

Cathodic Protection Studies on Coal Tar Epoxy-Coated Concrete Pressure Pipe

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Coal tar epoxy (CTE) is applied to the external mortar coating of concrete pressure pipe to prevent the ingress of chloride ions. However, pinholes and cracks in the CTE and mortar coating can form a path for chloride ingress corroding the underlying steel. Experimental results, corroborated by mathematical modeling, showed that cathodic protection can effectively protect the steel under cracked and chloride-contaminated mortar that has a CTE topcoat.

Concrete pressure pipe (CPP), prestressed concrete cylinder pipe (AWWA C301¹), and concrete cylinder pipe (AWWA C303²) is used primarily in industrial, agricultural, and residential water distribution systems. Since 1972, a 100% solids coal tar epoxy (CTE) has been applied over the mortar coating of CPP when corrosive conditions are anticipated. The coatings act as barriers to oxygen, carbon dioxide, and chloride ions and help prevent corrosion of the underlying steel. The CTE acts as a supplemental coating, and the mortar coating serves as the primary means of corrosion control because of its passivating properties.

Chlorides and oxygen that penetrate pinholes in the CTE can cor-

rode the steel. Chlorides move away from the pinhole by a combination of diffusion and capillary flow. CTE is applied to CPP in aggressive soil conditions and to pipelines that will be cathodically protected.

Corrosion engineers have been concerned that organic coatings might shield the steel from complete cathodic protection (CP) in the vicinity of localized defects. Results of laboratory experiments and current-distribution modeling demonstrated that sufficient cathodic current does flow through the pinholes to stop corrosion initiated by chlorides.

The results of three separate experiments are reported here, which show the distribution of chloride and half-cell potential in the vicinity of a pinhole in a dielectric coating on

mortar samples. The following experiments are reported:

- chloride distribution around a pinhole with and without CP of the underlying steel,
- potential and current distribution around a pinhole for several scenarios:
 - chloride-free mortar,
 - initially high chloride level in the mortar,
 - simulated crack in chloride-containing mortar.

Experiments of Diffusion of Chlorides Through Pinholes

Chloride diffusion experiments were performed using 660 μm of CTE over impact-applied mortar (1.9 cm thick) over underlying bar reinforcement and steel cylinder (Figure 1). The pinhole was created by drilling through the CTE coating. A high chloride solution above the pinhole (composition listed in Table 1) was maintained.

A poor quality and very permeable mortar coating was chosen to simulate a worse-case condition.

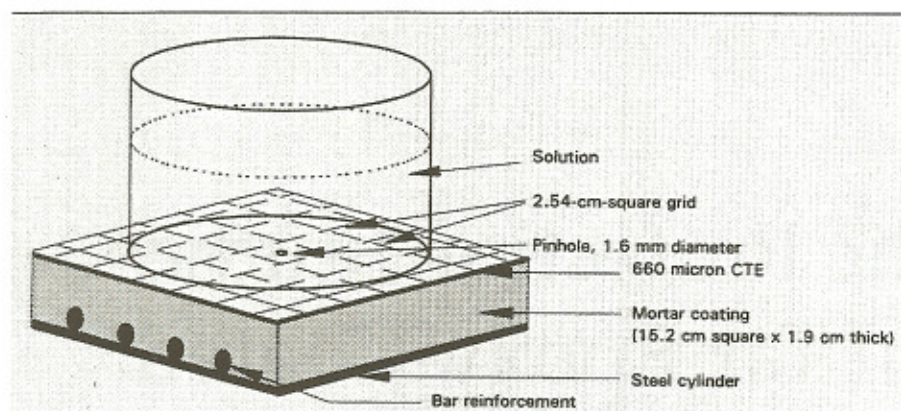


FIGURE 1

Test setup for chloride diffusion and CP through pinhole of CTE-coated CCP specimen.

