the availability of the aggregate in the local area. On occasions, the political conditions may force the use of less-than-quality local products due to its abundance and contribution to the local economy. It seems unfortunate that aggregates and other ingredients are selected for reasons other than providing the best quality concrete mix.

4.1.1.3 Admixtures

Admixtures are materials other than water, aggregates, and hydraulic cement added to fresh concrete immediately before or during the mixing process to modify the properties of the concrete in a favorable manner. Presently, the major classifications of admixtures are air-entraining agents, accelerators, retarders, and water reducers. All admixtures specified for use in concrete mixes

must meet the appropriate ASTM specifications (ASTM C260-77 and ASTM X494-80). As part of the concrete mix, admixtures may directly or indirectly influence the corrosion process.

The most widely used admixture is the air-entraining agent. This material, which forms a network of fine air voids (between 0.001 to 0.003 inches in diameter) in the cement paste of the concrete, provides resistance to surface scaling and spalling due to the freeze-thaw cycles experienced in freezing climates. In addition, the fine air bubbles tend to buoy up the sand particles during the pouring and setting of the concrete and thus, reduces segregation and bleeding. The entrained air imparts additional plasticity to the concrete mix and will allow the use of a higher aggregate to cement paste ratio for a given slump. Air-entraining agents provide numerous advantages, but the obvious disadvantage is that the increased air voids will increase the permeability of the concrete and allow the intrusion of chlorides and water. It is possible that the air-entraining agent may be proportioned such that the advantages it provides are realized while accepting some limited amounts of rebar corrosion due to chloride attack. However, for a reinforced concrete structure in a freezing environment, it is probably best to maximize the resistance to the freeze-thawing cycle by adding air-entraining agents and to overcome the corrosion problem by installing an effective cathodic protection system.

Accelerators are added to the concrete mix to decrease the setting time when rapid hardening is desired. Again, this admixture is used primarily in locations with cold weather and when a shorter construction period is specified. In recent past, the most widely used accelerator was calcium chloride ($CaCl_2 \cdot 2H_2O$). However, the chloride content of this accelerator has been shown to promote rebar corrosion and many European agencies have banned its use.

4.1.1.4 Water/Cement (w/c) Ratio

Of all the mix design factors, which offers the highest degree of protection to the steel reinforcements, the water/cement ratio is considered to be the most important. If the concrete mix contains less water, it is reasonable to assume that the transport of chloride ions through the concrete will be retarded. As shown in Figure 4.1, the chloride concentrations at all depths are less for the concrete with the lower w/c ratio. Therefore, the w/c ratio is directly related to the permeability of the concrete as shown in Figure 4.2. It is fortunate that with decreasing w/c ratios, the concrete mix actually develops higher compressive strength as shown in Figure 4.3. It is recommended that the w/c ratio of a mix be designed at about 0.40 for optimum use.

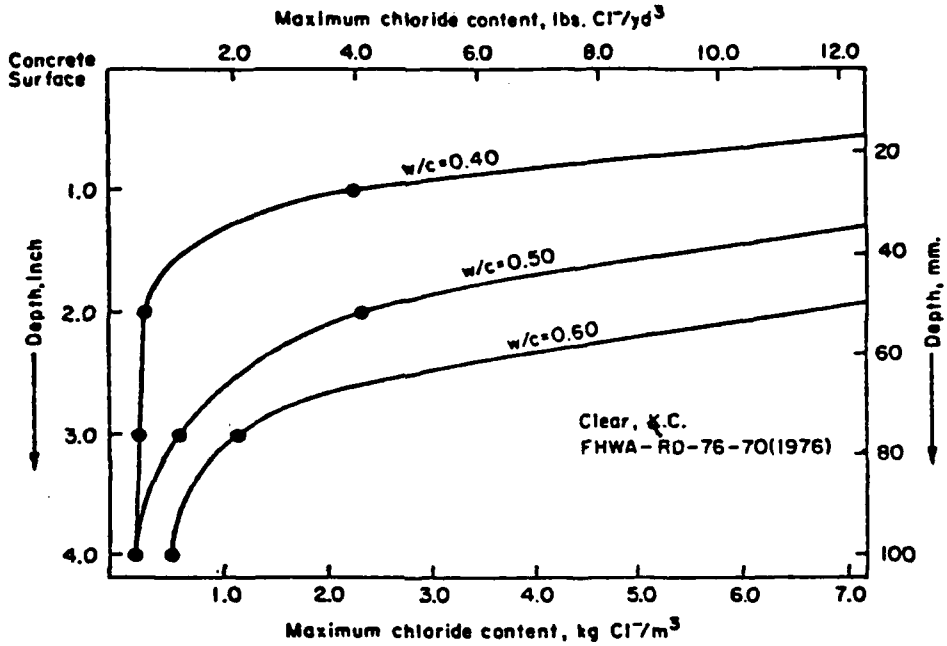
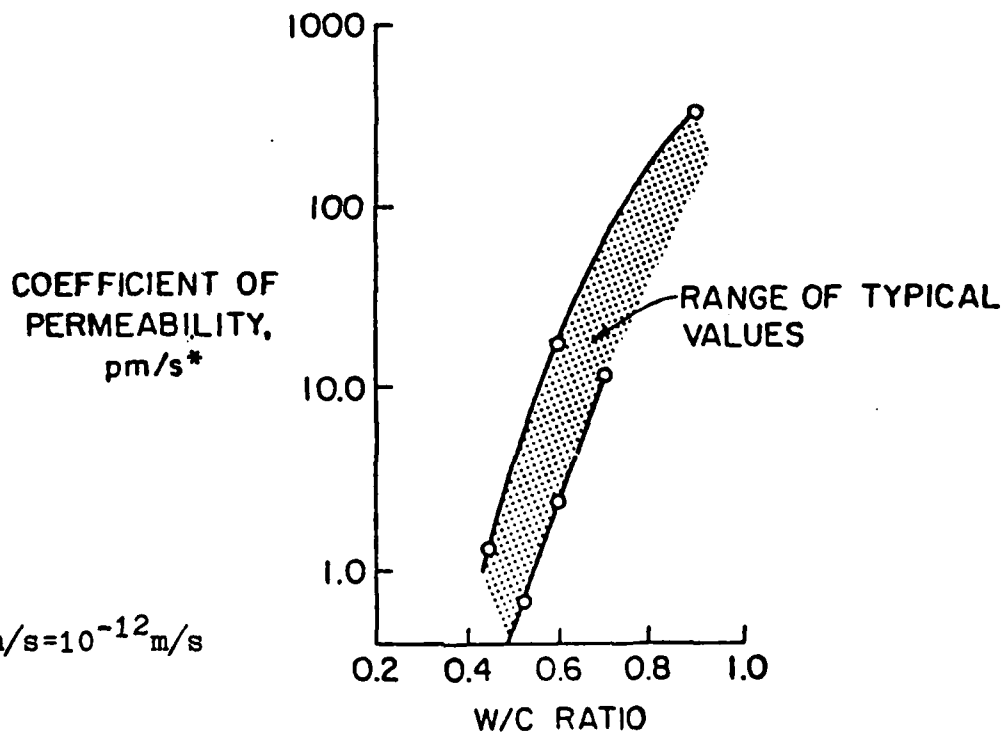


Figure 4.1 Maximum chloride profiles after 830 daily salt applications. [9]



*pm/s=10^{-12}m/s

Figure 4.2 Permeability of concretes as influenced by w/c ratio. [9]

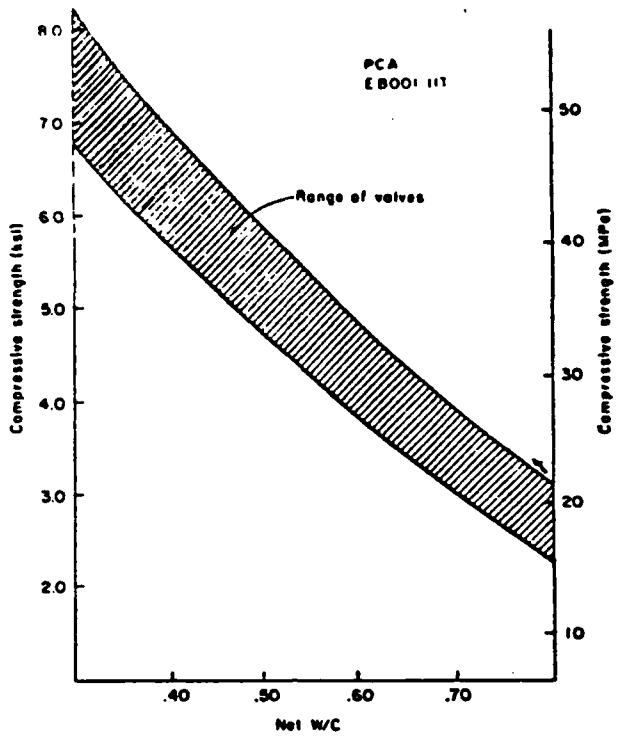


Figure 4.3 Strength vs. w/c ratio.[13]

Aggregate/Paste Ratios (by weight)

Required for Various Degrees of Workability

w/c	Very Low	Low	Medium	High
0.40	3.2	2.9	2.6	2.3
0.50	4.7	4.0	3.6	3.2
0.60	-	4.8	4.5	3.8

Table B Aggregate/cement paste ratios (by weight).[14]

4.1.1.5 Recommended Mix Design

A concrete mix is designed to meet three basic criterias, which are strength, durability, and workability. First, the strength requirement is satisfied by selecting the appropriate w/c ratio. For strength and corrosion protection, a w/c ratio of 0.4 is advised. Next, the workability or slump requirement must be satisfied by determining the optimum mix of ingredients and consistency. Since the consistency of the cement paste has already been determined by the w/c ratio, the selection of aggregate type and aggregate gradation, which minimizes the air voids between particles, is then made. The proper choice will maximize economy and improve placement. Next, the aggregate to cement paste ratio is determined. As indicated by Table B, a higher aggregate to cement paste ratio will produce a lower workability. That is to say, if the concrete mix is very rocky then it will not flow easily and will be more difficult to pour into place. For a given aggregate/cement paste ratio, the workability improves with higher w/c ratios. Therefore, the aggregate/cement paste ratio must be determined depending upon the local conditions and the construction method. If rebar corrosion is expected to be a problem, a low w/c ratio should be selected. This reduces the aggregate/cement paste ratio which means the cost of placing the concrete will increase.

