Prevention of Steel Corrosion by Concrete

by James H. Bailey

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Many years ago designers learned that the steel in reinforced concrete structures would not corrode except in very rare instances. The difference between success and failure was usually attributed to thickness of the concrete. Until recently there has been little understanding of the protective mechanism provided by the concrete, and even less about the limitations.

Basically, corrosion is an electrochemical process. That is, both electricity and chemistry are involved and three conditions must exist before corrosion can start. There must be two electrodes, a complete electrical circuit, and an electrolyte (a fluid) through which the current will flow. Corrosion prevention, then, is accomplished by stifling the electric current, by selecting the environment, or by electrical isolation of one or both of the electrodes. In most buried structures, metal is necessary and economics limits selection of the environment. The only alternative left is prevention of flow of current. This is frequently done by use of membrane-type dielectric coatings such as paints or wrappings. To be effective, these coatings must be maintained unbroken. Two or more coats are often applied to assure complete coverage of the surface.

Concrete, as mentioned, also prevents corrosion, but the mechanism by which it works is obviously quite different. The cement matrix is a finely porous structure that normally holds both air and moisture. Concrete is often applied over steel that already has a thin layer of corrosion products. In service the concrete may actually be cracked. These apparent deficiencies still lead some engineers, much less laymen, to discount concrete as a corrosion inhibitor in spite of its excellent record.

Research Program

To explain the principles by which concrete prevents corrosion, a systematic scientific research program was started some 8 years ago by the American Concrete Pressure Pipe Association. The program continued on a major scale for more than 4 years and is still continuing on a reduced scale. Gordon N. Scott, an internationally known consulting corrosion engineer, was retained to coordinate and guide the program in which the laboratory work was performed by the member companies.

The program had three objectives:

1. To explain why concrete and cement-mortar protect steel from corrosion

2. To explain what exposure conditions lessen this protective capacity

3. To discover ways to preserve the protective effect

A rather simple demonstration illustrates the protection afforded by concrete. Place a piece of steel in a jar containing ordinary tap water. In a short time the steel begins to show signs of corrosion. Repeat the same procedure but place a few pieces of concrete in the jar before the steel is added. This steel will not corrode. As the concrete is the only difference in the two jars, it must have caused a change in the chemical properties of the solution. While the water in the first jar still has a pH of about 7, the water in the second jar has a pH of about 12.5, which is about the same as that of hydrated cement. At this pH, corrosion of steel is prevented by formation of a protective iron oxide film on the steel surface. It can also be shown that the film will not be destroyed if chlorides are in the water. Further, the film will be effective even if oxygen is bubbled through the solution so long as the pH remains in the inhibitive range and the bubbles of oxygen are not trapped against the steel.

There is an unlimited number of examples of reinforced concrete submerged in seawater without corrosion problems. The jar with the concrete also explains why small cracks in a concrete coating are not necessarily damaging.

To this point, the actual flow of electricity to or from a reinforced concrete structure has not been discussed. Moist concrete is not normally considered a good electrical resistor. This can be demonstrated by placing two electrodes in an electrolyte and placing concrete between them. When voltage is applied and increased in small increments, a plot of voltage versus current shows a linear relationship. If the same test is repeated, but with the concrete cast between the electrodes, the curve shows a very different relationship (Fig. 1). This difference can only be attributed to an effect of the concrete on the steel surface.

Open Cup Cell

A further study of this phenomenon was made with an open cup cell (Fig. 2). Basically, the cell was composed of two concentric electrodes, the center one being surrounded by a cement mortar cup. For experimental purposes, the center electrode was coated with a cement slurry. The cell was so designed that an electrolyte separated the inner electrode from the cup, and the same or a different electrolyte separated the cup from the outer electrode.

Cement-Mortar-Coated Cathode

In one test, the voltage was applied so that the center electrode was the cathode. A 3.5 per cent sodium chloride solution was used for the outer electrolyte and the inner electrolyte was distilled water containing only soluble cement products from the mortar cup. As the voltage was increased the current through the circuit was measured. Readings were also taken of the electrode potentials with respect to a saturated calomel electrode (SCE), which was emersed in the surrounding electrolyte. At each level of applied voltage, the power was turned off and the electrode potentials were again measured. The open circuit, commonly called the polarization potential, indicates the chemical action at the

*Open cup cell; developed by American Pipe & Construction Co., Los Angeles.
electrode surface. One curve of Fig. 3 shows that as the impressed voltage was increased, the current flow was negligible up to about 0.60 v. Above this point, a definite change occurs and the current increases linearly with voltage. Evolution of hydrogen gas also began at this voltage, according to the equation:

$$2H_2O + 2e^- = H_2 + 2(OH)^-$$

The explanation for the change in current-voltage relationship is also seen in Fig. 3. A counter-potential resulting from the chemical reaction develops at the cathode at almost the same rate as the impressed voltage is increased. This reduces the net voltage and therefore the current. Beyond an impressed voltage of about 0.60 v the polarization potential of the cathode remains constant at about -1.06 v to the SCE and further increases in impressed voltage are seen as an IR drop in the cell. Fig. 3 also shows that the potential of the bare anode is unchanged throughout the test.

**Cement-Mortar-Coated Anode**

When an open cup cell is assembled as before, but with the mortar-coated center electrode serving as the anode, there is essentially no current flow until the impressed voltage reaches about 1.1 v as shown in Fig. 4. Beyond this point, the current-voltage relationship is again linear but oxygen instead of hydrogen is liberated at the mortar-coated electrode. This occurs according to the equation

$$2(OH)^- = 1/2O_2 + H_2O + 2e^-$$

The same counter-potentials as previously seen in Fig. 3 are shown in Fig. 4, but in this case the polarization potential is about 0.70 v.