The potential of the two CTE-coated CPP specimens without CP remained passive during the first 17 and 29 weeks with potentials ranging from -90 to -140 mV (saturated calomel electrode [SCE]). Potentials then shifted to more negative values ranging from -280 to -460 mV for the remainder of the three years of exposure. Upon disassembly, corrosion was found within a radius of 3.6 cm under the pinhole on the steel. This corresponded to the distribution of chloride on the steel surface. No corrosion was present outside of this central area.

Highly permeable mortar was cut into 2.54-cm² grids and the grids were layered in 1.6-mm depth incre-

ments to determine the spread of chlorides. Water-soluble chloride content was determined in selected layers according to AASHTO T260-90 "Standard Method of Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials."³ Chlorides did not penetrate farther than 3.8 cm from the pinhole at the surface layer and at the layer adjacent to the steel directly under the pinhole. As long as CP current is able to flow at least 3.8 cm from the pinhole, CTE-coated CPP can be adequately cathodically protected.

Similar chloride penetration tests of higher quality mortar coating produced essentially no chloride ion penetration in the mortar at the pinhole.

TABLE 1
Solution Composition

Component	Content (g/L)
Chloride	158.0
Sodium	82.3
Sulfate	2.8
Magnesium	7.8
Calcium	4.9
Potassium	2.1
Bicarbonate	0.1
pH	6.8
Resistivity (ohm-cm)	4.7

This indicates that CTE can be used as a supplemental coating without concern for penetrating chloride ions depassivating underlying steel.

CP Through Pinhole

CP was applied to two specimens identical to those discussed above. The potential of the underlying steel was maintained at -790 mV (SCE). After three years, the specimens were disassembled and the water-soluble chloride content of the mortar was determined.

Corrosion was not seen on the underlying steel in contrast to the corrosion found on the unprotected specimens reported previously. Chlorides did not penetrate the