Lastly, durability, which is defined as the ability to resist the freeze-thaw cycle, can be satisfied with the addition of air-entraining agents. For regions where freezing temperatures are not a problem, air-entraining agents are not required and may be ommited. However, for regions with freezing conditions, air-entraining agents are necessary and must be included. As previously stated, the entrained air allows further intrusion of chloride ions, but this is slightly offset by the use of a higher allowable aggregate/cement paste ratio.

4.1.2 Design Practices

The design practice which significantly influences the corrosion process is the "clear cover" or the depth of concrete covering the first row of reinforcements from the concrete surface. Experiments have shown that the probability of surface cracking decreased with increasing thickness of the clear cover. Also, the time it takes for cracks to first appear at the concrete surface, called the time-to-cracking period, increased with increased cover thickness.

A minimum of two inches of clear cover is required under normal conditions; however, in corrosive environments, the cover thickness should be suitably increased as the

conditions warrant.[15] The additional thickness in clear cover provides higher resistance against chloride infiltration, especially if the permeability of the concrete is low. Secondly, during the curing process, the concrete of the cover and the steel reinforcements exhibit different responses. While the concrete settles and contracts, the steel reinforcements restrain from any settlement. The resulting cracks are believed to be caused by the differential settlement of the two different materials. A thicker clear cover may possibly ease the settlement process and absorb some of the stresses produced.

4.1.3 Construction Practices

When steel reinforcements are delivered to the job site, care must be taken to minimize exposure to the elements, especially water and chlorides. If reinforcements are left bare for prolonged periods before being covered by concrete, the corrosion process could conceivably have already begun. Therefore, it is advisable to control this problem by using coated rebars, either epoxy coated or galvanized steel reinforcements. Detailed recommendations for providing overall quality in the placement, finishing, and curing of concrete may be found in publications by the Portland Cement Association (PCA),[16] U. S. Bureau of Reclamation,[17] American Concrete Institute (ACI)[18] and others.

Curing is the final essential phase of the concrete placement process.[19] One requirement is to maintain an adequate water content in the concrete to allow complete cement hydration. Secondly, the temperature of the concrete must remain above freezing to eliminate damages associated with volume changes during the transformation of water to ice. In addition, the temperature throughout the concrete must be kept reasonably uniform to minimize stresses due to thermal gradients. Lastly, time is required for the hydration and hardening process to fully develop for the safe use of the concrete structure. It takes approximately 28 days for concrete to attain yield strength, but curing time may vary as low as seven days depending upon the admixtures added to the concrete mix. In general, precautions must be taken throughout the construction process to ensure the properties of the concrete are not significantly altered from that which was designed or expected.

4.1.4 Concrete Coatings and Penetrants

Other methods of retarding chloride intrusion include the use of coatings (sealers) and penetrants. There are numerous organic and inorganic coating materials in use today which are applied directly and economically to the surface of new or existing concrete structures. These

coatings establish an impermeable barrier at the concrete surface to prevent chloride and water absorption into the concrete. Penetrants are applied directly on the concrete surface and diffuse into the concrete pore system. By filling all the voids, the penetrant and the cement aggregates establish a protective barrier against water and chloride intrusion.

In a 27-month study by the National Cooperative Highway Research Program (NCHRP), numerous coatings and penetrants were tested under differing environmental conditions to determine the most effective product.[20] The test objectives centered around the products ability to decrease the concrete's permeability. Besides preventing saltwater intrusion, the rate of water vapor transmission was evaluated since an effective material should also be able to allow the concrete to dry out during drying weather.

In the first test, the water absorption and chloride intrusion characteristics were evaluated among twenty-one products currently on the market. Subsequently the water vapor transmission characteristics were evaluated during the dry period. The water absorption characteristics of the twenty-one materials varied considerably with the five lowest values ranging from 10 to 30 percent of the value of the uncoated concrete as shown in Figure 4.4. Of the best five, four materials actually lost more weight by vapor

transmission during the drying period than they had absorbed during the water soaking period. As shown in Figure 4.5, the five best materials had chloride contents 79 to 97 percent less than the result of the uncoated control sample. The materials with the best results were identified as epoxy (#16), methyl methacrylate (#8), moisture-cured urethane (#4), alkyl-alkoxy silane (#6), and polyisobutyl methacrylate (#1C).[21] This study was not presented to imply that only these five materials are worth using, but to illustrate how effective the application of reliable coatings and penetrants may have on the rebar corrosion problem. Though corrosion may be reduced, exclusive use of coatings and penetrants will not completely eliminate corrosion problems. These effective and reliable products are already available for use, but additional tests will have to be conducted in the future as new, improved, and less expensive products are marketed.

4.1.5 Sealant

A special concrete mix, called wax bead concrete, is so named, because tiny wax beads are introduced into the mix during the mixing process. Thus, the wax beads are dispersed throughout the concrete matrix. After the setting and the curing of the concrete, heat is applied to the concrete surface, which in turn melts the wax beads. If the wax beads are evenly distributed throughout the concrete, the wax will

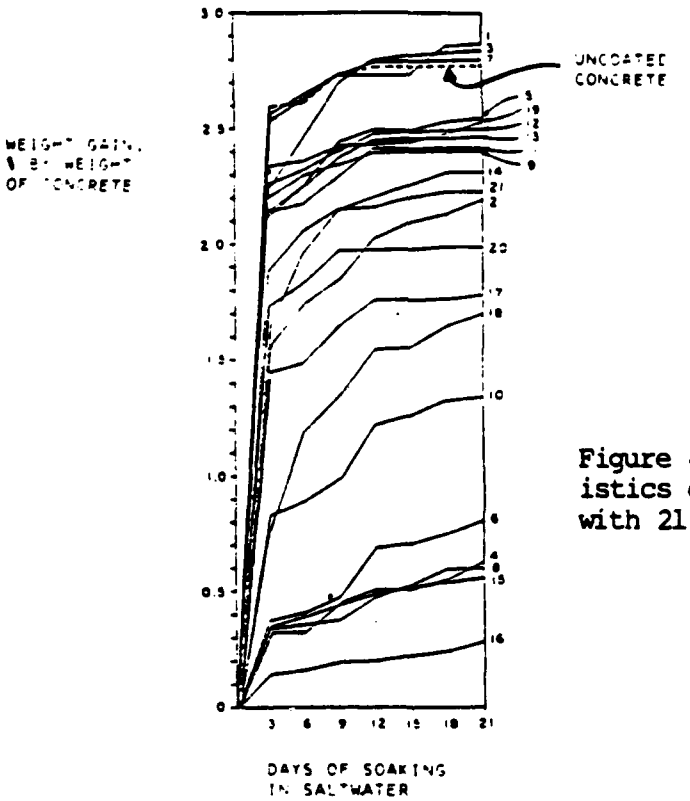


Figure 4.4 Water absorption characteristics of 0.53 w/c ratio concrete coated with 21 different coatings and sealers.[21]

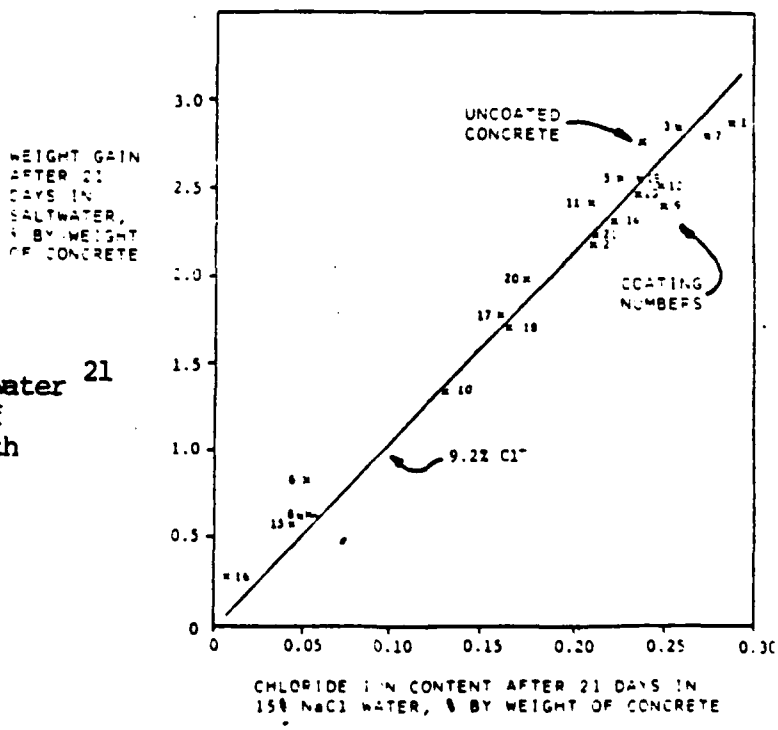


Figure 4.5 Relationship between water absorption and chloride content of 0.53 w/c ratio concrete coated with 21 different coatings and sealers.[21]

fill all the voids in the concrete and establish an almost impenetrable barrier to retard water and chloride intrusion. The cost of this method is relatively high due to the requirement for heating the concrete.

4.2 Protection of Reinforcing Steel

Having conceded to the presence of chloride ions in concrete exposed to corrosive environments, methods to protect the reinforcing steel can be effectively utilized to prevent, reduce, or arrest the corrosion process. The applications of specially coated reinforcing steel and cathodic protection are completely different, but the underlining purpose of inhibiting the corrosion process at the steel surface are common to both methods.

