

PRESTRESSED CONCRETE PIPE CORROSION RESEARCH

A SUMMARY OF A DECADE OF ACTIVITIES

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ABSTRACT

Prestressed concrete cylinder pipe (PCCP) is used in water and waste water systems that serve virtually every major city in North America. Although not required in most conditions, various methods are available to effectively provide corrosion resistance. Recommendations for corrosion control in various environments are provided by several associations, manufacturers, and corrosion engineering firms.^{1,2} They include supplemental coatings, latex addition to mortar, and cathodic protection. The data, results, and reasoning to support the recommendations are often not available in the literature.

This paper provides a summary of research performed during the past decade on mortar coating and prestressing wire. It includes information on reduction of chloride penetration by mortar mix design and addition of latex, chloride diffusion through the mortar coating, chloride content required to cause corrosion of the prestressing wire, inhibition of corrosion by lubricants present on prestressing wire, practicality of using organically-coated prestressing wire, corrosion prevention properties of steel in mortar subjected to stray current, usefulness of potential monitoring techniques, supplemental protection using barrier coatings, cathodic protection requirements, and hydrogen embrittlement concerns.

Keywords: Absorption, cathodic protection, chloride penetration, coated mortar, coated prestressing wire, concrete pressure pipe, corrosion threshold, hydrogen embrittlement, inhibitors, latex, lubricants, monitoring, mortar, PCCP, prestressing wire, stray current, styrene butadiene latex

INTRODUCTION

PCCP is a rigid, durable pressure pipe designed to take optimum advantage of the compressive strength and corrosion-inhibiting property of portland cement concrete and mortar and the tensile strength of prestressing wire. It includes a rigid concrete core, steel cylinder, circumferentially wrapped prestressing wire, and a protective mortar coating. In embedded-cylinder type pipe, the wire is wrapped on the concrete core in which the steel cylinder is embedded. In the lined-cylinder type, the wire is wrapped directly on the steel cylinder. The components of an installed PCCP are identified in Figure 1.

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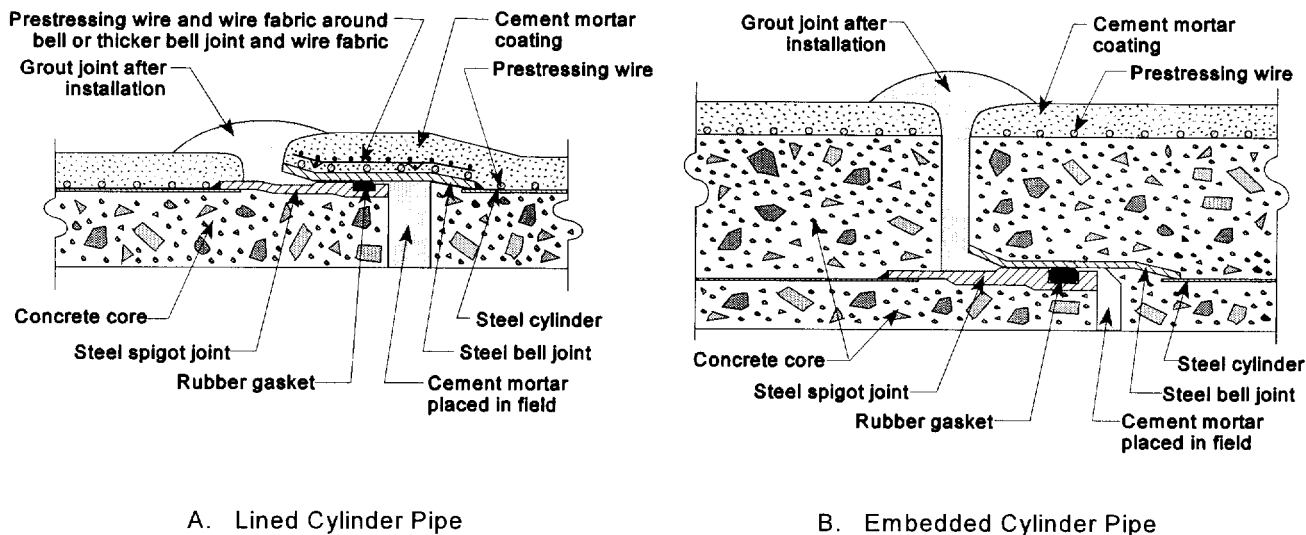


FIGURE 1 - Components of installed PCCP.

PCCP is used in water and waste water systems that serve virtually every major city in North America. It is primarily used for distribution of water for industrial, agricultural, and residential uses. It is manufactured in sizes from 16" (410 mm) to 21' (6.40 m) in diameter with pressure ratings up to 500 psi (3.45 MPa). It is typically manufactured and designed in accordance with AWWA C301³ and C304.⁴ Approximately 18,000 miles (29,000 km) of PCCP have been installed in North America during the last 50 years.⁵

Due to the passivating (corrosion inhibiting) properties of the highly alkaline portland cement, the cement slurry and mortar coating over the prestressing wire provides the only protection that PCCP normally requires. One survey showed that concrete pipe had the lowest problem occurrence rate and that the average level of satisfaction was highest for concrete pipe in more than 115,000 miles (185,000 km) of pipe surveyed.⁶ Another survey stated that the overall performance of PCCP has been excellent. Only about one project out of 700 (25 out of 17,400 total projects) has had any type of problem with external corrosion and that, in most cases, only one or two pipe sections were affected.⁵ Chloride-induced corrosion was the most common form of external corrosion found in the 25 projects and could have been prevented by the use of supplemental coatings or cathodic protection.

The impacted mortar coating is the primary means to prevent corrosion of the underlying prestressing wire. As such, it should restrict chloride ion penetration. The typical mortar consists of one part Type II, ASTM C150 portland cement to three parts ASTM C33 fine aggregate with a water content between 7% and 9% based on the dry weight of the sand and cement.

The prestressing wire is helically wrapped around the concrete core or steel cylinder at 75% of its minimum nominal tensile strength. This places the concrete core in compression which makes it possible to design PCCP to withstand the combined effects of internal pressure and external load without exceeding the tensile strength of the core. Experience and extensive testing have shown that this design approach ensures that the protective cement mortar coating will be visibly crack-free under operating conditions. Prestressing wire used in PCCP conforms to ASTM A648.

In unusual circumstances, such as in high chloride environments, the passivating properties of the highly alkaline cement may be compromised. In such environments, supplemental protection may be necessary. Supplemental protection is usually in the form of barrier coatings such as coal tar epoxy or, in rare cases, cathodic protection (CP).

This paper provides a summary of research performed during the past decade on mortar and prestressing wire as it relates to corrosion resistance. It includes information on reduction of chloride penetration by mortar mix design and addition of latex, chloride diffusion through the mortar coating, chloride content required to cause corrosion of the prestressing wire, inhibition of corrosion by lubricants present on prestressing wire, practicality of using organically-coated prestressing wire, corrosion prevention properties of steel in mortar subjected to stray current, usefulness of potential monitoring techniques, effectiveness of barrier coatings to provide supplemental protection, cathodic protection requirements, and hydrogen embrittlement concerns.

IMPACTED MORTAR COATING RESEARCH

Since the portland cement mortar coating provides the corrosion inhibiting environment, a dense, nearly impermeable mortar is required. The effects of water content, mortar thickness, and latex content were investigated to achieve the densest and most impermeable, practical mortar.

Effect of Water Content and Absorption on Chloride Penetration in Mortar

The effect of water content on the absorption and chloride ion penetration into impacted mortar coating was investigated. Absorption is historically the property used to determine the porosity of mortar. Absorption refers to the amount of evaporable water contained in saturated concrete and is therefore a measure of total voids or pore volume. It is determined in accordance with ASTM C497, Method A. As absorption decreases, porosity is reduced.

Approximately 6" (15.2 cm) square by 3/4" (1.9 cm) thick impacted mortar coating specimens made with 6.5% and 9.5% water content were sealed on the sides and bottom to allow penetration of chloride ions only through the top, outer surface. They were exposed to nine weeks of continuous exposure to artificial seawater. The mortar was layered in 1/16" (0.16 cm) thick depth increments and water-soluble chloride ion content in each layer was determined in accordance with AASHTO T260-84, Procedure A. They are reported as milligrams of chloride ions per kilogram of mortar (mg/kg). This can be converted to pounds of chloride ions per cubic yard of mortar by multiplying mg/kg by 0.00384 to 0.00396 based on mortar specific gravities of 2.28 to 2.35, respectively. The water-soluble chloride content of mortar typically ranges from 10 to 100 mg/kg.

The effect of absorption and water content on chloride ion penetration is shown in Figure 2. The mortar with the lower absorption of 9.5% and the higher water content of 9.5% had the lowest chloride penetration. Resistance of mortar to chloride penetration increases as water content increases and absorption decreases. The absorption values are not absolute values as different equipment, processes, and sand used in producing mortar coating will produce different absorptions with the same water content. However, the trend is still valid.

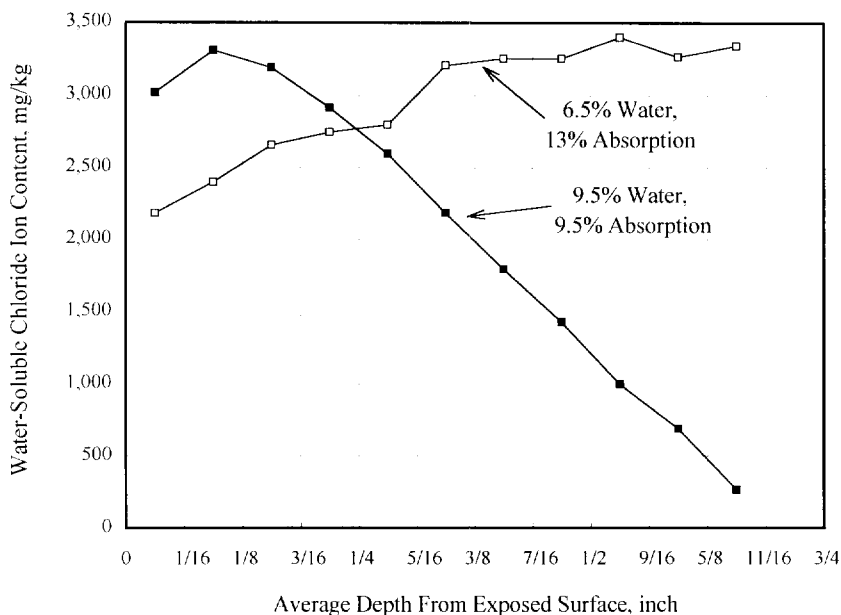


FIGURE 2 - Effect of water content and absorption on chloride penetration into mortar.