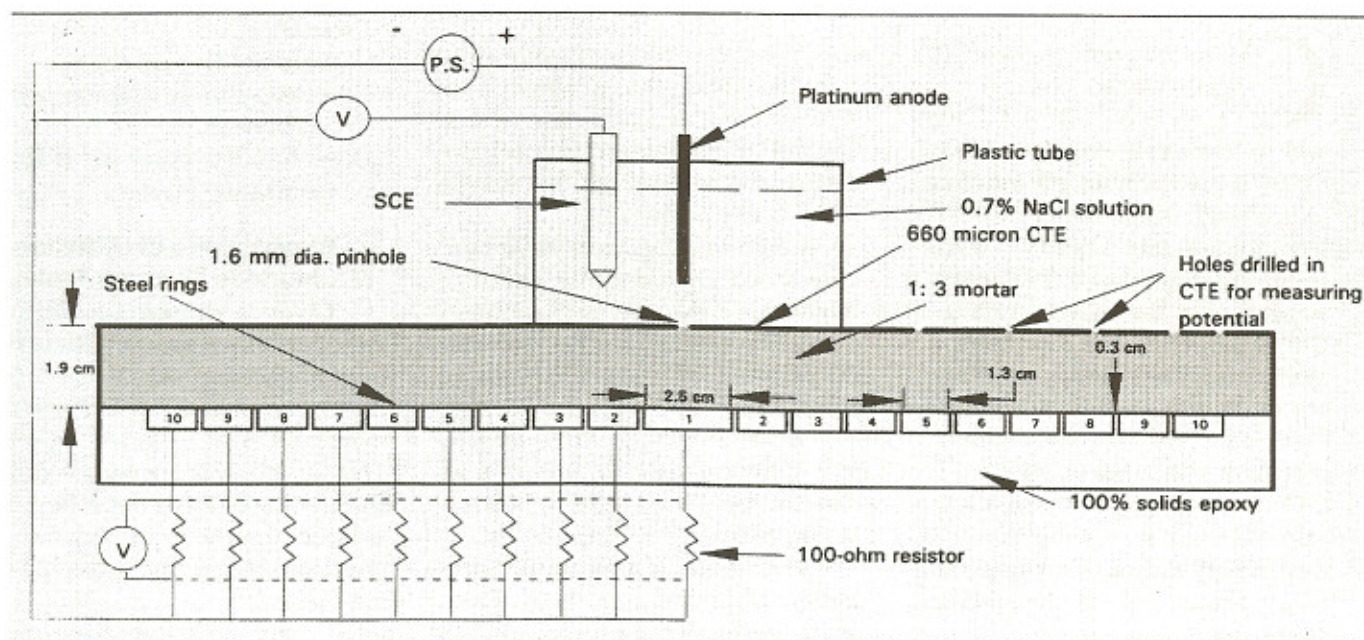


FIGURE 2

Schematic of setup for current distribution tests.

mortar coating of the first specimen, and the chloride content in the 2.54-cm² area under the pinhole in the second specimen was approximately 1,200 mg/kg throughout the depth, compared to 5,000 to 10,000 mg/kg found in the specimens without CP.

A white, semispherical deposit was found at the pinhole of the CP samples. Analysis by x-ray diffraction indicated that the deposit contained 83% magnesium. The passage of cathodic currents formed this deposit. It was not found on the non-energized specimens. The deposit may have been magnesium hydroxide produced by the repulsion of hydroxide ions and attraction of magnesium ions to the steel cathode. Blocking of the pinhole by the magnesium hydroxide precipitate or repulsion of chlorides during CP might have contributed to the significantly reduced chloride content found in the mortar.

Experiments on Current Distribution Under Pinholes

Specimens consisting of concentric 1.3-cm-wide steel rings coated with mortar and CTE were prepared to determine current distribution near a pinhole (Figure 2). Both chloride-contaminated and chloride-free mortar specimens were prepared.

Specimen Preparation

In the chloride-contaminated mortar, sodium chloride (NaCl) was dissolved in the mix water, prior to mortar batching, to produce a chloride content in the mortar of 5,000 mg/kg. The measured water-soluble chloride content ranged from 3,850 to 4,190 mg/kg, which was 77 to 83% of the chlorides added to the mortar. The remaining percentage of chlorides was bound within the cement paste and was not available to depassivate steel.

After curing, a 1.6-mm-diam simulated pinhole was drilled through the CTE, and the mortar was exposed to a 0.7% NaCl solution. The specimens were cathodically protected for nine days of mortar cure. Holes were drilled in the CTE out-

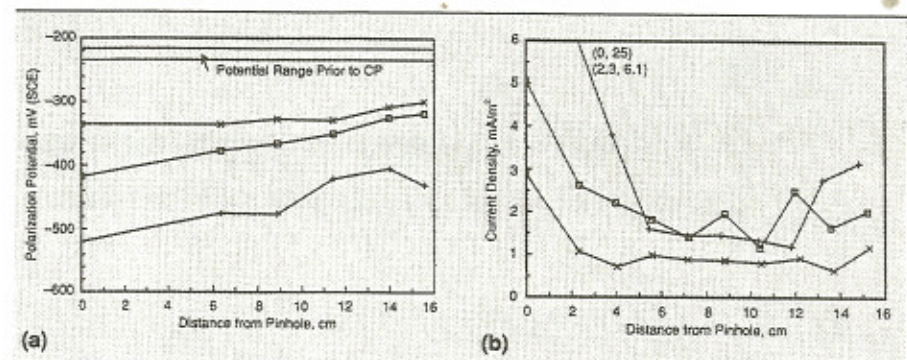


FIGURE 3

(a) Polarization potential; and (b) current density surrounding pinhole in noncontaminated mortar at 10 weeks of CP.