4.2.1 Coated Rebars

4.2.1.1 Galvanized (Zinc Coated) Reinforcing Steel

The manufacturing process and controls of galvanized reinforcing steel will be briefly described to gain further insight into its capabilities. In preparation prior to galvanizing, the rebar is submerged in a hot alkaline solution of caustic soda. Following a water rinse, the rebar is dipped in either hydrochloric or sulphuric acid for descaling and rust removal. Any residual acid or iron

salts remaining on the rebar is rinsed off before the rebar is dipped into a solution of zinc ammonium chloride. This solution forms a thin crystalline layer of salt on the rebar to shield it from exposure to the air while waiting to be galvanized. As the reinforcing steel is immersed in a bath of molten zinc, the zinc diffuses into the rebar at the surface and forms a layer of Zn-Fe alloy. The alloy growth around the rebar continues rapidly for the first minute and then decreases as the layer thickens and the diffusion path increases. Soon, only pure zinc layers form around the rebar and solidifies to a lustrous appearance as it is withdrawn from the bath. During the galvanizing process, the steel reinforcements are loosely bunched to ensure every layer of zinc properly covers the entire rebar. The rebar is supported at sufficient intervals to prevent any undue stresses. Finally, the galvanized reinforcing steel is completely submerged in a water-chromate solution to reduce any possible reaction between the alkaline cement paste and the zinc coating of the rebar. This process is also said to reduce possible electrochemical reactions with rebars of different potentials.[22] Galvanizing must be conducted in accordance with ASTM A767 - Standard Specification for Zinc Coated (Galvanized) Bars for Concrete Reinforcements.

The entire galvanizing process appears relatively successful in minimizing defects in the coating, but flaws, such as cracks, air bubbles, and pits, should be expected.

Additional defects are expected to occur during transportation, handling, bending, and shaping of the rebar. However, when the rebar is covered with cement, the formation of a zinc oxide layer on the rebar surface may tend to cover the defects and minimize potential problems. In the presence of water and chloride ions, the zinc coating sacrifices itself to cathodically protect the base metal. As previously stated, zinc oxide does diffuse into the concrete; thus, reducing a major buildup of internal pressure in the concrete. In a corrosive environment, the steel will eventually begin to corrode after the depletion of the zinc coating. This is not to imply that galvanized steel reinforcements do not afford satisfactory protection against corrosion. On the contrary, examination of existing structures constructed with galvanized reinforcements have provided encouraging results. Galvanized reinforcements do provide limited protection against corrosion, but depending upon the concentration of corrosive agents present, other protective measures must also be considered in the design.

4.2.1.2 Epoxy Coated Reinforcing Steel

Since the manufacturing process of epoxy coated rebars is significantly different from that of galvanized rebars, a brief description of this process is also provided. As it passes through an abrasive blast cleaning machine, the steel reinforcement is bombarded by steel shot

and grit. Thus, mill scale and rust are removed and a near white steel surface is produced. The rebar is then heated to a temperature of approximately 450°F by either a gas fired heating chamber or an electric induction coil. The rebar then passes through the coating chamber. The fusion bonded epoxy resin is applied to the rebar with an electrostatic powder spray gun. The grounded moving bar attracts the charged resin particle and the resin melts instantly on contact. The molten resin covers the rebar surface, gels in seven seconds, and solidifies within fifteen seconds. If the hardened epoxy is heated, it will not soften, because the process is an irreversible chemical reaction. Following the coating process, the rebars are quenched with water and allowed to cure. The finished product is monitored by electronic detectors searching for flaws or pinholes, known as "holidays". If more than two holidays per foot of reinforcement are detected, the rebar becomes rejectable. A minimum coating thickness of five mils is required to provide sufficient corrosion protection and a maximum of twelve mils is specified to maintain bonding with the concrete.[23] The standard specifications for epoxy coated reinforcing bars are provided in the ASTM A775-81.

This seemingly impermeable coating prevents the steel reinforcements from having direct contact with water and chloride ions. Therefore, the corrosion process is not expected to occur and the rebar is fully protected.

Laboratory tests of epoxy coated rebars in concrete cylinders have resulted in corrosion failures of only a few samples. When corrosion did occur, it apparently was initiated in the undetected flaws of the epoxy coating. From all indications, chloride ions are not able to penetrate or damage the epoxy coating and the continued use of epoxy coated rebars appears promising. Examination of existing structures, which contain epoxy coated rebars, reveal no apparent corrosion problems. It should be remembered that the use of epoxy coating dates back only ten years and the structures have more than forty years of expected life remaining. Thus, it may be a bit premature at this point to consider the use of epoxy coated rebars as the answer to all corrosion problems.

Visual inspections can only determine that the corrosion process is in the advanced stages if a surface crack should appear. If there are no surface cracks, it is uncertain as to whether corrosion of the reinforcing steel has been prevented or is developing, but has not developed sufficient internal pressure to crack the concrete. Presently, the preferred method of determining whether the corrosion process is occurring or not is to ascertain the electrochemical potential of the steel reinforcements with the use of a monitoring device called the potentiometer. When regularly plotting the potential of a rebar, a decreasing potential indicates a higher resistance in the

behavior of the rebar. It may then be concluded that the increased resistance is due to corrosion, which is altering the microstructure of the steel. In order to properly monitor the system, one lead from the potentiometer must be connected to the reinforcing steel and the other wire from the potentiometer is connected to a suitable reference electrode, which is positioned on the concrete surface over the rebar specimen to be measured. For the current to make a full circuit, it must flow from the rebar to the reference electrode. However, the epoxy coating is a very poor conductor and may cause inaccurate readings. In addition, the rebar system of a structure may be tied together, but the epoxy coating prevents metal-to-metal contact. Again, in order to have a complete circuit, leads would have to be connected to each rebar. Therefore, the enormous cost would almost preclude the use of a monitoring system for such a structure. Due to this problem, the use of galvanized reinforcing steel would be considered more advantageous, because the steel reinforcements can be monitored very easily.

4.2.2 Cathodic Protection

The application of cathodic protection in the construction industry has been limited primarily to underground pipelines, storage tanks, and other steel structures. In the last decade, the use of cathodic

protection for reinforced concrete structures in especially corrosive environments has gain popularity due to its proven ability to prevent corrosion and its economic benefits. Cathodically protected systems can expect very little corrosion problems during and possibly beyond the expected life of the structure. For existing facilities experiencing rebar corrosion, a cathodic protection system can be installed to arrest the corrosion process and extend the useful life of the structure at a reasonable cost.

4.2.2.1 Basic Principle

The cathodic protection system is based on the principles described earlier in Chapter Three. In a simple system, as shown in Figure 4.6, there exists two electrodes, a cathode (iron rebar) and an anode, connected by wires to a direct current source, generally a potential-controlled rectifier. Whereas the steel reinforcement acts as an anode supplying electrons during the corrosion process, the rebar now assumes the role of the cathode in the cathodic protection system. This is achieved by introducing an electrode having a more negative potential than the steel reinforcement. As the current source supplies electrons to the anode, the electrons complete the circuit by flowing through the pore system of the concrete to the steel rebar and back to the source. If the current is high enough, there will be sufficient electrons available to continue the

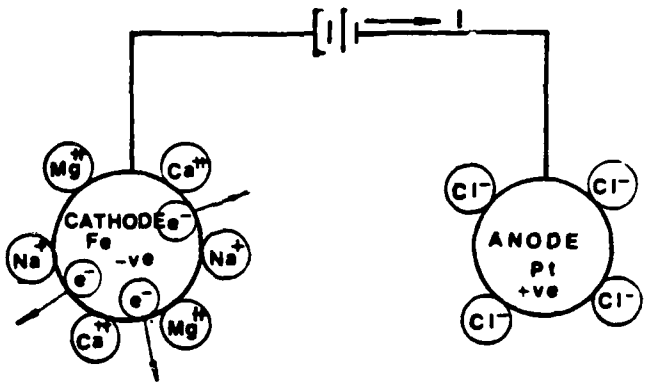


Figure 4.6 Cathodic protection system operating in presence of chloride ions. [24]

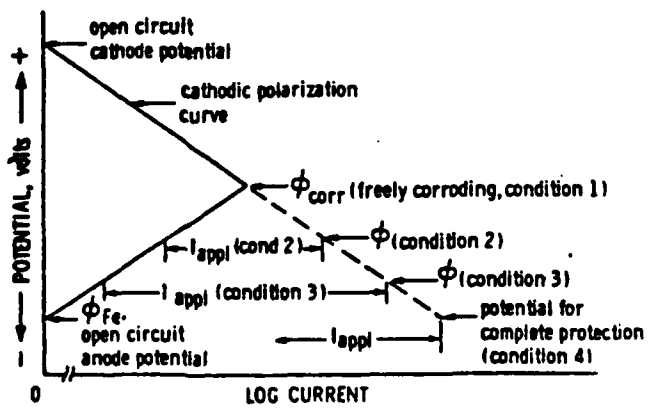


Figure 4.7 Polarization diagram illustrating how successive levels of cathodic polarization reduce the anodic current and thereby lower corrosion rate. [25]

circuit back to the source and also to establish a surplus of electrons at the surface of the steel rebar. In this state of electron saturation, the iron atoms, which make up the microstructure of the rebar, are less likely to lose their electrons and can easily replace those electrons that were lost. Thus, this prevents the formation of iron ions (Fe^{+2}) and their subsequent migration into solution. Secondly, chloride ions are attracted to the anode due to the emission of electrons by the anode. The chloride concentration around the steel rebar is effectively reduced and so is the primary cause of rebar corrosion.[24]

In the polarization diagram (refer back to Figure 3.1), corrosion of the iron rebar occurred because the system's mixed potential was lower (more positive) than the open circuit potential of the iron anode. However, when the metal is polarized to the reversible or open circuit potential of the anode, full protection is achieved. In fact, if iron ions are available near the metal surface, the surplus of electrons will produce iron precipitate, which may form on the metal surface. Cathodic protection may be defined as the maintenance of a critical potential at the surface of the cathode.

Figure 4.7 illustrates the amount of current required to provide a certain degree of cathodic polarization.[25] From it, the following equation is derived:

$$I_c = I_a + I_{appl}$$

where

I_c is the cathodic current at a particular potential.

I_a is the anodic current at a particular potential.

I_{appl} is the current supplied from the external source.