The chloride ion content of the specimen with the higher absorption and lower water content increased with depth over the corroding steel cylinder and reinforcing rod surface located at a mortar depth of 11/16" (1.7 cm). This increase in chloride content with depth over corroding steel has been observed several times by the author. It is believed to be due to the attraction of the negatively charged chloride ion to the positively charged corroding surface.

Effect of Water Content on Mortar Absorption

The absorption of impacted mortar coatings made with water contents from 5.25% to 9.2% was determined. As shown in Figure 3, higher water contents produce mortar with lower absorptions. AWWA C301 specifies a maximum average absorption value in a working shift of 9% with no individual absorption value greater than 11%. It also specifies a minimum water content of 7%. For impacted mortar coating, a water content greater than approximately 9% is not practical in a manufacturing environment since the mortar tends to fall off the rotating cylinder. Different equipment, processes, and sand are used by the pipe manufacturing companies in North America and each produces slightly different absorptions with the same water content. However, the trend of decreasing absorption with increasing water content is still valid.

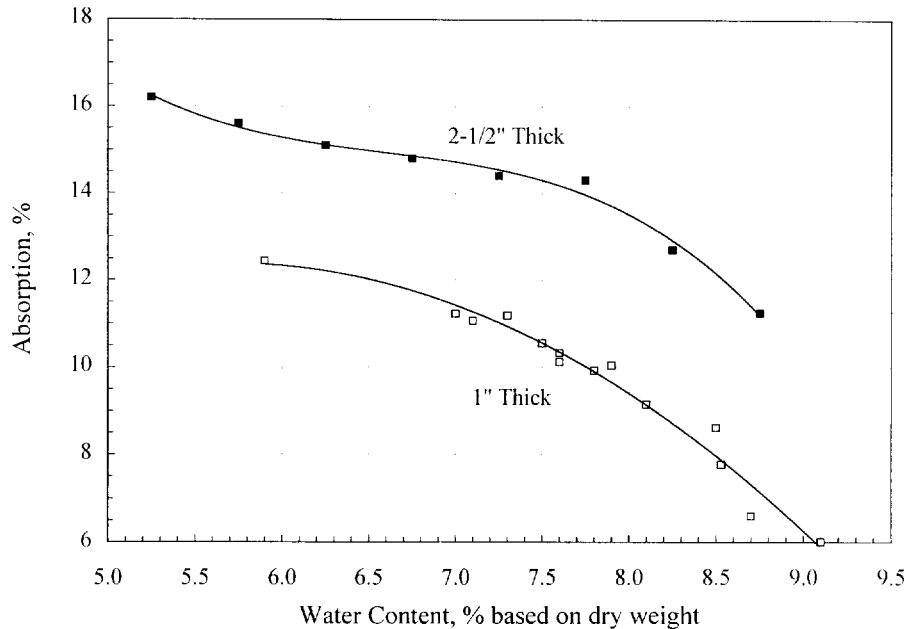


FIGURE 3 - Effect of water content and thickness on absorption of impacted mortar coating.

The concept of increasing the water content to obtain a lower permeable mortar is seemingly contrary to reducing the water to cement ratio of concrete to less than 0.40 or 0.45 to obtain the densest and less permeable concrete. However, in mortar consisting of one part cement to three parts sand with 7 to 9% water content, the water to cement ratio ranges from 0.28 to 0.36, respectively. This produces a dense and low permeable mortar. Since a certain amount of water is required for proper cement hydration, a water content lower than 7% does not produce a good quality mortar. The specified minimum water content in AWWA C301-92 is 7% to ensure a high quality, low permeable mortar.

Effect of Mortar Thickness on Absorption

The effect of increasing the thickness of the mortar coating from 1" (2.5 cm) thick to 2-1/2" (6.3 cm) thick is also shown in Figure 3. The absorption of the thinner coating at any water content is less than that of the 2-1/2" thick mortar coating.

The effect of increasing mortar thickness is also shown in Figure 4. Both coatings were made with 9.5% water content. The 1-5/16" (3.3 cm) thick coating was applied in one pass by slowing the pipe travel by approximately half. The absorption of the 11/16" (1.7 cm) thick coating was 9.5% compared to a higher absorption of 11% for the 1-5/16" thick coating. The specimens were subjected to a 9-week continuous immersion in seawater as explained in a previous section. The chloride ion penetration was less in the 11/16" thick coating and the amount that penetrated to the steel surface at 11/16" depth was less than that which penetrated to the steel level in the 1-5/16" layer. This indicates that a thicker coating does not increase the time required for chloride ions to penetrate to the steel surface. Impacting a thinner coating against a hard surface, such as a concrete core or steel cylinder, produces a denser and less permeable mortar. The outer surface of a thicker coating does not benefit from the hard surface.

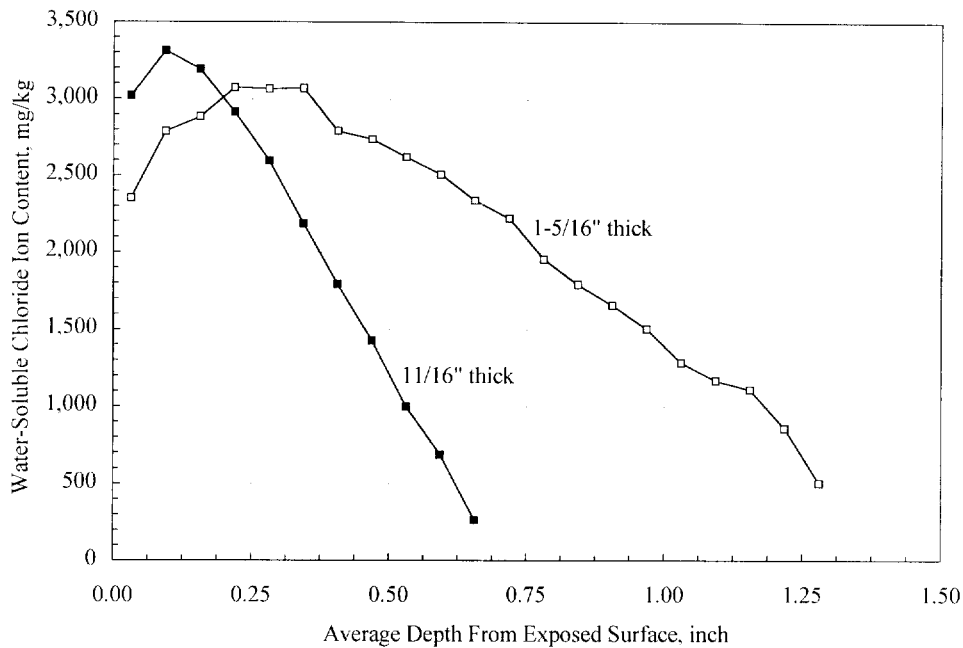


FIGURE 4 - Effect of thickness on chloride penetration into mortar coating made with 9.5% water.

Effect of Impact Damage to Mortar Coating

The effect of impact damage to the mortar coating of PCCP resulting in corrosion was investigated. A 48" (122 cm) diameter by 20 feet (6.1 m) long PCCP with and without impact damage was exposed to nine weeks of continuous seawater immersion followed by 44 weekly wet/dry cycles. Impact damage was produced by dropping a steel projectile 15 feet (4.6 m) through a small diameter pipe placed vertically on the mortar coating. This was done to simulate damage by a rock or boulder impacting the pipe during backfilling. The projectile weight varied from 30 to 40 pounds (13.6 to 18.2 kg). Four locations on the top of the pipe were impacted. A 6.25" (15.9 cm) diameter acrylic tube was bonded over each of the four impacted and non-impacted sites and filled with seawater. At nine weeks, the seawater was removed and heat lamps were used to dry the area at 110°F to 120°F (43°C to 49°C) for four days. The solution was then re-added for 3 days. This 3-day wet, 4-day dry, weekly cycling continued for 44 cycles. Potentials of the prestressing wire were measured using a saturated calomel reference electrode placed in the seawater in each tube. At 53 weeks of exposure, a 12" (30 cm) square section of mortar was removed at each impacted and non-impacted area to inspect the prestressing wire for corrosion.

Potentials of the non-impacted areas ranged from -25 mV to -210 mV (SCE) during the 53 weeks of exposure indicating that corrosion did not occur. The prestressing wire under the impacted areas initially showed passive potentials. At 9 to 41 weeks of exposure, the potentials of the wire under the impacted areas decreased at least 150 mV to potentials more negative than -340 mV (SCE) or -400 mV (CSE) indicating that corrosion of the wire was occurring. Upon removing the mortar, corrosion was seen on the prestressing wire under the impacted areas but no corrosion was seen under the non-impacted areas. Impact-damaged areas on PCCP caused by rocks or boulder during backfilling are more susceptible to corrosion than non-impacted areas.

Addition of Latex to Mortar

Styrene-butadiene latex has been used in concrete bridge decks as overlays or patch material for the last 30 years to protect against chloride induced corrosion from the use of deicing salts during the winter. Latex was expected to provide the same protection by reducing chloride penetration into mortar coatings in a buried pipe. This project compared the corrosion performance of latex-modified mortar coating to that of unmodified mortar.

Mortar coating specimens were impacted using 1 part cement to 3 parts sand with 5% and 7.5% by weight of the cement replaced with styrene-butadiene latex. The water content was 8%. The outer surface was subjected to 12 wet/dry cycles of 3 days immersed in a 0.70% sodium chloride (4300 mg Cl⁻/liter) solution followed by four days of drying at 100°F (38°C). The

coatings were then removed from exposure and layered in 1/16" (0.16 mm) depth increments. Water-soluble chloride ion content was determined in selected layers in accordance with AASHTO T260-84, Procedure A.