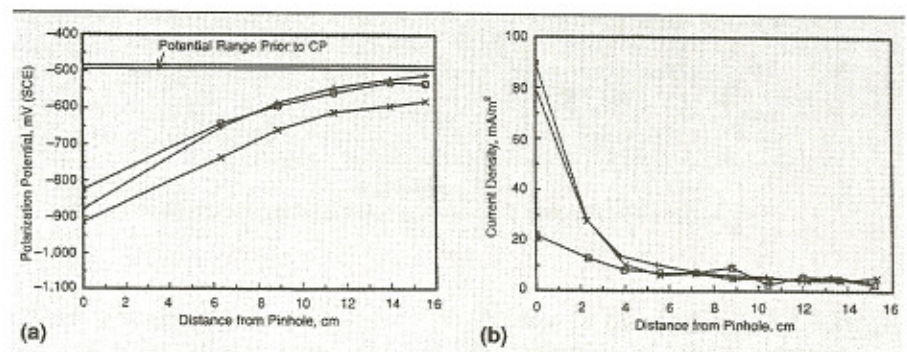


FIGURE 4

(a) Polarization potential; and (b) current density surrounding pinhole in chloride-contaminated mortar at 14 weeks of CP.

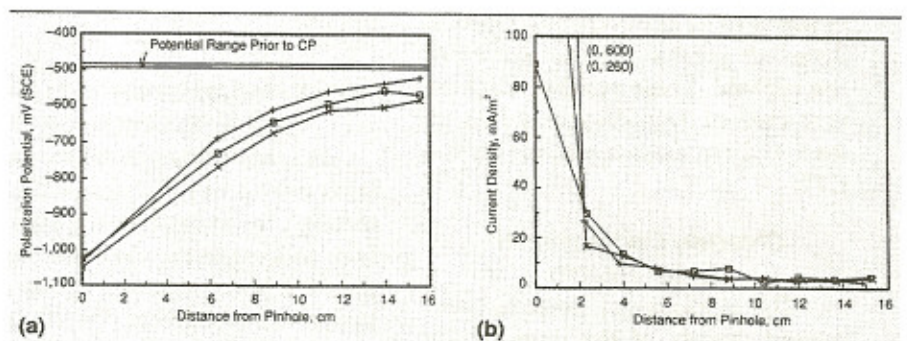


FIGURE 5

(a) Polarization potential; and (b) current density surrounding crack in chloride-contaminated mortar at 13 weeks of CP.

side the plastic tube to measure potentials of the underlying steel. Potentials at these holes were measured by placing the tip of the reference electrode with a drop of the 0.7% NaCl solution on the exposed mortar.

At 16 weeks, a 1.6-cm-diam hole was drilled at the location of the pinhole to the steel surface of the chloride-contaminated specimens to simulate cracked, chloride-contaminated mortar.

Chloride-Free Mortar Results

The polarization potential and current density of the rings in the chloride-free mortar of three specimens at 10 weeks of exposure are shown in Figure 3. The polarization shift of the steel directly under the pinhole ranged from 100 to 300 mV. The shift 15.2 cm from the pinhole ranged from 70 to 220 mV. Current density was highest immediately under the pinhole and decreased within