Past experiments have suggested the use of different potentials for various situations. According to Scott,[26] rebars with a damaged concrete cover can be cathodically protected by increasing the steel polarization potential to a range of -0.71 to -0.81 volts, referenced to a copper-copper sulfate ($Cu/CuSO_4$) electrode. Both Tomashov[27] and Hausman[28] agree that to prevent an uncorroded rebar from corroding a current must be applied to the rebar to raise its polarization potential to a minimum value of -0.51 volts, when referenced to a $Cu/CuSO_4$ electrode. Also, corrosion of a corroding rebar can be completely arrested if the polarization potential of the rebar is raised to -0.81 volts with sufficient current applied.

4.2.2.2 Problems with Cathodic Protection

As a form of electrolyte, concrete is a relatively poor conductive medium, especially if other measures are taken to reduce the permeability of the concrete. Though higher currents are required for low permeable concrete, an

impressed current cathodic protection system can easily handle the load. The problem lies in the system's ability to spread the current uniformly over the length of the reinforcement. High resistivity on the part of the concrete will concentrate the current on areas of the rebar in close proximity to the anode and areas further away may not receive sufficient current. Of course, anodes can be designed at closer intervals to provide more current uniformity at a higher construction cost. Various types of conductive overlays and coatings have been used with fairly successful results. A model of a reinforced concrete bridge deck, shown in Figures 4.8 and 4.9, details the arrangement of the steel reinforcements and the setup of the cathodic protection system. In Figure 4.10, a saw-cut slot has been filled with a conductive grouting material and a platinum-niobium anode. For concrete piles half submerged in seawater, platinum-niobium wires can be attached onto the concrete surface and then painted over with a conductive coating. This method is very effective, especially for use in the splash zone where rebar corrosion is expected to be a problem.

If all the steel reinforcements are not connected metal-to-metal and the reinforcements are not highly conductive, this will prevent a problem for a cathodic protection system and a polarization potential monitoring system. As previously explained, it will be very difficult,

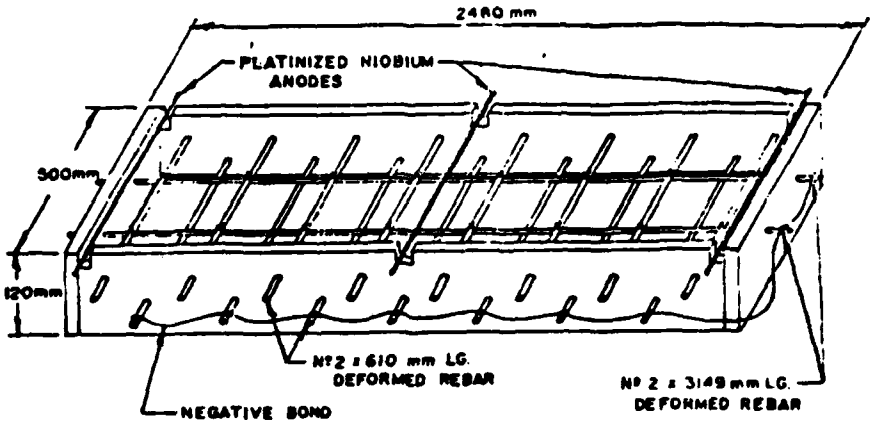


Figure 4.8 Model reinforced concrete deck.[24]

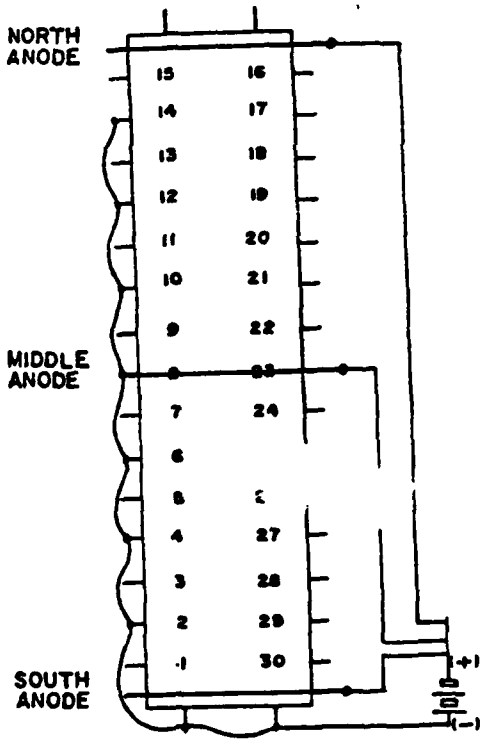


Figure 4.9 Reference potential locations in experimental deck.[24]

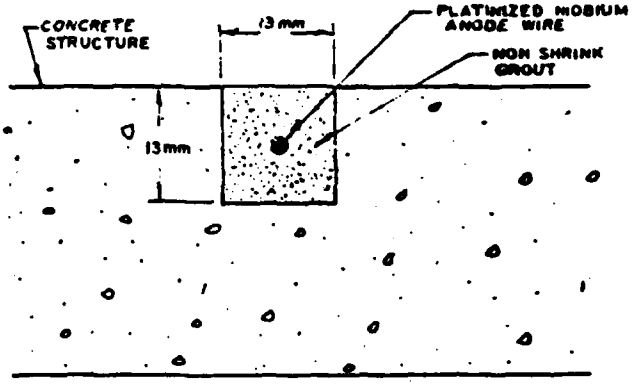


Figure 4.10 Installation of anode wires in saw slots.[24]

if not impossible, to use the cathodic protection system in conjunction with epoxy coated rebars since there is no metal-to-metal contact in the reinforcement arrangement. Therefore, present designs must include the above requirements and select the most effective materials to achieve maximum protection.

Caution must be exercised during the cathodic polarization of the steel reinforcement to ensure the potential does not greatly exceed its open circuit potential. Should the impressed current supply an overabundance of electrons, which accumulate at the steel surface, a condition known as hydrogen embrittlement may occur. The availability of excess electrons will result in hydrogen evolution at the steel surface. Should the atomic hydrogen penetrate into the steel structure, the rebar will lose ductility and tensile strength. This condition may prove extremely harmful since the steel reinforcements may experience abrupt failure. Thus, a cathodic protection system must be complemented with monitoring devices to prevent such conditions from occurring.

4.2.2.3 Design of Cathodic Protection Systems

After having decided upon utilizing a cathodic protection system, the first consideration in its design should be the local conditions in which the structure will

function. Determine the resistivity, chloride and sulfate concentrations, and the pH of the soil and seawater, as well as the characteristics of the concrete mix. There are two basic types of cathodic protection systems from which to choose. First, the use of sacrificial anode materials, such as zinc, aluminum, and magnesium, may be used to supply the required current. These metals have potentials more negative than that of iron, which causes the flow of electons to cathodically protect the steel rebar. As the anode deteriorates, it must be periodically replaced. Secondly, an impressed current system utilizes a DC current source, such as a rectifier, connecting wires and an anode. In the selection of an impressed current anode, platinum-niobium wire with or without copper cladding is suggested,[29] because of its ability to uniformly distribute electrical current and to withstand erosion. The advances made in our understanding of cathodic protection for reinforcing steel and the availability of new materials to optimize its use have made cathodic protection an economically attractive alternative. Since it was first used in reinforced concrete over a decade ago, cathodic protection has been proven reliable and its cost to implement has steadily decrease.

CHAPTER FIVE

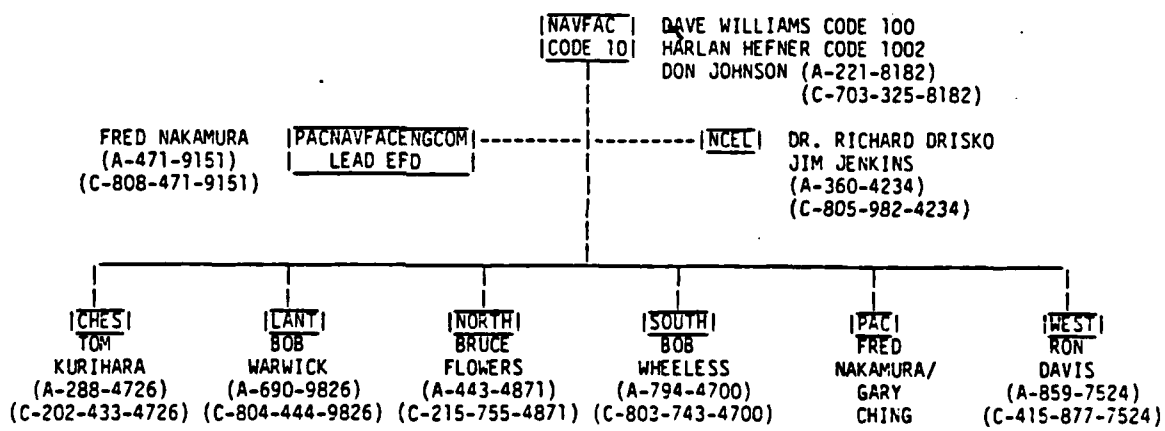
U. S. NAVY'S CORROSION CONTROL PROGRAM

5.1 Navy Program for Shore Facilities

The Navy's current program pertaining to corrosion control of shore facilities consists of about ten instructions and design manuals. Perhaps due to other more urgent requirements, the use of corrosion control measures out in the field appears to have been neglected by design engineers and ignored by management. However, prompted by costly corrosion problems experienced by U. S. naval shore installations throughout the world, the Naval Facilities Engineering Command (NAVFACENGCOM) will soon be implementing its C^4 Program: Corrosion Control by Coatings and Cathodic Protection.