As shown in Figure 5, the replacement of 5% cement with an equal amount by weight of latex reduced chloride penetration by 50%. The replacement of 7.5% cement with latex resulted in no chloride penetration beyond the 0.45" (1.1 cm) depth.

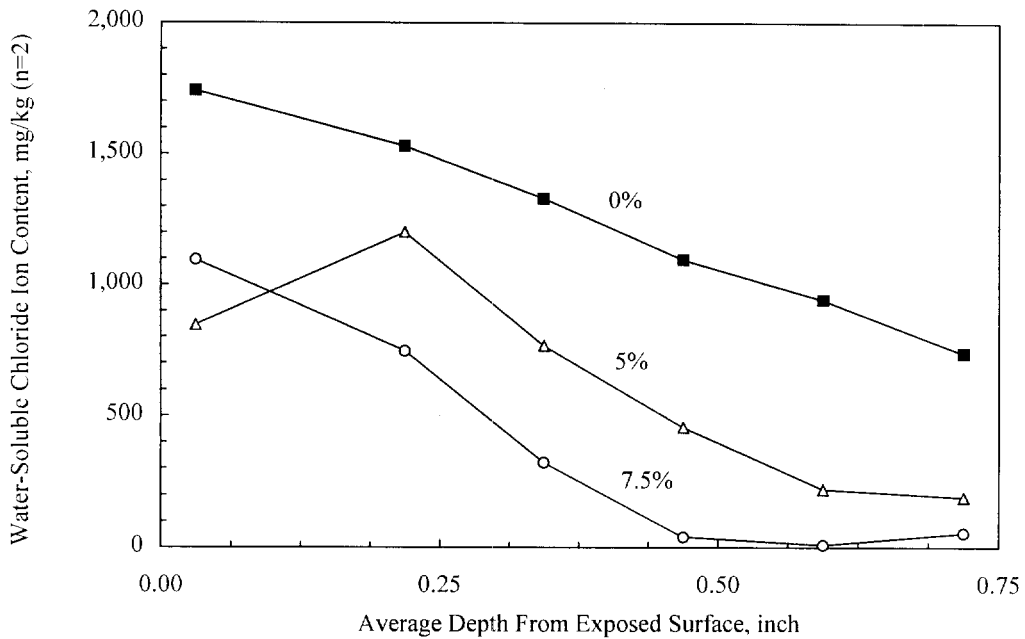


FIGURE 5 - Effect of latex addition on chloride penetration into mortar coating.

Additional investigation of the effect of latex-modified mortar was undertaken to determine if latex mixed with mortar and in contact with the prestressing wire allowed the wire to passivate or whether a film of latex would surround the wire not allowing a proper passivation film from forming. After 31 months of exposure, the potentials of prestressing wire embedded in latex-modified and unmodified mortar and partially immersed in seawater indicate that the wire remains passive.

PRESTRESSING WIRE RESEARCH

Chloride Content Required to Initiate Corrosion

In 1984, a 66" (167 cm) diameter by 20 feet (6.1 m) long PCCP with a cast concrete coating was removed after 23 years of service due to line relocation. The chloride ion content of the soil was very high at 1100 to 1200 mg/kg. Upon inspection, a 1' (0.3 m) diameter area on the bottom of the pipe was stained with corrosion products. Upon removing the mortar, severe corrosion of the prestressing wire only within this 1' diameter area was found. The water-soluble chloride ion content of the cast mortar over the corroded area was 670 mg/kg (2.7 lbs/yd³) at the outer 1/16" (0.16 cm) surface layer and increased to 9910 mg/kg (39.7 lbs/yd³) at the 1/16" thick layer immediately above the wire. Over an uncorroded area within two feet (0.6 m) of the corroded area, it was 710 mg/kg (2.9 lbs/yd³) at the outer 1/16" layer and increased to approximately 2500 to 3000 mg/kg (10.3 to 12.4 lbs/yd³) at the 3/16" (0.48 cm) layer and stayed at that level to the wire surface. At 2500 to 3000 mg/kg, no corrosion was found on the prestressing wire. This is ten to twenty times greater than the 0.06% (600 mg/kg of cement or 150 mg/kg of mortar) of water-soluble chloride content based on the cement weight given in ACI 318⁷ and the 1 lb/yd³ of concrete (250 mg/kg) given in NACE International RP0390-90.⁸

In 1991, a 48" (122 cm) diameter by 20 feet (6.1 m) long PCCP was exposed to nine weeks of continuous seawater immersion followed by 44 weekly wet/dry cycles. The test setup consisted of bonding four 6.25" (15.9 cm) diameter acrylic tubes along the length of the top of the pipe and filling the tubes with the solution. At nine weeks, the solution was removed and heat lamps were used to dry the area at 110°F to 120°F (43°C to 49°C) for four days. The solution was then re-added for 3 days. This 3-day wet, 4-day dry, weekly cycling continued for 44 cycles. Potentials of the prestressing wire were measured using a saturated calomel reference electrode (SCE) placed in the seawater in each tube. Potentials ranged from -25 mV to -210 mV (SCE) during

the 53 weeks of exposure indicating that corrosion was not occurring. At the end of the 44 cycles, the mortar was cut out and layered in 1/16" (0.16 mm) depth increments. Water-soluble chloride ion content of selected layers was determined in accordance with AASHTO T260-84, Procedure A. The mortar absorption was 8.7%.

The chloride penetration at the four replicate locations is shown in Figure 6. The last data point of each curve, at approximately a depth of 1" (2.54 cm), is the chloride ion content of the mortar between the wire. The second to the last point is the chloride content in the 1/16" (0.16 cm) layer directly above the wire. The chloride ion content of mortar from a specimen never subjected to seawater was less than 50 mg/kg (0.2 lb/yd³). Chloride ion content at the 1/16" (0.16 cm) layer above the prestressing wire at approximately a depth of 1" (2.54 cm) and between the wire ranged from 2400 to 2800 mg/kg (9.6 to 11.2 lbs/yd³). No corrosion was evident on the prestressing wire. As discussed above for the 66" PCCP, this is a very high level which is eleven to sixteen times greater than the 0.06% (600 mg/kg of cement or 150 mg/kg of mortar) of water-soluble chloride content based on the cement weight given in ACI 318⁷ and the 1 lb/yd³ of concrete (250 mg/kg) given in NACE International RP0390-90.⁸

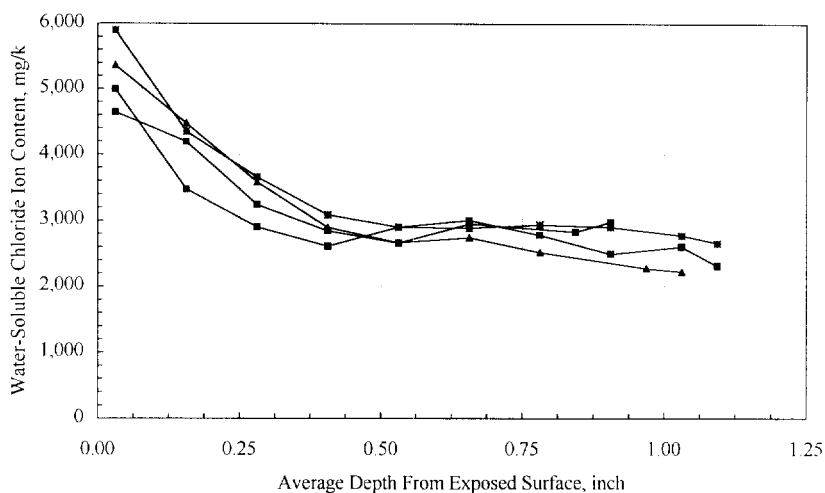


FIGURE 6 - Chloride penetration into mortar coating of 48" PCCP after 9 weeks of continuous immersion and 44 weekly cycles in seawater.

Inhibition by Lubricants on Wire

As shown above, higher chloride contents are required to depassivate prestressing wire than are usually required to depassivate reinforcing steel. It was found that some prestressing wire manufacturers use zinc phosphate as a lubricant during the drawing process. Zinc phosphate is a known corrosion inhibitor⁹ so it was proposed that greater levels of chloride ions were required to depassivate prestressing wire than ordinary reinforcing steel.¹⁰

Prestressing wire was removed from two PCCP sections and from a coil of wire never placed on a pipe. The surface of the wire was analyzed using SEM/EDAX. Zinc and phosphorus were found on wire removed from one of the two pipe sections and from the coil. The three wire samples and one reinforcing rod sample with no known zinc phosphate were embedded in mortar which contained 0 or 1000 mg/kg (4.0 lbs/yd³) of chloride ions by dry weight of the cement and sand. The specimens were partially submerged in seawater and potentials taken weekly. The time-to-corrosion was taken as the time that potentials more negative than -300 mV (CSE) were measured. At the end of exposure, a 1/32" (0.079 cm) thick layer surrounding the wire or rod was drilled out and water-soluble chloride ion content was determined.

As shown in Table 1, potentials indicated that corrosion initiated on the prestressing wire without zinc phosphate at 20 weeks of exposure. The addition of 1000 mg/kg (4.0 lbs/yd³) of chloride ions directly to the mortar decreased the time-to-corrosion by one to five weeks since lower levels of foreign chlorides had to diffuse through the mortar to the steel surface. The time-to-corrosion of the wire with zinc phosphate taken from a 48" (122 cm) PCCP with or without added chlorides occurred at 23 to 27 weeks, four to eleven weeks longer than the wire without zinc phosphate. The time-to-corrosion of the wire never placed on a pipe was 35 to 46 weeks, eight to 20 weeks longer than the wire with zinc phosphate taken from the 48" pipe. SEM/EDAX analysis indicated that lower levels of zinc and phosphorus were present on the wire taken from the 48" pipe than

on the wire never on a pipe. As such, a lower time-to-corrosion is reasonable. Time-to-corrosion of the reinforcing rods in the chloride containing mortar occurred at 3 to 4 weeks indicating that only 1000 mg/kg (4.0 lb/yd³) of chloride ions are required to depassivate reinforcing steel. The reinforcing steel in the uncontaminated mortar showed corroding potentials at 24 and 25 weeks, very similar to the time-to-corrosion of the wire removed from the 48" pipe. Most of the prestressing wire and reinforcing rod specimens repassivated and depassivated on a weekly to monthly basis after the initial depassivation.