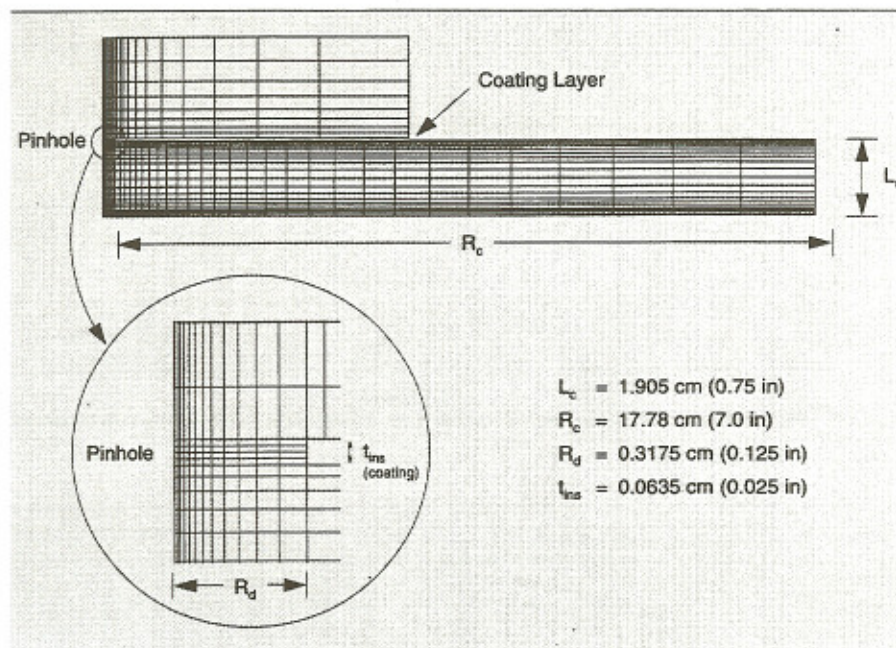


FIGURE 6

Finite element model grid used to simulate coating pinhole experiment.

the first 2.5 to 5 cm to a relatively constant level. Upon disassembly of the three specimens, no corrosion was found.

IR drops ranging from 350 to 500 mV occurred at the pinhole. IR drops of less than 40 mV were measured at distances greater than 6.4 cm from the pinhole. These results indicated that current was distributed to at least 15.2 cm from a pinhole in the CTE.

Chloride-Contaminated Mortar Results

The polarization potential and current density of the rings in the chloride-contaminated mortar at 14 weeks of CP are plotted in Figure 4. The corrosion potentials prior to CP ranged from -483 to -494 mV, indicating that chlorides had depassivated the steel. The polarization shift directly under the pinhole during CP ranged from 340 to 420 mV. The shift 15.2 cm from the pinhole ranged from 20 to 100 mV. Current density decreased within the first 3.8 cm to a relatively constant level. Small spots of corrosion were found on the specimen. This corrosion probably occurred prior to CP during the initial nine days of cure.

The results indicated that CP current was distributed at least 15.2 cm from a pinhole in the CTE applied to mortar coating and that even a 20-mV polarization shift effectively protected the steel 15.2 cm from the pinhole.

Chloride-Contaminated Mortar with Crack

A crack in the mortar was simulated by drilling a 1.6-mm-diam hole through the mortar to the steel surface and exposing the bare steel to the 0.7% NaCl solution. Polarization potential and current density of the

rings at 13 weeks of CP are plotted in Figure 5.

The polarization shift directly under the crack ranged from 520 to 580 mV. The shift 15.2 cm from the crack ranged from 20 to 100 mV. Current density was highest immediately under the crack and decreased within the first 5 cm to a relatively constant level. Small spots of corrosion were found on the specimen. This corrosion occurred prior to CP during the initial nine days of cure. Substantial corrosion was found at the end of the exposure period on specimens prepared as controls without CP.

The results indicated that CP current was distributed at least 15.2 cm from a pinhole where CTE was applied to mortar coating and that even a 20 mV polarization shift effectively protected the steel 15.2 cm from the pinhole.

Within 24 hours of turning off the CP system at the end of the test, the potentials of the specimens depolarized to a range of -192 to -262 mV, which indicated passivation of the steel. CP repelled the chloride ions from the steel and generated additional hydroxide ions at the steel to repassivate the surface.