This past July, a rough draft of NAVFAC INSTRUCTION 11014 (see Appendix A) was distributed to each major participating command for review and comments. The instruction is expected to be issued in the near future. The instruction defines the duties and responsibilities of the shore activities, the engineering field divisions (EFDs), NAVFACENGCOM, and the Naval Civil Engineering Laboratory (NCEL). In conjunction with this instruction, NAVFACENGCOM has recently established a program committee consisting of command representatives from NAVFACENGCOM, NCEL, and the Navy's six EFDs. Figure 5.1

NAVFAC - C^4 PROGRAM - CORROSION CONTROL BY COATINGS AND CATHODIC PROTECTION



NAVFAC - ESTABLISH CORROSION CONTROL POLICY AND TECHNICAL CRITERIA

LEAD EFD (PACDIV) - 1. ASSIST NAVFAC IN THE DEVELOPMENT OF NAVY-WIDE POLICY AND CRITERIA ON CATHODIC PROTECTION
2. SUPPORT HEADQUARTERS & OTHER EFD'S IN HIGHLY TECHNICAL MATTERS RELATING TO THE MAINTENANCE AND REPAIR CATHODIC PROTECTION SYSTEMS

NCEL - RESPONSIBLE FOR RESEARCH & DEVELOPMENT OF CORROSION ENGINEERING TECHNOLOGY

EFD'S - ASSIST IN IMPLEMENTATION OF EFFECTIVE CORROSION CONTROL PROGRAM AT MAJOR COMMANDS AND ACTIVITIES

(A-AUTOVON PHONE NUMBER)
(C-COMMERCIAL PHONE NUMBER)

Figure 5.1 ORGANIZATION CHART AND CORROSION PROGRAM CONTACTS

illustrates the organization chart and identifies the point of contacts of the C^4 program, as well as the responsibilities of each command. Once fully implemented, the Navy's corrosion control program will cover policies and technical criteria, research and development, and implementation and monitoring of corrosion control programs at each major command and activity.

5.1.1 Research and Development

In a recently published technical memorandum,[30] NCEL assessed the latest concrete technology in practical use today and its possible use by the Navy in a marine environment. In addition, the authors of the report indicated that the design activities required technical data and criteria for cost effective application of new corrosion control measures, such as epoxy coated rebars, concrete coatings, and polymer portland cement concrete, just to name a few. The bulk of the report contains prioritized candidate task descriptions (CTDs), which describes the purpose, description, relevance, and cost of each proposed project. However, due to the competition for funds against other research topics and navy requirements, it is expected that only a portion of the funds requested to further concrete technology will be provided. NCEL has efficiently organized its program to ensure the limited funds are first spent on the highest prioritized CTDs. Also, NCEL personnel have

contacted other federal and state agencies and private research institutions to exchange research information and to prevent duplication of research effort. Since the application of new concrete technology is expected to realize cost savings exceeding the research expense, it is recommended that additional RDT&E funds be provided to NCEL for its continued research in concrete technology. With the scarcity of funds being a way of life, NCEL must conti e to use other agencies as a source of information by keeping abreast of new research development. The findings must be assessed as to its value to the Navy and from the findings, criteria must be developed and timely distributed to the field activities.

5.1.2 Program Implementation at the Activity Level

The success of the corrosion control program will largely depend upon the involvement at the activity level. This is expected to be accomplished by NAVFACINST 11014, which requires the activities' participation in the Navy's corrosion control program and outlines their responsibilities. The activities will be required to submit a list of cathodically protected systems, which are in their real property inventory, to their respective EFDs and to follow-up with quarterly potentiometer readings of each system. Existing facilities not protected are to be identified and listed as a candidate project considered for

future funding. However, the instruction itself will not guarantee total or even partial success of the program. Attention must be focused at the activity level to overcome problems presently being experienced by the activities.

Due to insufficient funds in the past, corrosion control measures have not always been included in the project design. This practice of reducing construction cost became acceptable, because it, at least, provided for the construction or repair of the facility as desired. If the reduced construction cost provided excess funds, other more visible or higher prioritized project scope could be funded. However, this practice has created corrosion problems, which must now be dealt with by today's managers and engineers. Labor and material costs are now higher and construction and repair funds are still inadequate to correct all deficiencies. On the other hand, the cost of including corrosion control measures in the project design is now reasonably priced and offers an economically viable alternative. The inclusion of these measures provides several benefits to the activities, such as extending the life of the structure, delaying future replacement costs, reducing repair and maintenance costs throughout its expected life, and enhancing safety considerations.

In a telephone conversation with Mr. Bob Wheeles,[31] corrosion engineer at SOUTHNAVFACENGCOM, Mr. Wheeles

indicated that the activities lack experienced and knowledgeable personnel in the field of corrosion engineering. Before undertaking this report, the author, like most civil engineers, was not familiar with the principles and mechanics of the corrosion process. If engineers are unaware of corrosion mechanics and possible corrosion problems, preventive measures will not even be considered in the project design and nor will assistance be sought from the corrosion engineer. A good training program may resolve part of this problem. The NCEL offers a very informative corrosion seminar, in which highly qualified instructors travel to areas of densely populated naval activities to train design engineers in the field.

The NAVFACINST 11014 will require the EFDs to review project drawings to screen projects for possible application of corrosion control measures. However, not all designs prepared at the EFD level are forwarded to the corrosion engineer for his or her review. If the design engineer does not consider corrosion as a problem in the design or neglects to forward the drawings to the corrosion engineer for his or her review, the design is passed through the system without being properly checked for conditions conducive to corrosion. For the same reasons, designs prepared by Architect-engineer (A-E) firms and coordinated by a Navy project manager may not be checked for possible corrosion problems. In addition, the design process can be

accomplished at the activity's own Public Works Department (PWD), the nearest Public Works Leading Activity (PWLA), or the nearest Public Works Center (PWC). The design does not necessarily have to be forwarded to the EFDs (except for projects with special systems, such as fire protection systems) for approval. The corrosion engineer at the EFDs probably would not have enough time to review the full load of all activity drawings. Therefore, it is important that measures be prescribed to review project drawings at the activity level. Most activities would prefer the entire design be completed and reviewed within their own organization and not be required to be forwarded to the EFD, since a review at the EFD would increase the design period. This concept would require the designation of a qualified corrosion engineer at all PWCs and PWLAs to review the designs generated at these activities.

5.1.3 Policy and Criteria

In accordance with NAVFACINST 11014, NAVFACENGCOM will be responsible for establishing the policy and criteria for the corrosion control program of naval shore facilities. NAVFACENGCOM serves as the head of the technical engineering chain of command; however, it has no operational control over the naval shore activities, with the exception of the six EFDs, three Construction Battalion Centers, the nine PWCs, and a few other small activities. It is the

responsibility of the major claimant to provide their shore activities with operation and maintenance funds to finance the activities' operations. Therefore, to develop a successful program, NAVFACENGCOM must solicit the support of the Chief of Naval Operations (CNO), the Chief of Naval Material (CNM), and other major claimants. It is imperative that the major claimants express their support for the program and direct their activities to fully cooperate and participate in the program. With such support at the major claimant level, the priority to establish and maintain a strong corrosion control program at the activity level may be raised high enough to include corrosion control as an integral part of a continuing facility maintenance program.

In addition, assistance to the activities may be in the form of additional construction or maintenance funds to be used only for corrosion control measures, such as cathodic protection systems. This specially "fenced" source of funds from NAVFACENGCOM or the major claimant will provide an additional awareness and incentive at the activity level to include corrosion control measures into the activity's maintenance program. The facility maintenance officer, who is able to acquire special funds, such as for energy conservation and pollution abatement projects, is considered aggressive and exemplary by his or her superiors.

The failure to include corrosion control measures in the project design is primarily due to the lack of interest or concern on the part of the activity management. As the commander for facilities engineering, NAVFACENGCOM can exercise its authority to overcome this problem. For candidate projects to be included in the Military Construction Program (MILCON) and the Special Project Program, DD Form 1391 and Step II submittals, respectively, must be prepared and forwarded to the activity's major claimant. These submittals provide the major claimant with a description of the projects' scope, the activity's justification for requesting funding approval, and a government estimate of the total project cost. When energy conservation became an issue of concern, all project submittals, which included the installation of individual or central air conditioning units, were and still are required to be accompanied by an economic analysis indicating the feasibility of such a proposal. This requirement is explicitly stated in the OPNAVINST 11010.20, Facilities Project Manual. An inclusion of such a procedure into the OPNAVINST 11010.20, which would require a feasibility study of possible corrosion control measures for all projects, would certainly receive a lot of attention and would eliminate the problem discussed earlier of a project passing through the design phase without being reviewed for possible corrosion problems.

Recognizing the need for corrosion control measures during the preparation of the project submittal benefits the Navy in two ways. First, a thoroughly developed project scope will identify the need for corrosion control measures, if required, and specify the type and cost of measures to be applied. If measures are introduced during the design phase, additional design time will have to be added to allow the design engineers sufficient time to properly complete the design. Thus, the schedule of the engineering department must be shuffled to accommodate the changes. If the design is being undertaken by an A-E firm, a change order to the design contract must be negotiated in response to the additional request. In both cases, the schedule of the design engineers are adjusted and additional work must be performed to administer the changes.

Secondly, the inclusion of corrosion control measures, later in the design phase or even in the construction phase, will require additional funds from the activity's major claimant. Since projects compete for limited funds at the major claimant level, a project requiring additional funds may only receive funds initially requested by the project submittal. In such cases, the additional request for funds may not be approved and the corrosion control measures would be left out of the project. Had the cost been included in

the project submittal, funds for the entire project would most likely have been approved.

After review of the final drawings, the activity's corrosion engineer must sign and date a section in the title block designated for the corrosion engineer. Before the contracting officer advertises the contract, the title block of the final drawings are checked for the signatures of the owner/customer, the engineering director, the design engineers, and the corrosion engineer. If the plans are not signed by any one of the above individuals, they are returned for the final signature.

It should be noted that smaller projects requiring only the approval of the activity's commanding officer do not require the forwarding of a project submittal and major claimant approval. Generally, projects within the local commanding officer's funding authority and greater than $20,000 require plans and specifications prepared by the engineering department. Though the corrosion engineer may not participate in the early phase of the design, he or she will eventually be asked to review the drawings and sign them. For such small projects, input from the corrosion engineer at a later stage of design would not cause significant scheduling and funding problems.

Prior to formally submitting such a request to the CNO level, NAVFACENGCOM may decide to implement this procedure on a trial basis at certain activities. If it proves to be successful, the results will provide NAVFACENGCOM with additional support for its request to have it incorporated into the OPNAVINST 11010.20.