TABLE 1
TIME-TO-CORROSION, CHLORIDE CONTENT, AND PRESENCE OF CORROSION
ON PRESTRESSING WIRE WITH AND WITHOUT ZINC PHOSPHATE

Source	Specimen No.	Admixed Chloride (mg/kg)	Length of Exposure (weeks)	Time-to-Corroding Potentials (weeks)	Chloride Content at Wire Surface (mg/kg)	Presence of Corrosion on Wire Surface
1/4" wire removed from PCCP; No Zn or P present	1-1	0	58	20	8,620	A few 1 to 2 mm ² brown stains
	1-5	1000	58	15	8,780	A few 1 to 2 mm ² brown stains
	1-3	0	104	22	13,500	None
	1-6	1000	104	19	11,500	None
6 gage wire removed from 48" PCCP; Minor amount of Zn & P present	2-2	0	58	25	8,050	None
	2-5	1000	58	23	14,100	None
	2-3	0	104	27	13,700	None
	2-6	1000	104	26	11,700	None
6 gage wire taken from a coil; Zn & P present	3-2	0	58	35	13,800	None
	3-4	1000	58	38	9,600	A few 1 to 2 mm ² brown stains
	3-3	0	104	46	12,600	None
	3-6	1000	104	38	10,600	None
1/4" reinforcing rod taken from stock; No Zn or P present	4-1	0	64	25	8,160	One 3 to 4 mm ² corroded area
	4-6	1000	64	4	8,450	One 16 mm ² corroded area
	4-2	0	104	24	7,990	A few 2 to 3 mm ² corroded areas
	4-5	1000	104	3	7,670	Two 10 mm ² corroded areas

The time-to-corrosion indicated that the prestressing wire with zinc phosphate was more resistant to depassivation by chloride ions. When the specimens were cut opened, green and black corrosion products were found on the cut ends of all of the specimens. Upon exposure to air, the corrosion products oxidized to the more familiar reddish corrosion products. Obviously, no zinc phosphate was present at these cut ends. Two of the four wire specimens which did not have a zinc phosphate coating showed a few brown stains that appeared to be corrosion products on the uncut surfaces. Seven of the eight wire specimens with the zinc phosphate coating showed no corrosion or loss of cross section on the uncut surface. In addition, the 1000 mg/kg (4.0 lb/yd³) of chloride ions added was not high enough to depassivate the ends of the wire during the initial 15 to 38 weeks of exposure based on the passive potentials measured. Corroding potentials were measured only when enough chloride ions in the seawater had penetrated through the mortar to the cut ends of the wire.

The chloride ion content measured in the 1/32" (0.079 cm) thick layer surrounding the wire or rod is also shown in Table 1. The chloride content around the wire ranged from 8,050 to 14,100 mg/kg (32 to 56 lbs/yd³) without any indication of corrosion. The chloride content around the reinforcing rod was approximately 8,000 mg/kg (32 lbs/yd³) with small corroded areas present. This indicates that chloride ion content less than this initiated corrosion of reinforcing rods. It was stated earlier that the 1000 mg/kg (4.0 lb/yd³) of chloride ions added to the mortar quickly initiated corrosion of the reinforcing rod. This indicates the extensive resistance of prestressing wire to depassivation by chloride ions even in those wire specimens which were not drawn using the zinc phosphate lubricant. However, the time-to-corrosion values indicate that the onset of corrosion is later for wire with zinc phosphate.

Coatings Applied to Prestressing Wire

Several different types of organic barrier coatings were applied to prestressing wire to determine whether coatings on prestressing wire could provide protection. A fusion bonded epoxy (FBE) coating occasionally used on prestressing strands for prestressed bridges was investigated. This process required the wire to be heated to 450°F (232°C). As specified in AWWA C301-92, the surface temperature of prestressing wire should not exceed 360°F (182°C) during the drawing process. Temperatures above this level are believed to strain-age the wire making it more brittle and increasing the wire's susceptibility to hydrogen embrittlement. As such, the effect of temperature on prestressing wire was determined.

Prestressing wire specimens conforming to ASTM A648, class III with a diameter of 1/4" (0.635 cm) were placed in an oven at 300°, 325°, 350°, and 375°F (149, 163, 177, and 190°C) for 15 minutes, removed, and allowed to cool. The number of turns to break in continuous torsion was determined in accordance with the test method given in ASTM A648. The specimen length between the grips was 100 times the wire diameter or 25" (63.5 cm). Continuous torsion is a property of the ductility of prestressing wire.

The number of turns to break with respect to temperature is given in Table 2. The wire was severely damaged at 375°F. The number of turns to break decreased substantially as temperature increased to 375°F and the type of break went from a smooth transverse break which indicates a very ductile material to a jagged transverse break with a helical crack which indicates a very brittle material. As such, heating the wire to 450°F to apply a FBE coating should seriously affect the ductility of the wire.

TABLE 2
EFFECT OF TEMPERATURE
ON 1/4" PRESTRESSING WIRE

Test	Temperature, °F (°C)				
	73 (23)	300 (149)	325 (163)	350 (177)	375 (190)
Continuous Torsion (turns to and type of break in 25" length)	15a 18a	19a 15a 21a,b	16a,aj 17a,b 2aj	12a 16a,b 18a,b	1aj 3aj,c 1aj,c

"a" refers to smooth transverse break; "b" refers to inclined break;
"aj" refers to jagged transverse break; "c" indicates a helical crack.

The physical properties of prestressing wire specimens with and without the FBE coating were determined in accordance with the test methods given in ASTM A648. Tensile strength, reduction of area, continuous torsion, and performance in the wrap and bolt cutter test are given in Table 3. Tensile strength was slightly elevated and reduction of area decreased slightly. Continuous torsion was severely affected. Wrap and bolt cutter performance was not affected. Based on the drastic decrease in ductility in continuous torsion, the high temperature required to apply FBE coating is detrimental to prestressing wire and should not be used.

TABLE 3
PHYSICAL PROPERTIES OF NON-COATED AND
FBE-COATED 1/4" PRESTRESSING WIRE

Test	Tensile Strength (ksi)	Reduction of Area (%)	Continuous Torsion (turns to & type of break in 25" length)	Wrap Test	Bolt Cutter Test
Non-Coated Wire	259	49.0	15a	Pass	Pass
	265	50.6	18a		
	253	54.2	20a		
	249	53.1	20a		
FBE-Coated Wire	268	47.3	5aj	Pass	Pass
	268	49.6	4aj		
	271	50.1	2aj		

"a" refers to smooth transverse break; "aj" refers to jagged transverse break.

Although the ductility was severely affected, the FBE-coated wire did not break during the prestressing operation. However, the FBE coating severely disbonded and cracked during prestressing.

Several additional coatings specifically formulated to survive the prestressing operation were investigated. As with the FBE coating, the materials severely disbonded and cracked during the prestressing operation.

CORROSION INHIBITING PROPERTIES OF STEEL IN MORTAR UNDER STRAY CURRENT DISCHARGE

The effects of anodic or stray current discharge on corrosion of steel in mortar were investigated. An earlier study showed that current discharge can be tolerated for long periods without damage to steel.¹¹ This project determined current density levels and length of discharge before corrosion occurred.

Twenty-four prestressing wire specimens embedded in mortar and partially immersed in tapwater were exposed to no anodic current and anodic current densities of 16 to 25, 100 to 150, and 1000 mA/ft² (172 to 269, 1080 to 1610, and 10,800 mA/m²) for up to 33 weeks. Specimens were examined weekly. They were removed from exposure, cut open, and photographed when mortar cracking was found. After 33 weeks of exposure, the remaining specimens were removed from exposure. Weight loss of the prestressing wire was determined.

The results are given in Table 4. At anodic current densities of 16 to 25 mA/ft² with resulting current-interrupted potentials of +700 to +800 mV (SCE), no corrosion was seen on the prestressing wire at 33 weeks of current discharge. According to Faraday's Law of Electrolysis, the 5,080 coulombs passed is equivalent to 1.5 grams of iron or 12% of the weight of the prestressing wire. This amount should have corroded if the anodic reaction was steel corrosion, $Fe \rightarrow Fe^{2+} + 2e^-$. Since no corrosion or loss of metal was seen, a reasonable anodic reaction in the highly alkaline mortar is the consumption of hydroxide ions to produce oxygen and water, $4OH^- \rightarrow O_2 + 2H_2O$. This is the reverse reaction of oxygen reduction typically seen as the cathodic reaction in neutral or alkaline environments. It appears that diffusion and/or the electrochemical attraction of the negatively-charged hydroxide ions from the bulk of the mortar to the positively-charged steel surface replenished the hydroxide ions being consumed at the wire surface.

TABLE 4
EFFECT OF STRAY CURRENT ON PRESTRESSING WIRE IN MORTAR

Specimen Number	Length of Exposure (weeks)	Anodic Current Density, mA/ft ² (mA/m ²)	Total Coulombs Passed (A*sec)	Theoretical Weight Loss Based on $Fe \rightarrow Fe^{2+} + 2e^-$		Measured Weight Loss		Corroding Surface Area of Wire (%)
				Grams	%	grams	%	
1 to 6	33	0	0	0	0	<0.1	<1	0
7 to 12	33	16 to 25 (172 to 269)	5,080	1.5	12	<0.1	<1	0
13	2	100 (1,080)	3,030	0.7	6	0.1	1	0
14 & 15	23	100 to 150 (1,080 to 1,610)	19,700	5.7	47	0.1 to 0.2	2	25
16 to 18	33	100 to 150 (1,080 to 1,610)	28,000	8.1	67	0.1 to 0.7	1 to 6	50 to 60
19 to 24	2	1,000 (10,800)	16,500	4.8	40	0.1 to 0.3	1 to 3	100

At anodic current densities of 100 to 150 mA/ft² with resulting current-interrupted potentials of +1600 mV, no corrosion was seen on the wire of 1 specimen removed at 2 weeks of discharge although 6% of the weight of the wire should have been lost if steel corrosion was occurring. At 23 weeks of exposure, corrosion was seen on the bottom 3/4" (3.8 cm) of the wire of 2 specimens. The measured weight loss was only 1 to 2% rather than the 47% calculated based on the anodic reaction of steel corrosion. At 33 weeks, corrosion was seen over approximately 50 to 60% of the wire surface of the remaining 3 specimens. The measured weight loss was 1, 2, and 6% rather than 67% calculated based on steel corrosion. A crack was present in the mortar and a longitudinal split was present in the wire which had a 6% weight loss. The primary anodic reaction appears to be the consumption of hydroxide ions. A smaller secondary reaction of steel corrosion occurred probably due to the inability of sufficient hydroxide ions to diffuse and/or to be attracted to the steel surface.