Modeling of Coating Defect Experiment

A simplified electrochemical model was developed to simulate the results of the current distribution tests. The potential and current distribution of the segmented specimen were modeled with a finite

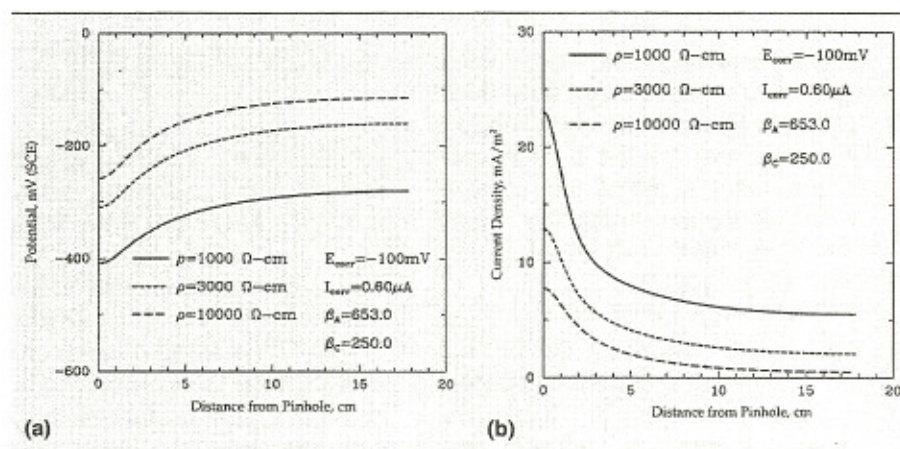


FIGURE 7

(a) Potential; and (b) current distribution in segmented specimen model.

element grid (Figure 6). The counter and reference electrodes were placed at the top plane of the NaCl solution in the model. The pinhole in the CTE is contained within the circled region in Figure 6 and is expanded in the blowup.

The Tafel-like expression,

$$i = i_{\text{corr}}(e^{n/\beta_a} - e^{n/\beta_c})$$

where $n = E - E_{\text{corr}}$, was used to model the electrochemical kinetics of oxygen reduction at the cathode surface. The parameter values were based on the electrochemical measurements made on steel in mortar specimens. The corrosion potential (E_{corr}) of -100 mV (SCE), corrosion current (i_{corr}) of 6 mA/m², and anodic and cathodic Tafel constants (β_a , β_c) of 653 and 250 mV/decade, respectively, were used in the model.

Conceptually, the model consisted of an electrode system with an available driving force equal to the imposed potential. The interaction of IR drop within the system and kinetic and diffusion potential losses at the electrode surface determined the total current and distribution along the electrode surface.

The potential and current distribution of the segmented specimen with mortar resistivities between 1,000 and 10,000 ohm-cm are shown in Figure 7. The current distribution is within a factor of 10 of the measured values reported in Figure 3(b), depending on the resistivity of the mortar.

Conclusions

For the case of high ambient chloride concentrations, chloride ions did not diffuse farther than 3.8 cm from a CTE pinhole in highly permeable mortar. Therefore, CP current must only distribute itself approximately 3.8 cm from the pinhole.

CP current is distributed at least 15.2 cm from a pinhole or crack in CTE applied to chloride-free and contaminated mortar coating. This is evident from the polarization potential shifts, current density distribution, and lack of corrosion 15.2 cm from the pinhole or crack.

Corrosion did not occur 15.2 cm

from a pinhole or crack when a polarization shift of 20 mV or subsequently greater depolarization occurred. Current density is highest immediately under the pinhole and decreases within the first 2.5 to 5 cm to a relatively constant level.

CTE can be used as a supplemental coating on CPP to reduce concern for chloride penetration at levels that cause depassivation.

CP can be used to protect CTE-coated CPP.

References

1. American Water Works Association (AWWA) Standard C301, "Prestressed Concrete Pressure Pipe, Steel-Cylinder Type, for Water and Other Liquids" (Denver, CO: AWWA, 1993).
2. AWWA Standard C303, "Reinforced Concrete Pressure Pipe, Steel Cylinder Type, Pretensioned, for Water and Other Liquids" (Denver, CO: AWWA, 1987).
3. American Association of State Highway and Transportation Officials (AASHTO) Standard Method T260, "Standard Method of Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials," (Washington, DC: AASHTO, 1990).