5.2 Design Manuals (DMs)

From a technical viewpoint, if the design process is considered the heart of the corrosion control program, then the guidance provided by the Navy's design manuals must reflect current practices to achieve success. A brief examination of present design manuals pertaining to corrosion control was conducted to review and evaluate their contents.

5.2.1 Concrete Structures - General

The most significant design manual covering the design criteria for concrete use is NAVFAC DM-2.4, Concrete Structures.[32] For the most part, this manual simply directed the use of other standard references. For example, the manual references the ACI Standard 318, Building Code Requirements for Reinforced Concrete, for reinforced concrete structures and the ACI Standard 322, Building Code Requirements for Structural Plain Concrete, for plain

concrete structures. This attempt to be current with the latest ACI standards is, perhaps, a means of avoiding duplication of effort. However, the brevity of the manual causes most design engineers to refer directly to the ACI standards and, for the most part, totally neglect the design manual. The design manual should be a more resourceful reference that provides numerous criteria and recommendations for the designer, which prompts the designer to confidently seek guidance from it during the course of a design.

Under the special consideration section, the problem of rebar corrosion is recognized, but the criteria certainly lack completeness and depth. The manual does suggest the use of increased concrete cover, smaller size rebars, surface coatings and sealers, and coated (zinc or plastic) reinforcements. Unfortunately, one brief sentence will not adequately provide the information required by the designer to overcome such a complex problem as corrosion. For structures continuously exposed to corrosive environments, the inclusion of the following items is recommended:

a. Site examination be conducted by the design engineer or corrosion engineer to obtain a full perspective of the conditions under which the completed structure or system will function. Specifically, the chloride concentration and pH of the water or soil, wave action and tidal changes, existing facilities or systems, which will be attached to

the new facility, and possible stray current conditions during its use.

b. Gather information concerning available resources for the probable maintenance plan of the facility. This may help to decide which corrosion control measure to employ for this particular project.

c. In a repair project, the reasons for the facility's present failure must be determined to allow countermeasures to be implemented.

d. Perform an alternatives and cost analysis to determine the best method of corrosion protection and emphasize quality and cost over the expected life of the facility.

e. Specify a quality concrete mix which is practical, while considering the environmental conditions, cost and availability of materials. Usually for corrosive environments, Type II or Type V cement is used with possibly the addition of fly ash pozzolanic material, because of their excellent corrosion resistant properties. A water/cement ratio of 0.4 should be specified for low permeability of the concrete. The strength requirement of the concrete is already listed in the Navy and ACI manuals.

f. The use of concrete coatings and sealers or special concretes, such as polymer and wax bead concretes, should be considered.

g. Cathodic protection should be considered, with reference to the cathodic protection manual.

The purpose of providing all the above information in the design manual is to make the design engineer aware of the fact that the various conditions make the project unique and only by considering all the conditions will the best solution be obtained.

5.2.2 Tropical Engineering

For concrete construction in tropical regions, NAVFAC DM-11.1, Tropical Engineering,[33] applies. This manual is much more detailed and provides a lot of useful information. It covers the components of a concrete mix better than NAVFAC DM-2.4, but more thorough specifications would enhance its final product. Also, it states that the use of cathodic protection was found to be uneconomical. Without having full knowledge of the conditions in which the study was conducted, one can doubt, but cannot disagree with that statement. If an electrical source is not readily available in the area or if a maintenance crew is not on hand to properly maintain and monitor the system, the use of cathodic protection may not be a feasible alternative and the use of galvanized or epoxy coated reinforcements would be a more practical solution. However, if there are no outstanding problems in installing a cathodic protection system, which would drive up the construction cost, the system should prove to be a feasible alternative and be comparable with the other corrosion control measures. This

manual does recognize and discuss the potential problems, which may be caused by the use of local coral aggregates and seawater.

5.2.3 Cold Region Engineering

For concrete construction in cold regions, the standards in NAVFAC DM-9, Cold Region Engineering,[34] applies. This manual, also, is a bit more thorough than NAVFAC DM-2.4. It addresses the two major problems of freeze-thaw cycles and the mixing and pouring of concrete in below freezing conditions. The requirement for air-entraining agents is much more important for concrete construction in cold regions than it is for tropical regions, but strangely, the specifications for air-entraining agents are not provided in NAVFAC DM-9 and are published in NAVFAC DM-11.1. Therefore, it is recommended that specifications for air-entraining agents and other admixtures be included in this manual.

5.2.4 Cathodic Protection

The technical guidance for cathodic protection is clearly stated in NAVFAC DM-4.6, Electrical Engineering: Lightning and Cathodic Protection.[35] NAVFAC DM-4.6 addresses the application of cathodic protection on all types of steel structures and systems, but fails to consider the use of

cathodic protection on reinforced concrete structures. Otherwise, the requirements specified for cathodic protection of other structures are quite thorough and descriptive. Though the overall requirements are fairly up-to-date, since it was last revised in 1979, the latest improvements in material and equipment should be included as an addendum or as part of a guide specification. In addition, specific requirements for protection of petroleum fuel facilities are stated in NAVFAC DM-22, Petroleum Fuel Facilities.

5.3 Design Specifications

Requirements used in Navy contract specifications are taken from the Naval Facilities Guide Specification (NFGS) series. These publications were not reviewed. However, Boettcher[30] states that the NFGS requires revision to reflect the most up-to-date knowledge of specifying durable concrete.

In specifying concrete mix, it has been the usual practice to simply specify the required strength of the concrete. Should more stringent requirements be specified for the proportions of the concrete mix, the cost of construction will increase since the contractor assumes a greater risk. Should the contractor fail to provide the concrete mix called for by the specification, the contractor must bear

the cost of removing the unsatisfactory product and place new concrete, which does satisfy the specifications. The price of concrete will increase for the owner, but the owner must recognize the higher cost as the price one pays for a quality product. All too often, the owner's design engineer considers the initial cost of the project over the quality of the product. Where quality concrete is specifically required for use in corrosive environments, the design engineer must proceed beyond the normal performance specs and clearly specify the w/c ratio, the aggregate type and size, the proper proportion of admixtures, and the proper construction practices. The Navy must not compromise the quality of the concrete for lower construction costs, because in the long run, the total life cycle cost of the reinforced concrete structure made of quality concrete will be less than the total life cycle cost of the structure made of normal concrete.

5.4 Quality Control

For all projects, especially marine projects, it is desirable to obtain the services of a contractor who is experienced and qualified to properly execute the contract. In marine projects, the lowest bidder often lacks the experience required and, therefore, is unaware of the additional risks he accepts of providing a higher quality concrete mix. In addition, there are more requirements for

placing the concrete, which the contractor may not be aware of and which is not reflected in the proposed bid. There is an experience clause in the Navy Contracting Manual, which can be used to exclude inexperienced contractors. To resolve this problem, Navy contracting officials must properly screen the bidding contractors and exercise this option when appropriate to ensure the contract is awarded to the lowest qualifying bidder.

The contractor is responsible for hiring a quality control person to monitor the quality of the contractor's work. For larger projects, the Navy may specify the hiring of an experienced staff of quality control personnel. However, in either case, the contractor has the final decision on hiring the quality control personnel. To avoid liability, the Navy should remain divorced from the selection process, but should have the authority to set the criteria for selection.

The Resident Officer-in-Charge of Construction (ROICC) is responsible for quality assurance of the project. The ROICC and staff inspectors frequently visit the job site to ensure the contractor adheres to the contract specifications. To accomplish this task, the ROICC and inspectors must request and review the laboratory and field test results required by the contract specifications to be performed by the contractor. A dedicated staff will keep the contractor

performing at a level of quality equal to or above that, which is specified. If quality assurance is not properly performed, then detailed specifications by designers and strict enforcement of contracting procedures by contract administrators will be compromised to the disadvantage of the Navy.

CHAPTER SIX

CONCLUSION

The Navy's corrosion control program for shore facilities is making steady advancements. In the past, corrosion problems did not receive adequate attention from design engineers and managers at all levels. Perhaps, this was due to more urgent requirements or the lack of concern or awareness. Also, the program lacked specific guidance from top level management and coordination between NAVFACENGCOM, the EFDs, and the shore activities. However, the new C^4 Program: Corrosion Control by Coatings and Cathodic Protection appears to have the right ingredients to resolve the major problems. NAVFACENGCOM is stressing its concern for the high cost associated with corrosion and is emphasizing a higher priority and deeper concern for this problem to the naval activities. The new NAVFACINST 11014 clearly states the duties and responsibilities of each command, which should catch the attention of management at the activity level. The motivation to establish a strong program does exist, but there is no certainty that the activities will respond in a very positive manner.

For this program to be successful, NAVFACENGCOM must solicit the support of CNO, CNM, and other major claimants, since most shore activities are not under the operational control of NAVFACENGCOM. With such high level support, the priority

to establish and maintain a strong corrosion control program at the activity level may be raised high enough to include corrosion control as an integral part of a continuing facility maintenance program.

Though reinforced concrete has been in use for over a century, improved materials and methods developed in recent years have produced considerable improvements. Though the Navy's design manuals and guide specifications are generally up to date, revisions or addendums are required to reflect the current state of the art, with respect to corrosion control. The design manuals need to be more descriptive in providing information and criterias for the design engineers. This is due to the fact that the average civil engineer is not thoroughly trained in corrosion engineering. However, the design engineer does not have to be nor is he or she expected to be so well trained in corrosion engineering, if sufficient background and guidance on corrosion is provided. If design engineers become more familiar with corrosion problems and methods to prevent or arrest it, the project design will reflect greater quality, safety, and economy.

Reliable coatings and penetrants effectively reduce corrosion of reinforcing steel when applied to reinforced concrete structures. Reasonably priced and relatively easy

to apply, coatings and penetrants, also, substantially delay the initiation of rebar corrosion.

The use of coated reinforcing steel is preferred over plain uncoated reinforcing steel for two reasons. First, corrosion of plain rebars may start before the rebars are covered by the concrete mix. This is due to the moisture in the air, which attacks the rebar while in storage or during transporting. Second, after the corrosion process is initiated, the corrosion product of steel will produce greater internal stress within the concrete than the corrosion product of zinc. Thus, cracking of the concrete will occur earlier in concrete embedded with plain rebars.