At anodic current densities of 1000 mA/ft², the specimens were removed at 2 weeks of discharge when a crack was found in the mortar of one of the specimen. "Fizzing" could be heard from these specimens which is consistent with the production of oxygen occurring during hydroxide consumption. Upon cutting open the specimens, black corrosion products were found along the entire length of the prestressing wires. The measured weight loss was only 1 to 3% rather than the 40% calculated based on steel corrosion. Again, it appears that the primary anodic reaction was the consumption of hydroxide ions with a minor secondary reaction of steel corrosion. It is believed that with enough time the secondary reaction of steel corrosion may become the primary reaction since diffusion or electrochemical attraction of hydroxide ions may be insignificant at a high current density of 1000 mA/ft².

In another test, a 6" (15.2 cm) wide by 26" (66.0 cm) long plastic enclosure was bonded to the mortar coating at the top of a 36" (91.4 cm) diameter by 32" (81.3 cm) long concrete cylinder pipe specimen. The enclosure was filled with tapwater and the underlying steel was subjected to an initial anodic current density of 200 mA/ft² (2150 mA/m²) which decreased to 28 mA/ft² (300 mA/m²) at 30 days. During this period the current-interrupted potential of the steel went from +800 mV to +2800 mV (SCE). The current could not be maintained at 200 mA/ft² due to the formation of a calcium carbonate deposit on the mortar surface which increased the electrical resistance of the system. This caused the impressed voltage to increase from 10 volts at the start of the test to 104 volts at 30 days. After 50.7 A•hr/ft² (550 A•hr/m²) of current passed in 30 days, the mortar was removed and the underlying steel inspected. Only superficial to no corrosion was seen on the steel surface although 53 grams of the steel over the exposed 6" by 26" area should have corroded based on the amount of coulombs passed. It again appears that the primary anodic reaction was the consumption of hydroxide ions with a minor secondary reaction of steel corrosion.

Anodic current on steel in mortar does not initially and may never cause corrosion. The initial anodic reaction is the consumption of hydroxide ions in the high pH mortar environment to produce water and oxygen. When the pH or alkalinity cannot be replaced by diffusion or attraction of hydroxides ions through the mortar to the steel surface, steel corrosion is initiated. Potentials more positive than approximately +700 mV are required before hydroxide ions are consumed.¹¹ Large impressed voltages appear necessary to achieve +700 mV. Typical cathodic protection systems on foreign pipelines probably cannot achieve these levels. Stray current from electric rail systems may be able to cause these levels.

SIGNIFICANCE OF POTENTIAL MONITORING OF PCCP

Potential Monitoring Techniques

Various techniques are used to evaluate the corrosion state of a buried pipeline. The two most commonly used are the pipe-to-soil (P/S) and cell-to-cell potential techniques. The cell-to-cell consists of a fixed-cell-to-moving-cell technique and a moving-cell-to-moving-cell technique. However, only a few references exist relating to the use of these monitoring procedures for PCCP. Various corrosion engineering firms have confidence in one or the other technique without being able to provide the rationale for their preference.

This project consisted of setting up simulated corrosion cells on a 48" (1.22 m) diameter by 240' (73 m) long PCCP line and allowing five corrosion engineering firms the opportunity to use their potential monitoring techniques to locate corroding sites. The results were reported at CORROSION/94.¹²

Over-the-line pipe-to-soil potential surveys by the five corrosion engineering firms are shown in Figure 7. The peaks indicate the location of the corrosion site. A shift of 60 to 100 mV occurred over pipe no. 5 when the anode at the top of the pipe was activated. Although only the over-the-line pipe-to-soil potential data are shown, the consultants were able to locate the site using all of the potential techniques mentioned.

The following conclusions were reached:

- Electrically continuous and discontinuous PCCP can be monitored for corrosion depending on the intensity of corrosion and the location of the corrosion site on the pipe circumference. The results from potential monitoring techniques can provide useful, but not necessarily definitive, indications of corrosion activity on PCCP.
- Pipe-to-soil, fixed cell-to-moving cell, and moving-cell-to-moving-cell potential techniques are appropriate measuring techniques. A shift in potential from the apparent baseline of the survey indicates that corrosion of steel in PCCP may be occurring.

- The potential monitoring techniques are meaningful when conducted in soil with adequate moisture. If the soil surface is not adequately moist or insufficient contact of the reference cell is made to the soil, erratic and erroneous potentials are measured.
- Identifying corrosion occurring directly on the bottom of the pipe may be difficult using the over-the-line potential survey unless the corrosion activity polarizes the pipe steel further up the circumference of the pipe.
- Coal-tar epoxy coated PCCP can be monitored for corrosion. Similar results were obtained using the three potential monitoring techniques.

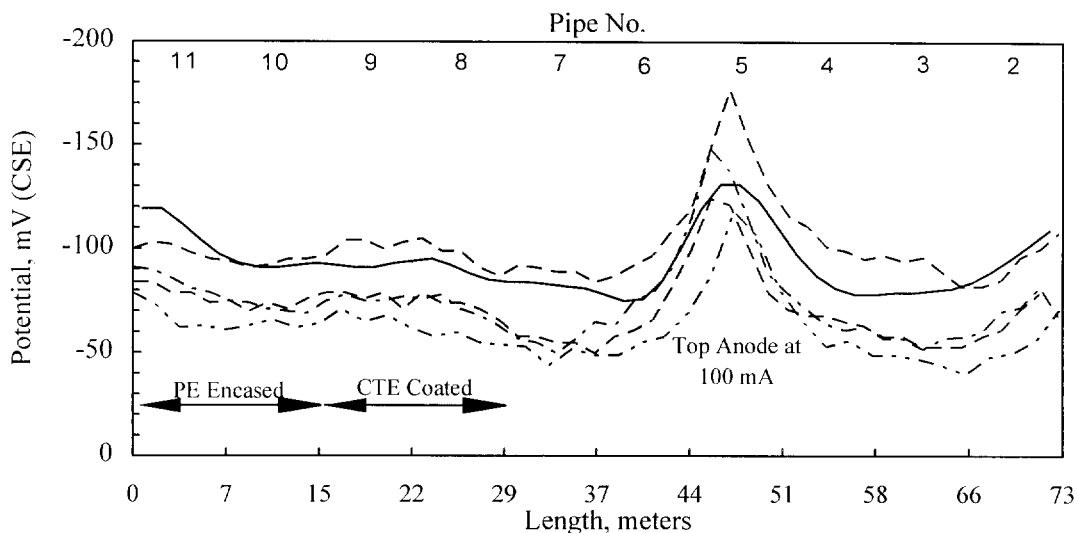


FIGURE 7 - Over-the-line pipe-to-soil potential of bonded PCCP line with simulated corrosion cell at top of pipe no. 5.

Potential measurements do not provide a definitive picture of the corrosion rate or corrosion cell dimensions but serves as an indicator of corrosion activity. When potential changes are found indicative of corrosion, other reasons for the shifts should also be investigated. Connection to steel appurtenances will cause potential shifts in the negative direction as will stray current pickup or connections to a cathodic protection system.

Effect of Soil Resistivity, Pipe Diameter, Depth of Cover, and Corrosion Location, Area, and Intensity on Ability to Monitor

The above potential monitoring study was performed in only one environment while maintaining pipe diameter, soil cover, soil resistivity, and anode size constant. A computer model was developed and validated based on the above monitoring project and the model was used to explore the effects of variation in pipe diameter, location and size of anodic areas, depth of ground cover, soil resistivity, and corrosion current.¹³ A summary of the results is shown in Table 5.

Based on Table 5, the following conclusions were reached:

- Soil cover, anode position, and anode area have the most significant impact on ground surface potentials.
- As soil cover increases, potential changes at the ground surface decrease.
- The corrosion cell position is clearly a critical variable due to the distribution of current relative to the ground surface. The plane of symmetry of the potential distribution rotates with the corrosion cell position. As the corrosion cell moves from the top to the bottom of the pipe, only fringe currents reach the ground surface.
- As corrosion cell area increases, total current increases resulting in greater current flow and potential changes at the ground surface.

- Pipe diameter has a small effect on potentials at the ground surface. As pipe diameter increases, potential shifts increase slightly when the corrosion cell is at the top. It is expected that pipe diameter would decrease the potential at the ground surface if the corrosion cell was at the pipe bottom due to the greater depths of the corrosion cell at the pipe bottom.
- Soil resistivity did not affect the measured surface potential. However, corrosion currents increased substantially with decreasing resistivity. This indicates that identical potentials measured on pipelines with similar size and soil cover can produce different degrees of corrosion based on the different soil resistivity. This shows the importance of measuring soil resistivity along the pipeline during the potential monitoring survey. A corrosion intensity factor (CIF) equal to the potential change divided by the soil resistivity ($CIF = \Delta E/\rho$) can be used to determine the location with the highest level of corrosion activity along a pipeline. The location with the greatest CIF should indicate the location with the greatest corrosion activity.