To complete this phase of the research, a test similar to the above was made with both electrodes encased in cement-mortar and the results as reported by Haussmann were even more dramatic. Fig. 5 shows that current flow was negligible until the impressed voltage exceeded 1.6 v. The circuit was equivalent to the two previous circuits connected in series, and the curves show the magnitude of the counter-potentials to be the same as for the separate cells.

**Cathodic Protection and Bond Strength**

The association research program continued along several other lines but one in particular should be noted at this time. Tests were made to determine whether bond between steel and concrete was reduced or destroyed by cathodic protection. Shaw reports tests made on tapered rods which were cast in concrete and then spring loaded. Potentials of -0.74, -1.14, and -1.54 v were applied and no loss of bond was

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**Fig. 1. Effect of Concrete on Flow of Electricity**

A and B indicate steel electrodes; C, concrete. E represents electromotive force; I, current; R, resistance; and v, voltage.

**Fig. 2. Open Cup Cell**

A indicates battery jar; B, outer electrode; C, center electrode; D, cement shurry; E, inner electrolyte; F, outer electrolyte; G, rubber stopper; H, plastic cap; and I, cement-mortar cap.

**Fig. 3. Flow of Electricity in Open Cup Cell With Cement-Mortar-Coated Cathode**

Solid curve in upper diagram shows results obtained with sodium chloride solution outer electrolyte and distilled water inner electrolyte. Curves in lower diagram show readings of electrode potentials with respect to a saturated calomel electrode emersed in surrounding electrolyte; solid curve for current on and interrupted for steel anode; dashed curve, coated cathode, current interrupted; dotted curve, coated cathode, current on.
noted after nearly 2½ years. The first two were tested to destruction by pulling on the rods at 880 days and the third at 994 days. The measured bond strengths were the same as the control specimen. Another specimen under excessive cathodic protection of -2.14 V (SCE) and 400 ma per square foot initial current density failed after 197 days.

**Conclusions**

Several important contributions were made by the American Concrete Pressure Pipe Association studies toward a better understanding of the protection afforded steel by concrete. Some of the conclusions drawn from that portion of the research which has been covered by this article are:

1. Concrete prevents corrosion of steel even in the presence of free oxygen and chlorides, as long as the oxygen is not trapped against the steel.

2. The hydroxyl ions from the calcium hydroxide of portland cement are credited with formation of an iron oxide film on the steel surface, and this film tends electrically to isolate the steel from its environment.

![Fig. 5. Flow of Electricity in Open Gap Cell With Both Electrodes Encased in Cement-Mortar](image)

**Fig. 5. Flow of Electricity in Open Gap Cell With Both Electrodes Encased in Cement-Mortar**

Solid curve in upper diagram shows results obtained with sodium chloride solution outer electrolyte and distilled water inner electrolyte. Curves in lower diagram show readings of electrode potentials with respect to a saturated calomel electrode immersed in surrounding electrolyte; solid curve, for current on and interrupted for steel cathode; dashed curve, coated anode, current on; dotted curve, coated anode, current interrupted.

![Fig. 6. Flow of Electricity in Buried Pipe](image)

**Fig. 6. Flow of Electricity in Buried Pipe**

A indicates pipe on left side of diagram, acting as anode; B, pipe on right side, acting as cathode; S, soil; C, concrete. E represents electromotive force; I, current.

3. Except where cathodic interference exists, cathodic protection is unnecessary for a sound reinforced concrete structure.

4. Between applied potentials from about +0.6 to -1.0 V (with respect to the copper sulfate electrode) current is controlled by polarization effects rather than by resistance of the concrete.

**Significance of Research Program**

In a water distribution system, pipe buried in a natural soil environment is a major part of the system. Differences in electrical potential along the pipe may develop due to variations in moisture or oxygen content, or differences in soil characteristics. There is a tendency for current to flow from one location on the pipe, through the soil, back to the pipe, and finally along the metal of the pipe to the starting point. If the pipe is bare or has a punctured membrane type coating, corrosion will begin immediately. If the pipe has a sound cement mortar coating, the current must pass through the metal to mortar interface twice (Fig. 6) and the current flow will be impeded unless the potential exceeds the relatively high value of about 1.5 V.

Sometimes a pipe is exposed to voltages from such sources as a cathodic protection system on another pipe. If the interference causes a pipe-to-soil potential on the water line of less than about 1 V, polarization effect will greatly reduce the discharge of current and it is therefore unlikely that the cathodic interference will be damaging.

As has already been discussed, cement-mortar-coated steel lines can be placed under cathodic protection if exposed to excessive cathodic interference. This can also be done if the
mortar coating is known to be damaged. A frequent topic of conversation is the matter of voltages and current requirements, and therefore the cost of this cathodic protection. As proven in the research program, as long as the potentials are within the limits of the polarization potentials, current requirements are very small. Scott\(^1\) recommends a potential of 0.7–0.8 v to the copper sulfate electrode for complete protection. Current requirements are less in saturated soil than in well drained soil, and decrease with time. Hausmann\(^2\) reports a test installation in saturated soil in which the current density was only 2.3 \(\mu\)A per square foot after 7 months and the applied potential was about 0.85 v.

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**References**