Galvanized reinforcing steel provides protection from corrosion, but the steel will eventually begin to corrode after the depletion of the zinc coating. Then the rebar will exhibit the same properties as plain rebars.

Thus far, epoxy coated reinforcing steel have proven to be very successful against corrosion in field tests. However, the epoxy coating precludes the use of any type of cathodic protection and monitoring system, since electrical currents cannot pass through the epoxy coating.

The use of a cathodic protection system is an attractive alternative and it can be easily complimented with a

monitoring system. However, care must be taken to prevent hydrogen embrittlement, which causes the reinforcing steel to lose ductility and tensile strength.

Lastly, performance specifications of concrete, currently used by the Navy, are not adequate to ensure the placing of quality concrete. The specifications for the concrete mix must include, besides strength capability, the optimum water/cement ratio, aggregate type and size, and proportion of admixtures. Specifications for quality concrete are a must, if concrete structures, especially in corrosive environments, are expected to maintain their usefulness over their expected life.

CHAPTER SEVEN

RECOMMENDATIONS

Following review of the Navy's corrosion control program for shore facilities, recommendations are presented to suggest improvements in the program.

1. Specifications for quality concrete mix should include:

a. A water/cement ratio of 0.4.

b. The selection of proper size gradation and shape of aggregates.

c. The selection of proper proportions of admixtures, depending upon desired setting time and workability.

d. The use of fly ash to replace up to 20 percent of portland cement.

e. The use of Type II or Type V cement in corrosive environments.

f. In cold regions, the use of air-entraining agents in the concrete mix and the installation of a cathodic protection system.

2. Design should include:

a. The use of galvanized or epoxy coated rebars.

b. The use of coatings and penetrants on the concrete's surface.

c. The use of cathodic protection, if determined to be an economically attractive alternative.

d. A thickness greater than two inches for the concrete clear cover, depending upon the corrosiveness of the environment.

3. The Navy's design manuals and guide specifications must be revised to reflect the current state of the art, with respect to corrosion control.

4. Funding for NCEL be increased for its continued research in corrosion and concrete technology.

5. In addition to corrosion engineers at the EFD level, qualified corrosion engineers must be designated at all PWCs and PWLAs to review the designs generated at these activities.

6. A provision be added to the OPNAVINST 11010.20, which would require an economic analysis for corrosion control measures be prepared and included in all MILCON DD Form 1391 and Special Project Step II submittals.

7. After reviewing the drawings, the activity's designated corrosion engineer must sign and date a section of the drawing's title block specifically designated for the corrosion engineer. The contract must not be advertised without the corrosion engineer's approval of the drawings.

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
200 STOVALL STREET
ALEXANDRIA, VA 22332

IN REPLY REFER TO
NAVFACINST 11014.
FAC 1002

NAVFAC INSTRUCTION 11014.

From: Commander, Naval Facilities Engineering Command

Subj: Corrosion control of shore facilities

Ref: (a) SECNAVINST 11010.11A (NOTAL)
(b) OPNAVINST 11000.16
(c) OPNAVINST 11010.20, Facilities Project Manual
(d) NAVFAC DM-3, Mechanical Engineering
(e) NAVFAC DM-4.6, Electrical Engineering Lighting and Cathodic Protection
(f) NAVFAC DM-22, Petroleum Fuel Facilities
(g) NAVFAC DM-25.6, General Criteria for Waterfront Construction
(h) NAVFAC MO-104, Maintenance of Waterfront Facilities
(i) NAVFAC MO-110, Paints and Protective Coatings
(j) NAVFAC MO-230, Maintenance Manual - Petroleum Fuel Facilities
(k) NAVFAC MO-306, Corrosion Prevention and Control
(l) NAVFAC MO-307, Cathodic Protection Systems Maintenance

Encl (1) Corrosion Control Program
w/o ~~(2)~~ CFR Title 49 Chapter 1 Part 192 Subpart I - Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards
w/o ~~(3)~~ CFR Title 49 Chapter 1 Part 195 - Transportation of Liquids by Pipelines (selected paragraphs only)

1. Purpose. To establish policy and responsibility for corrosion control including application, inspection, assessment, maintenance, and operations as set forth in enclosures (1) through (3).

2. Cancellation. This instruction cancels and supersedes NAVFACINST 11014.11E of 31 January 1972, NAVFACINST 11162.3 of 27 May 1975 and NAVFACINST 11300.25 of 8 June 1972.

3. Background. References (a) and (b) state the objectives and policies of the DOD and Navy Real Property Maintenance Activities (RPMA) program. To achieve the RPMA program goal to maintain and repair all active real property to a standard which will permit continued use for designated purposes in the most cost effective manner, a corrosion control program as described in enclosure (1) is required. Enclosure (1) describes the recommended corrosion control program. Enclosures (2) and (3) cite Federal Safety requirements for the corrosion protection of natural gas and POL pipelines and storage facilities, and establish policy for corrosion protection of these facilities. Reference (c) provides guidance for the installation of cathodic protection systems as part of repair projects. References (d) through (l) provide information on design, construction, operation and maintenance of corrosion control systems.

4. Discussion. The naval shore establishment losses to corrosion are estimated at one-half billion dollars annually. These losses have resulted in facilities being downgraded or removed from operation for repairs or replacement. Corrosion related costs and the adverse impact on mission readiness are of increasing concern. Corrosion control must be considered in the design, construction, maintenance, repair and operation of all facilities. Corrosion protection systems should not be deleted from projects because of low priority or inadequate funding. To minimize corrosion losses, corrosion control systems must be monitored and maintained. Therefore, a comprehensive and effective corrosion control program must be continually conducted to assure that all naval shore facilities are adequately protected and reliable. Assistance in implementing a corrosion program and complete copies of enclosures (2) and (3) are available through the corrosion engineer (Code 102) at the Naval Facilities Engineering Command Field Divisions.

5. Policy. Corrosion control systems shall be installed, monitored and maintained for:

a. All shore facilities as described in enclosure (1).

b. All natural gas pipelines in accordance with enclosure (2).

c. All POL (petroleum, oil and lubricants), liquid fuel, pipelines and storage facilities in accordance with enclosure (3).

6. Action. Commanders/Commanding Officers responsible for corrosion control shall take actions as outlined in enclosures (1) through (3) to minimize damage and to insure maximum readiness of shore facilities.

7. Reports and Forms.

a. Reports. The following requirements are approved by CNO for 3 years from the date of this instruction:

(1) Cathodic Protection Inventory and Summary Record, Report Symbol NAVFAC 11014-17A, discussed in enclosure (1) and shown in Attachment (1).

(2) Cathodic Protection Structure-to-Electrode Potential and Rectifier Report, Symbol NAVFAC 11014-17B, discussed in enclosure (1) and shown in Attachments (2) and (3).

b. Forms

(1) Cathodic Protection Inventory and Summary Record Format shown in Attachment (1) will be generated and maintained on NAVFAC word processing equipment.

(2) NAVFAC 9-11014/74A (4-83), Cathodic Protection Structure-to-Electrode Potential and NAVFAC 9-11014/74B (4-83), Cathodic Protection Rectifier Report will be available through normal supply channels.

CORROSION CONTROL PROGRAM

1. Definition. Corrosion is the deterioration of any material in contact with its environment. This includes all conditions that adversely affect the properties of a product that must be maintained. The corrosion control program can be divided into the following major operations:

a. Inspection and Assessment. This portion of the corrosion control program includes the identification of corrosion problems, determination of cause, the evaluation of damage and the applicability of corrosion control.

b. Protection and Maintenance. This portion of the corrosion control program involves application of appropriate corrective measures and monitoring of preventative systems.

2. Scope. Corrosion control is an ongoing program to protect facilities. All facilities are subject to corrosion and should be considered in the program. The following types of facilities have traditionally been found to benefit substantially from the application of corrosion control.

a. POL & Gas Systems.

b. Buildings.

c. Utility Systems.

d. Waterfront Structures.

e. Antenna Systems.

3. Justification. Corrosion control, as a maintenance technique, must be effective to be considered for specific applications. In addition to life cycle cost, an economic analysis should consider all benefits. For naval activities, the justification for the application of corrosion control shall consider, but is not limited to, the following:

a. Readiness to support mission capability through prevention of corrosion failures.

b. Safety through extension of material reliability.

c. Energy conservation through prevention of loss of product such as fuel oil, natural gas or compressed air.

d. Environmental protection through the prevention of spills and leaks.

e. Reduced manpower for inspection and maintenance of facilities.

f. Savings in maintenance and repair costs.

4. Corrosion Control. The corrosion control systems described below are those most commonly used on shore facilities.

a. Protective Coatings. Protective coatings provide protection to a variety of substrates (e.g., metals, wood, concrete, etc.) by forming a barrier from the surrounding environment. The continuing integrity of this barrier film is necessary for continuing protection.

b. Cathodic Protection. Metal structures buried or immersed in electrolyte (e.g., soil or water) can be cathodically protected from corrosion. This protection, usually used in conjunction with coatings, is achieved by applying a specific level of electrical charge to the structure. Cathodic protection systems require monitoring, maintenance and adjustment to insure system integrity and to provide continuous control of corrosion.

c. Other systems for corrosion control include:

(1) Design to eliminate conditions favoring corrosion (e.g., contact dissimilar metals).

(2) Use of materials resistant to the particular environment.

(3) Use of chemical inhibitors for metal in a closed system.

5. Responsibilities. Implementation of an effective corrosion control program requires continuous and coordinated effort as follows:

a. Activities

(1) Establish an effective corrosion control program.

(2) Designate in writing by the Commanding Officer the person responsible for the corrosion control program.

(3) Coordinate corrosion control review with the Engineering Field Divisions (EFDs).

(4) Arrange adequate training for all personnel involved in corrosion control.

(5) Analyze facilities, structures and systems for signs of corrosion necessitating some form of corrosion protection.

(6) Inspect and maintain corrosion control systems and components.

(7) Notify EFD's and claimants of corrosion control problems and the need for assistance.