TABLE 5
EFFECT OF SOIL RESISTIVITY, PIPE DIAMETER, SOIL COVER, AND ANODE POSITION AND SIZE ON POTENTIAL CHANGE AND CURRENT

Variable	Anode		Soil Resistivity (ohm •cm)	Pipe Diameter (inches)	Soil Cover (feet)	Potential Change at Surface (mV)	Current	
	Location	Area (ft ²)					Total (mA)	Density (mA/cm ²)
Soil Resistivity	Top	1.0	1	48	6	57	163	175
			3			58	55	59
			10			59	17	18
			30			60	5.7	6.0
			100			62	1.8	1.9
Pipe Diameter	Top	1.0	10	48	6	59	17	18
			96	72	15	16		
			252	79	18	19		
Soil Cover	Top	1.0	10	48	6	59	17	18
				10	23	18	19	
				20	6.0	20	21	
Anode Position	Top	1.0	10	48	6	59	17	18
	Side	1.0				11	15	18
	Bottom	1.0				-3.4	18	19
	Bottom	10.0				-9.4	45	4.8
Anode Area	Top	0.1	10	48	6	11	6.7	72
		1.0				59	17	18
		10.0				187	44	4.7

Monitoring in Low Resistivity Soils

In the above project, monitoring was performed in relatively high resistivity soil where the potential gradient at the ground surface did not expand beyond 48 feet (14.6 m). On another pipeline which was located within the water table with a resistivity of 200 to 400 ohm•cm, potentials of -600 to -700 mV (CSE) were measured along the entire length of the pipeline. After excavation at four sites, only small ½" (1.2 cm) diameter areas of corrosion were found at the joints. The potential of the steel reinforcing rod underneath the mortar with the reference cell placed on the mortar coating was -400 mV and depolarizing. This indicated that the potentials being read during the over-the-line potential survey were due to small, inconsequential corroding areas at the joint and were not indicative of general corrosion of the pipeline. This shows that a few excavations should be performed to determine the reason for the "corroding" potentials prior to possibly unnecessary remedial action.

It has been verbally reported to one of the authors that "corroding" potentials on PCCP when it is located within the water table is not an indication of corrosion. Rather, it is caused by the unavailability of oxygen by restricted diffusion through the mortar. Without oxygen, corrosion will not occur. However, the "corroding" potentials are probably due to inconsequential corrosion areas as reported in the above paragraph. To determine whether a "water table" will produce more active potentials, a test was performed to duplicate a water table. Prestressing wire embedded in mortar was immersed in tapwater for five years. Potentials were taken weekly. The potentials were passive throughout the immersion and have no tendency to move in the more

negative direction. This indicates that sufficient oxygen is present in the mortar, that sufficient oxygen can diffuse through the mortar to provide whatever oxygen is required to maintain the passive film, and/or that oxygen is not required to provide passive potentials. The corroding potential measured in the field were most likely small corroding sites at the joint which transferred over a large area in the low resistivity water as discussed in the previous paragraph.

SUPPLEMENTAL PROTECTION USING BARRIER COATINGS

In high chloride environments, a barrier coating is recommended to prevent the intrusion of chloride ions into the mortar coating. This type of a coating is referred to as supplemental since the primary corrosion control measure is the corrosion inhibiting mortar coating.

Chloride ion penetration into mortar is normally low. Chloride ion penetration into mortar of four PCCP sections removed from service after 10 to 33 years of service are shown in Figure 8. The typical chloride content of mortar prior to installation ranges from 10 to 100 mg/kg. The mortar absorption ranged from 5.2% to 9.3%. The water-soluble chloride content of the soils was as high as 145 mg/kg which produced virtually no chloride ion penetration into the mortar coating during the many years of service. At these levels, supplemental coatings are not necessary. Chloride ion content in soil or ground water is rarely high enough to penetrate into the mortar coating and depassivate the prestressing wire.

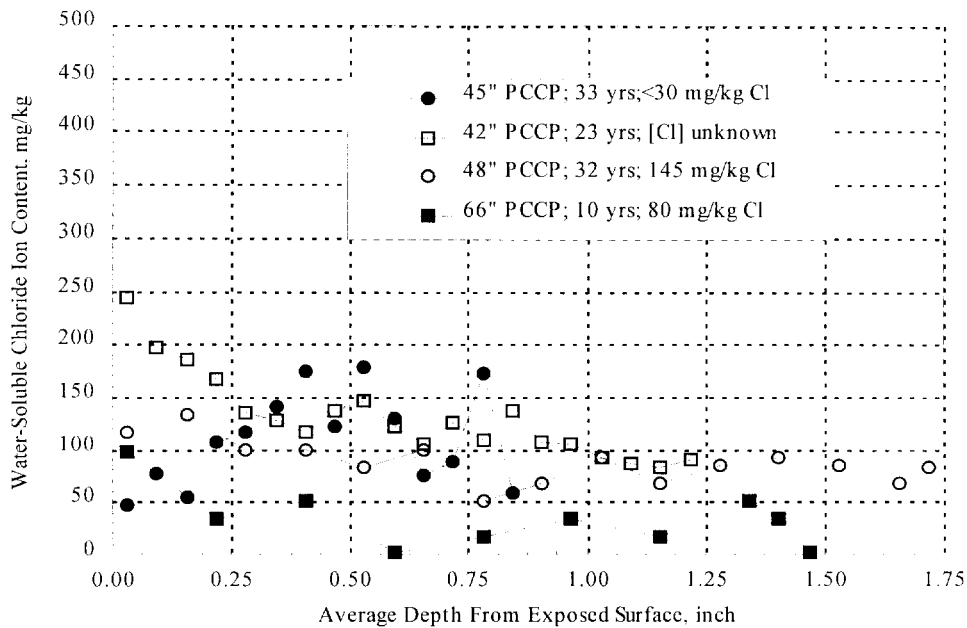


FIGURE 8 - Chloride ion penetration into PCCP after many years of service in soils with various chloride contents.

In high chloride environments, a barrier coat will prevent the ingress of chloride ions as shown in Figure 9. Three 3" square by 1" thick mortar coating specimens with an absorption of 7.2% were sealed on the sides and bottom and another three were also sealed on the top with a 100% solids coal tar epoxy. A 1/32" (0.8 mm) diameter pinhole was drilled through the epoxy at the top of the three sealed specimens. They were then immersed in a 0.70% sodium chloride solution (4300 mg Cl/liter) for 3 days and dried at 100°F (38°C) for 4 days. After 96 weekly cycles, essentially no chloride ions penetrated into the mortar with a supplemental coal tar epoxy coating even with a 1/32" diameter pinhole. It also showed that even at the critical 3/4" depth over the wire, the chloride ion content in the uncoated mortar after 96 cycles was 740 mg/kg. This level was shown in a previous section to be substantially lower than that required to depassivate prestressing wire. It is evident that severe conditions must occur before sufficient chloride ions can penetrate mortar and depassivate prestressing wire. However, it is recommended that barrier coatings are needed when the chloride ion content of the soil or ground water is greater than 350 mg/kg or 350 mg/l, respectively. A more stringent limit of 150 mg/kg may be appropriate in soils subjected to cyclical wetting and drying, an occurrence which accelerates the buildup of chlorides in the mortar coating.

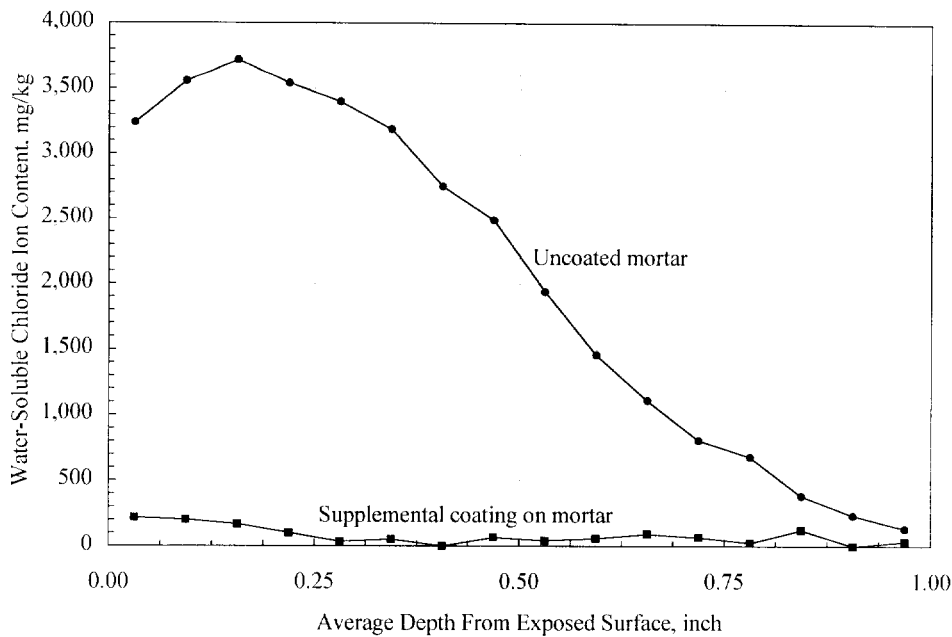


FIGURE 9 - Chloride penetration into mortar coating with and without supplemental coating.

CATHODIC PROTECTION RESEARCH

Cathodic Protection Criteria

The potential criterion required to achieve protection of underground organically-coated oil and gas pipelines has been under considerable debate for the past 10 years. The commonly accepted criterion of -850 mV (CSE) is often used on bare or organically-coated steel.¹⁴ A 100-mV polarization or depolarization shift is another criterion that is used to protect organically coated steel or steel in concrete.^{14,15,16} Polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar.¹⁷

Electrical Continuity

CP requires that all steel elements within the pipe and between each pipe section be electrically continuous (or bondec). In most cases, the pipe joints have a bell and spigot configuration with a rubber gasket. This configuration requires that the joints be bonded for CP to be effective. Most PCCP lines installed in the Western United States in the last 15 years have been bonded. In the Eastern United States, most pipelines are not bonded.

Current Density Requirements

Under certain conditions, such as high chloride environments, the prestressing wire can depassivate, leading to corrosion. Under these conditions, cathodic protection (CP) can be used to protect the encased steel elements. The purpose of this project was to determine current density requirements of PCCP with and without supplemental barrier protection. This project consisted of installing a CP system on a 48" (1.22 m) diameter by 240' (73 m) long PCCP line and measuring current, polarization, and depolarization of the pipeline during two to three months of system activation. Additional details and results of the project are reported elsewhere.¹⁸

The following conclusions were reached:

- A current density of approximately $25 \mu\text{A}/\text{ft}^2$ ($270 \mu\text{A}/\text{m}^2$) on uncoated PCCP produced a 180-mV polarization during 3 months of CP. Upon CP deactivation, a depolarization shift of 100 mV at 4 hours and 200 mV during the first week occurred.