(8) Monitor operating conditions of cathodic protection systems and forward copies of the below listed reports to EFD's quarterly or as requested. Report symbol NAVFAC 11014-17B is assigned:

(a) Structure-to-Electrode Potential readings shall be recorded quarterly on NAVFAC Form 9-11014/74A (4-83) as shown in Attachment (2). EFD (Code 102) shall be contacted immediately when assistance in balancing the system is desired.

(b) Rectifier settings and outputs shall be recorded quarterly on NAVFAC Form 9-11014/74B (4-83) as shown in Attachment (3). EFD (Code 102) shall be advised immediately when inconsistent readings are observed.

(9) Maintain local real property records to assist in evaluating corrodable systems.

(a) Leaks and maintenance.

(b) Repairs and replacements.

(c) Current drawings:

(1) Underground utility systems.
(2) Cathodic protection systems.
(3) Location of rectifiers, anode beds and test stations.

b. Naval Facilities Engineering Command (NAVFAC). Provide support to activities through publications, training aids, correspondence, conferences, and assistance visits. Provide claimants with summary of corrosion control accomplishments, problems, activity needs and recommendations.

(1) NAVFAC Headquarters.

(a) Establish and promulgate basic guidelines, criteria, specifications and standards for inspection, assessment, design, operation, testing, maintenance and repair of corrosion control systems.

(b) Develop guidelines, specifications, and standards for contract or in-house accomplishment of corrosion surveys.

(c) Convene a committee meeting of EFD corrosion personnel every two years to:

(1) Evaluate effectiveness of the corrosion control program.
(2) Review the state-of-the-art, guidelines and procedures.
(3) Update instructions and recommend changes to the program.

(2) Engineering Field Divisions (EFD's).

(a) Provide assistance to activities for implementation of an effective corrosion control program.

(b) Assist with the preparation and review of projects for the application of cathodic protection systems and/or modification to existing systems.

(c) Recommend corrosion control for consideration and inclusion, where appropriate, in all projects.

(d) Conduct or contract for corrosion control surveys.

(e) Provide technical guidance and assistance during installation of new corrosion control systmes or major modifications to existing systems and assist in the development or review of maintenance and operation plans.

(f) Assist activities in training programs for personnel involved in the corrosion control program.

(g) Monitor the performance of corrosion control systems by:

(1) Evaluation of records submitted in accordance with paragraph 4.a.(8). Report symbol NAVFAC 11014.17B.

(2) Reviewing and assessing activity records outlined in paragraph 4.a.(9).

(3) Scheduled site visits.

(h) Maintain a cathodic protection inventory and summary records, as shown in Attachment (1), listing existing and potential corrosion control systems for all activities in their assigned area. Telecommunicate updated information annually by 15 October to PACDIV (Code 102). Report symbol NAVFAC 11014-17A is assigned.

(i) Insure Navy compliance with enclosures (1) and (2).

(3) Pacific Division, NAVFACENGCOM (PACDIV).

PACDIV (Code 102) is assigned maintenance expertise for corrosion control to assist NAVFAC Headquarters in the following:

(a) Provide technical advice to NAVFAC Code 100.

(b) Assist EFD's in unique problems.

(c) Prepare and/or review draft instructions, manuals, and specifications.

(d) Evaluate and submit via NAVFAC Code 100 RDT&E and EI taskings or proposals.

(e) Conduct biennial corrosion committee meetings.

(f) Represent the Navy at association meetings and confrerences.

(g) Keep NAVFAC informed on any new or changes to Federal regulations.

(h) Assist in the development of training courses.

(i) Maintain, consolidate, and provide NAVFAC (Code 100) and claimant EFD's (Code 102) with Navy-wide and claimant inventories and summaries of corrosion control systems based on information required by paragraph 4.b.(2).(h).

(4) Claimant EFD.

EFD's shall prepare triennial corrosion control status reports for claimants located in their area based on information required by paragraph 4.b.(3).(i). and discussions with EFD corrosion personnel.

(5) Naval Civil Engineering Laboratory (NCEL).

(a) Perform research, development, testing and evaluation in support of guidelines, criteria, specifications, equipment, procedures, techniques and standards required for an effective corrosion control program when tasked by NAVFAC.

(b) Provide direct technical assistance to activities in the investigation of corrosion problems and the recommendations of corrosion control procedures.

CATHODIC PROTECTION INVENTORY AND SUMMARY RECORD *

The following is a sample format for information to be submitted to NAVFAC Code 100 and PACDIV Code 102 annually by 15 October. This report shall be prepared for all cathodically protected facilities and for all structures that should be considered for cathodic protection.

ST	SNDL	ACTIVITY	MAJR CLAM	EFD	NO./TYPE FACILITIES	SAT	UN-SAT	PROJCD LOSSES $000	REMARKS	CAT CODE	REPLC COSTS $000	PROJCT COSTS $000	RECOM NO-YR	FIELD REVEW YR-MO
ZQ	FKM9	SUPPLY CTR SEA PORT	SUP	P	6 POL TNKS	2	4	698	1	125-10	20800	29	01-83	81-01
ZQ	FKN5	PWC SEA PORT	FAC	P	2 WATER	2	0	0		845-20	924		NONE	82-10
ZQ	FKN5	PWC SEA PORT	FAC	P	1 STEAM	0	1	1236	2	822-22	842	213	02-83	83-02
ZQ	FB10	NAVSTA SEA PORT	FLT	P	2 PIERS	1	1	6114	1,3	151	10400		03-83	83-09
ZQ	FB10	NAVSTA SEA PORT	FLT	P	2 PIERS	0	2	14582	2,4	151	14582	659	NONE	81-03
ZQ	FKP7	NAVSHIPYD SEA PORT	SEA	P	UNKNOWN				5					NONE

- S A M P L E -

REMARKS

1. Potential loss because of lack of maintenance.
2. Estimated cost if a cathodic protection system is not installed or cost saving with or without the system.
3. Corrosion has weakened pier Alpha to approximately 75% of its capacity.
4. If unchecked, corrosion will affect operations on pier Beta in approximately 4 years.
5. No reports submitted.

RECOMMENDATIONS

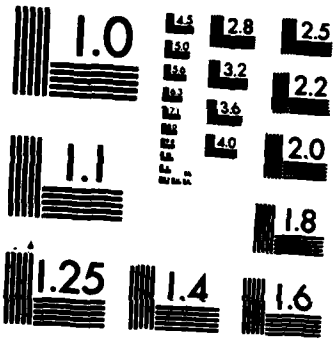
01-83 Fund maintenance needed for a POL facilities at estimated cost of $29,000.
02-83 Install cathodic protection system on steam lines at estimated cost of $213,000.
03-83 Repair steel pier piles with concrete jackets in splash zone at an estimated cost of $659,000.

* Format generated and maintained on NAVFAC word processing equipment.

Attachment (1)

AD-A139 974 CORROSION CONTROL FOR REINFORCED CONCRETE(U) FLORIDA UNIV GAINESVILLE DEPT OF CIVIL ENGINEERING R M TORIGOE 1983 2/2

UNCLASSIFIED F/G 11/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

NAVFAC INST 11014.

REPORT NAVFAC 11014-17B

CATHODIC PROTECTION
STRUCTURE-TO-ELECTRODE POTENTIAL REPORT

NAVFAC 9-11014/74 A (4-83)

ACTIVITY: DIEGO GARCIA - CAUSEWAY POL TANK FARM

STRUCTURE - TO - SOIL POTENTIAL READINGS

PERIOD ENDING 12-31-81

TS NO.	LOCATION OR IDENTIFICATION	P/S VOLT	SHUNT mv	SHUNT RES	SHUNT ma	INSPECTOR	DATE	REMARKS *
32-1	TANK 32	-.495				FN/TT	10/8/81	TANK #32
32-2	TANK 32	-.415				FN/TT	10/8/81	NOT PROTECTED
31-1	TANK 31	-.773				FN/TT	10/8/81	TANK #31 HAS
31-2	" "	-.803				FN/TT	10/8/81	A CP SYSTEM
31-3	" "	-.790				FN/TT	10/8/81	HOWEVER,
31-4	" "	-.781				FN/TT	10/8/81	PROTECTION IS INADEQUATE
A	OLD 12" FUEL LINE	-.861				FN/TT	11/8/81	ADEQUATE
B	OLD 12" FUEL LINE	-1.025				FN/TT	11/8/81	ADEQUATE
1	6" LINE	-.750				FN/TT	12/8/81	INADEQUATE
2	6" LINE	-.755				FN/TT	12/8/81	INADEQUATE
3	6" LINE	-.885				FN/TT	12/8/81	ADEQUATE
4	6" LINE	-.886				FN/TT	12/8/81	ADEQUATE

SAMPLE

* IDENTIFY TEST ELECTRODE IF OTHER THAN COPPER-SULFATE

Attachment (2)

NAVFAC INST 11014.

CATHODIC PROTECTION
RECTIFIER REPORT

REPORT NAVFAC 11014-17B

NAVFAC 9-11014/74B (4-83)

ACTIVITY DIEGO GARCIA, PIER - INITIAL SETTINGS | Period Ending 12-31-81

RECT. IDENT	DATE	ENSP INIT.	TAP SETTING		A.C.		1st D.C. OUTPUT		2nd D.C. OUTPUT		3rd D.C. OUTPUT		REMARKS
			COARSE	FINE	VOLT	AMP	VOLT	AMP	VOLT	AMP	VOLT	AMP	
1	11/12/81	FN	A	4	–	–	4.0	130					①
2	11/12/81	FN	A	4	–	–	4.2	130					①
3	11/12/81	FN	A	5	–	–	5.5	235					①
4	11/12/81	FN	A	4	–	–	4.3	155					①
5	11/12/81	FN	B	1	–	–	7	340					①

SAMPLE

GENERAL REMARKS

① FIER RECTIFIERS: GOODALL MODEL CSCYTD 24-500E2
SERIAL # 80C1717
PRIMARY: 460 VAC, 22.1 A, 3φ, 60 HZ
DC: 24V, 500 A

Attachment (3)

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