- A current density of approximately $3 \mu\text{A}/\text{ft}^2$ ($32 \mu\text{A}/\text{m}^2$) on coal-tar epoxy coated PCCP produced a polarization shift of 150 mV at 2 months and a depolarization shift of 65 mV during the first 4 hours and 75 mV at one month.
- A current density of approximately $3 \mu\text{A}/\text{ft}^2$ ($32 \mu\text{A}/\text{m}^2$) on PE-encased PCCP produced a polarization shift of 100 mV at 3 hours and remained essentially unchanged during the next 3 months of CP. It produced a depolarization shift of 140 mV during the first 4 hours and 200 mV at one week.

Since $25 \mu\text{A}/\text{ft}^2$ ($270 \mu\text{A}/\text{m}^2$) produced a polarization shift greater than 100 mV, the current density was decreased to $12 \mu\text{A}/\text{ft}^2$ ($130 \mu\text{A}/\text{m}^2$). The polarization shift was approximately 120 mV at 1 month. The polarization shift is shown in Figure 10. The depolarization shift was 100 mV in 4 hours and 120 mV after 1 week.

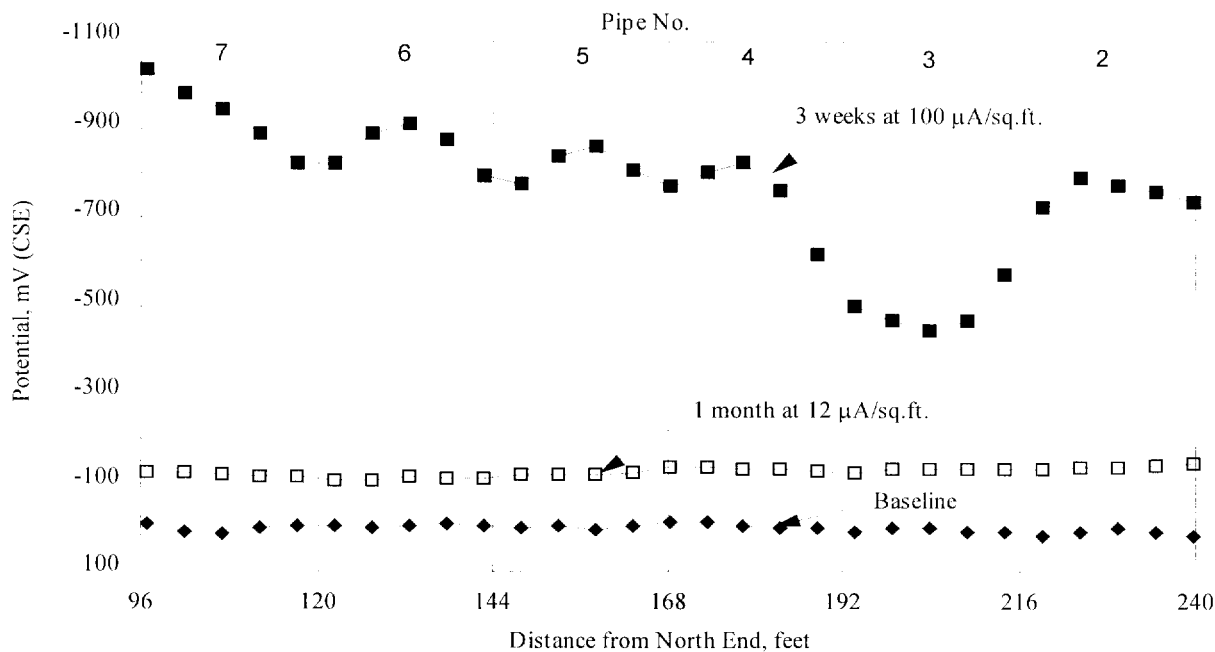


FIGURE 10 - Baseline and polarization potentials of PCCP line under CP at 12 and $100 \mu\text{A}/\text{ft}^2$ (130 to $1080 \mu\text{A}/\text{m}^2$).

In addition, the current density required to achieve potentials not less than -1000 mV (CSE) was determined. To achieve -1000 mV on the pipe nearest the anode, an average current density of $100 \mu\text{A}/\text{ft}^2$ ($1080 \mu\text{A}/\text{m}^2$) was required. The polarization potentials of the pipeline are given in Figure 10. This would indicate that the maximum design current density for PCCP is $100 \mu\text{A}/\text{ft}^2$ ($1080 \mu\text{A}/\text{m}^2$). Within each 24' (7.3 m) PCCP section which were produced with shorting straps, the most negative potential is in the center of each pipe section, not at the joint. It is believed from these results that a close interval survey of older pipelines, which do not have shorting straps, will adequately indicate the level of polarization in the center of each pipe section. The reason for the large dip in potential at pipe 3 has not been determined.

Cathodic protection is rarely required on a supplementally-coated PCCP. If monitoring shows that corrosion is occurring¹², cathodic protection is a suitable means to control the corrosion under the pinholes and cracks in the coating.¹⁷

Current Flow to Prestressing Wire and Cylinder

The amount of current flowing individually to the prestressing wire and cylinder was also determined with the current density at 12, 100, and $680 \mu\text{A}/\text{ft}^2$ (130 , 1080 , and $7300 \mu\text{A}/\text{m}^2$ - 6.4, 36.6, and 250 mA) based on the mortar coating surface area. A 1-ohm resistor was placed between the end of the prestressing wire and the power supply and another between the end of the cylinder and the power supply on one pipe section. The prestressing wire surface area was 65% of the cylinder surface area. It was found that lower levels of current flow onto the prestressing wire than onto the cylinder. At $12 \mu\text{A}/\text{ft}^2$, the current density on the wire was $4.4 \mu\text{A}/\text{ft}^2$ compared to $18 \mu\text{A}/\text{ft}^2$ on the cylinder. At $100 \mu\text{A}/\text{ft}^2$, the current density on the wire was $30 \mu\text{A}/\text{ft}^2$ compared to $97 \mu\text{A}/\text{ft}^2$ on the cylinder. At $680 \mu\text{A}/\text{ft}^2$, the current density on the wire was $450 \mu\text{A}/\text{ft}^2$ compared to $490 \mu\text{A}/\text{ft}^2$ on the cylinder.

Cathodic Protection Design

When applying cathodic protection to a PCCP line, the polarization potential should not be more negative than -1000 mV (CSE) to prevent hydrogen embrittlement of the prestressing wire as discussed in the next section. The polarization potential should be at least 100 mV more negative than the nearby most anodic site. Under circumstances when only one anode bed is anticipated, the polarization potential of the pipe furthest from the anode bed should be at least 100 mV more negative than its most anodic site at that location with potentials never greater than -1000 mV. When the line is longer and more than one anode bed is anticipated, the pipe nearest the anode bed can be set at approximately -1000 mV. The potential will decrease down the length of the pipeline until a potential 100 mV more negative than the baseline potential is reached. Another anode bed would then be placed from the first anode bed at twice the distance from the first anode bed to the point where the minimum 100-mV polarization shift was achieved. The distance between the two anode beds would be the approximate distance for any additional anode beds required.

Hydrogen Embrittlement of Prestressing Wire

Due to the use of high strength prestressing wire in PCCP, the effect of high levels of CP at the potential required to cause hydrogen embrittlement must be addressed. The most probable reaction occurring on the pipe under excessive CP at pH greater than 7 is the electrolysis of water, $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$. During the formation of H_2 , hydrogen atoms (H°) are produced on the metal surface. Prior to combining to form hydrogen gas, atomic hydrogen may penetrate the steel. This entry causes a loss of ductility, or embrittlement, of the prestressing wire.

Based on the above reaction, the potential at which hydrogen evolution occurs can be calculated using the following Nernst Equation:

$$E = E^\circ - (RT/nF)\ln\left(\frac{[\text{H}_2\text{O}]^2}{[\text{H}_2][\text{OH}^-]^2}\right)$$

where

- E = Hydrogen evolution potential, V
- E° = Oxidation potential = +0.828 V (SHE)
- R = 8.314 J/°K·mole
- T = 298.2°K (25°C)
- F = 96,500 coulombs/equivalent
- n = 2 equivalents/mole (electrons in reaction)
- $[\text{H}_2\text{O}]$ = Activity of water = 1
- $[\text{H}_2]$ = Activity of hydrogen = 1 atmosphere
- $[\text{OH}^-]$ = Hydroxide ion activity = antilog(pH minus 14)

Therefore, at a pH of 12.5, $E = +0.739$ volt (SHE) for the oxidation reaction. For the reduction reaction (hydrogen production), the sign is changed and -0.316 volt is added to convert from the standard hydrogen electrode (SHE) to the copper-copper sulfate electrode (CSE). Thus at typical pHs of portland cement mortar of 12.5 to 13.5, the hydrogen evolution potential is -1055 mV to -1114 mV (CSE), respectively.

The project consisted of determining the effect of CP on time-to-failure, hydrogen content, tensile strength, and reduction of area of prestressing wire. Additional details and results of the project are reported elsewhere.¹⁸ Prestressing wire from three manufacturers was subjected to no CP and to CP polarization potentials of -850 mV and -1000 mV as well as cathodic over-protection values of -1200 mV to determine the effect of CP on the performance of prestressing wire. The wire was stressed and maintained at 60% of its specified minimum tensile strength in a saturated calcium hydroxide solution. This is the approximate stressed value of the wire on PCCP.

The effect of CP on tensile strength, reduction of area, and hydrogen content of prestressing wire from two manufacturers maintained at 60% of its specified minimum tensile strength in a saturated calcium hydroxide solution for 3, 6, and 12 months was determined. Tensile strength was not affected by level of CP. Reduction of area remained at approximately 50% at no CP and CP levels of -850 mV and -1000 mV at all exposure lengths and wire manufacturers. A significant decrease in reduction of area values to 32% to 43% was evident at polarization potentials of -1200 mV. These results were consistent with results from unloaded prestressing wire which showed that excessive CP at -1100 mV (CSE) and more negative values decrease the ductility of prestressing wire.

Hydrogen content of the wire ranged from 0.5 to 2.5 ppm at no CP and CP levels of -850 mV and -1000 mV. A significant increase in hydrogen content of 5 to 10 ppm was evident at polarization potentials of -1200 mV. This is consistent with the observation that copious amounts of fine bubbles were produced and collected on the specimens at -1200 mV. No

bubbles were seen or collected at -1000 mV. This is consistent with the calculated hydrogen evolution potential of -1055 mV (CSE) at a pH of 12.45. The increase in hydrogen content is consistent with the decrease in reduction of area at -1200 mV.

Time-to-failure of prestressing wire specimens from three manufacturers held at -1200 mV at 60% of its specified minimum tensile strength is shown in Figure 11. It is plotted as a function of its initial ductility, as expressed by turns to break in continuous torsion. The time-to-failure varied from 9 to 41 months and is dependent on the number of turns to break in continuous torsion determined on non-exposed (control) specimens. The fractures were all brittle in nature and the reduction of area at the failure point was less than 2%. This indicated that embrittlement of the wire occurred. Longitudinal splits terminating near the center of the wire were found on some of the specimens held at -1200 mV. Hydrogen contents of a 1" long section containing a fractured end were 5 to 20 ppm. It appears that wire with higher turns to break in continuous torsion has a lower susceptibility to hydrogen embrittlement. This supports the continuous torsion requirement in AWWA C301.

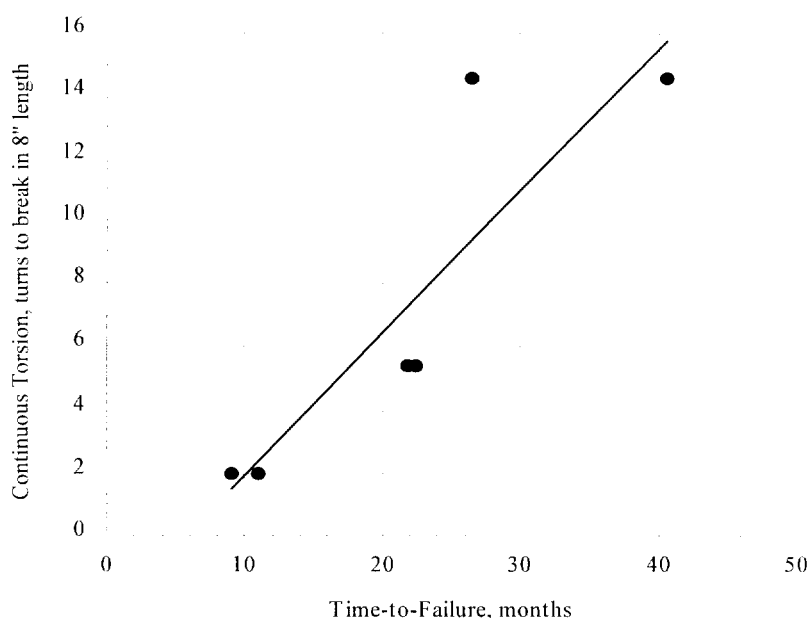


FIGURE 11 - Time-to-failure of prestressing wire held at -1200 mV as a function of continuous torsion.

Prestressing wire held at -1000 mV or more positive potentials, where hydrogen is not produced, have not failed after up to 62 months of exposure. Exposure of the specimens at these more positive potentials is continuing.

Prestressing wire is susceptible to hydrogen embrittlement at potentials negative enough to generate hydrogen. Polarization potential should be maintained at potentials less negative than -1000 mV to avoid hydrogen embrittlement and possible failure of the pipe.

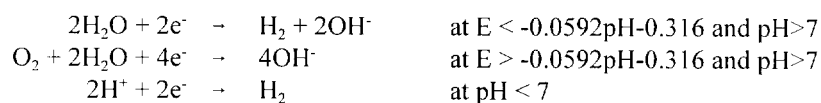
Diffusion of Hydrogen from Prestressing Wire

The effect of discontinuing high levels of CP on the recovery of ductility as expressed by reduction of area was determined. Prestressing wire specimens which had been at -1100 mV, -1180 mV, and -1260 mV for 26 weeks to 3 years were removed from CP and reduction of area of the specimens were determined 4 to 8 weeks later. Reduction of area essentially recovered to its initial, pre-test value. Most of the recovery occurs during the first four weeks, but at least 8 weeks were required for full recovery. This indicates that the loss of ductility or embrittlement is reversible.

The hydrogen content of the immersed section of two specimens held at -1200 mV for 6 months were also determined 7 weeks after removing them from CP exposure. The hydrogen contents decreased from an average of 7.4 ppm immediately after removal to 4.1 ppm 7 weeks after removal. This is consistent with the above findings in which recovery of reduction of area after discontinuing CP took at least 8 weeks.

CP in Carbonated Mortar or Concrete

In carbonated mortar, the calculated potential for hydrogen evolution is more positive by approximately 59.2 mV for each decrease in one pH unit. However, under CP, the pH at the wire surface will increase rapidly in a few hours to days to a value greater than 12.4 due to the production of hydroxide ions or consumption of hydrogen ions in accordance with the following reactions:



Since hydroxide ions but no hydrogen are produced in the second reaction, low levels of current at the indicated potential can be used to increase the pH without the production of hydrogen. At a low current density of $1 \mu\text{A}/\text{ft}^2$ ($11 \mu\text{A}/\text{m}^2$), it would require only 70 hours to bring the pH in a $1 \mu\text{m}$ thick layer around a steel rod from 7 to 12.45 in accordance with Faraday's Law. A current density of $1 \mu\text{A}/\text{ft}^2$ is not expected initially to polarize the steel to values more negative than -730 mV $[(-59.2)(7)-316]$, the value where hydrogen production begins at a pH of 7. This value will decrease to -1055 mV as the pH increases to 12.45.

Under higher levels of CP, the predominant reaction is the first reaction above. Hydrogen is produced but the pH also increases. Based on a high current density of $100 \mu\text{A}/\text{ft}^2$ ($1080 \mu\text{A}/\text{m}^2$), it would require only 42 minutes to increase the pH from 7 to 12.45. As shown in the previous section, more than 9 months is required before failure due to hydrogen embrittlement can be expected, not 42 minutes. Once the pH reaches 12.45 and potentials more negative than -1055 mV are not exceeded, hydrogen in the wire will diffuse out. In actual practice, the current densities and polarization potentials determined in the previous section can be used to protect steel in carbonated mortar which will quickly increase the pH around the prestressing wire and prohibit the production of hydrogen.

PLANNING FOR CORROSION CONTROL

Proper planning in the design of a PCCP pipeline can prevent corrosion problems. Planning should include a survey to determine soil resistivity, pH, and chloride and sulfate contents along the right-of-way. Location of parallel and crossing pipelines, cathodic protection and other DC sources, and connections to other pipelines should also be determined. A qualified corrosion engineer should be retained to interpret the information and to recommend corrosion control provisions.

SUMMARY

- Resistance of impacted mortar coating to chloride ion penetration increases as mortar absorption decreases. Higher water contents of 7% to 9% in mortar during mixing produces the lowest possible absorption of impacted mortar coating. Thicker mortar coatings do not decrease the time required for chloride ions to reach the steel surface. They are more permeable than thinner coatings so allow chloride ions to penetrate faster. Impact-damaged areas caused by rocks or boulder during backfilling are more susceptible to corrosion than non-impacted areas. The addition of 5% styrene-butadiene latex to mortar reduces chloride ion penetration by 50%. Passivation of steel embedded in latex-modified mortar is not affected.
- Water-soluble chloride ion content of 2400 to 2800 mg/kg (9.6 to 11.2 lbs/yd³) at the prestressing wire surface does not initiate corrosion in impacted mortar coating. Chloride ion contents as high as 14,100 mg/kg (56.4 lbs/yd³) in cast mortar also does not initiate corrosion of prestressing wire. Prestressing wire is more resistant than reinforcing rods to depassivation by chloride ions. The use of zinc phosphate as a lubricant during the wire drawing process may be responsible for this effect.
- Due to the stringent physical requirement of the wire while going through the prestressing equipment, the practicality of performing the prestressing operation on coated wire is remote. Based on the drastic decrease in ductility in continuous torsion, the high temperature required to apply a FBE coating is detrimental to prestressing wire and should not be used.
- Due to the effect of the high alkalinity, high pH environment, PCCP is not as susceptible to steel corrosion due to stray current discharge as bare or organically-coated steel or ductile iron pipe. However, prolonged stray current on PCCP is not recommended and the pipe should be protected with a dielectric supplemental coating when stray current discharge is anticipated for a new pipeline or CP should be applied when discharge is found on an installed pipeline.
- Electrically continuous and discontinuous PCCP lines can be monitored for corrosion depending on the intensity of corrosion and the location of corrosion sites on the pipe circumference. The results from potential monitoring techniques can provide

useful, but not necessarily definitive, indications of corrosion activity on PCCP. Soil cover, position of corrosion site, and corrosion area have the most significant impact on the usefulness of potential monitoring techniques.

- In most environments, a supplemental barrier coating is not required. A barrier coating can be used to prevent chloride ions from penetrating the mortar coating in soils or ground waters with high chloride content.
- A minimum cathodic protection potential criterion is 100 mV polarization or depolarization shift. A current density of 12 $\mu\text{A}/\text{ft}^2$ (130 $\mu\text{A}/\text{m}^2$) achieved a shift of approximately 120 mV. It is recommended that the CP polarization potential for PCCP be maintained at potentials less negative than -1000 mV (CSE) to prevent hydrogen embrittlement which may ultimately lead to failure of the pipe. More negative potentials embrittle and split prestressing wire, greatly increase the cost of CP, and do not improve corrosion protection. An average current density of 100 $\mu\text{A}/\text{ft}^2$ achieved this level of polarization. Current density flow onto the prestressing wire is lower than that onto the underlying embedded cylinder. The ductility of prestressing wire under excessive CP recovers after CP is discontinued. Most of the recovery occurs during the first four weeks but at least eight weeks are required for full recovery. Cathodic protection will increase the pH around the steel in carbonated mortar to initial uncarbonated levels.
- Prestressed concrete cylinder pipe is inherently corrosion resistant. The use of impacted mortar coatings passivates the underlying prestressing wire and reduces chloride ion penetration. The underlying prestressing wire is more resistant than reinforcing rods to depassivation by chloride ions.

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