

Cathodic Protection of Prestressed Members: An Update

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Research is being conducted in use of cathodic protection of highly stressed steel tendons, both prestressed and posttensioned, embedded in concrete bridge structures. These tendons are subject to embrittlement by hydrogen generated by cathodic protection under certain conditions. Research indicates that hydrogen penetrates steel and causes ductility reduction at potentials equal to or more negative than those normally considered necessary for the thermodynamic stability of iron. Other criteria commonly proposed for protection of steel reinforcement produce potentials considerably less negative than the potential required to generate hydrogen at the steel-concrete interface. Because of the critical dependence of hydrogen evolution on potential, cathodic protection must be potential controlled and the detection circuit must be free of IR effects. The use of freely corroding iron as a reference is suggested. Ongoing research includes studies on cathodic protection to answer questions about surface anode behavior, current distribution within bridge members, and use of cathodic protection on posttensioned and segmented bridge construction.

The deterioration of concrete bridge components is a major problem facing highway agencies in the United States. An important factor related to the deterioration of concrete is corrosion of embedded steel reinforcement. This corrosion results in cracking of the concrete, spalling, and eventually an actual weakening of the structure. In addition to reinforced decking, other structural members may include standard embedded reinforcement, concrete members with pretensioned or posttensioned high-strength steel tendons in embedded ducts, and segmented bridge construction.

When high-strength, pretensioned and posttensioned components are involved, there is a special problem. High-strength steels are subject to a phenomenon known as hydrogen embrittlement, which occurs when atomic hydrogen is released by electrochemical action at the steel interface with the environment. Ordinarily, in an alkaline environment such as cement mortar, this does not take place; however, once corrosion begins, loss of the alkaline environment permits direct release of hydrogen from the steel acid reaction into the steel matrix. Therefore, embrittlement can occur as a result of corrosion.

Hydrogen can also be formed at the steel-concrete interface through application of cathodic protection. Under certain conditions, electrolysis of moisture into atomic hydrogen can occur. The hydrogen can then enter the metal matrix and cause embrittlement. Embrittled high-strength steels exhibit reduced ductility and strength. Therefore, failure without

warning caused by brittle fracture may occur in such members at strength levels well within design limits.

The FHWA Turner-Fairbank Research Center is sponsoring research into the use of cathodic protection for corrosion control of prestressed and posttensioned concrete structures. The objectives of this research are to define the effects of hydrogen on the high-strength steel used in bridge members and to define appropriate cathodic protection criteria. The research also includes studies to improve application and performance of surface applied anodes used in cathodic protection of concrete bridge members. Results that have been obtained to date in the hydrogen embrittlement studies are described.

BACKGROUND

Details of the corrosion mechanism of steel in concrete and common methods used to protect steel are provided elsewhere in the literature (1,2). Parkins et al. (3) performed stress corrosion tests on notched and precracked prestressing steel strands in calcium hydroxide solutions varying in pH and chloride ion concentration using the constant extension rate (slow strain rate) technique (CERT). Enhanced cracking occurred at potentials lower than -0.900 volt [saturated calomel electrode (SCE)], irrespective of solution pH, and there was a second regime of cracking at potentials higher than -0.600 volts. In the intermediate region (between -0.900 and -0.600 volt), cracking was either absent or less severe. At potentials below -0.900 volt, the amount of quasi-cleavage observed on fracture surfaces increased when the potential became more negative and failure was caused by hydrogen embrittlement. On the other hand, failure in the second regime appeared to be dissolution related, as cracking occurred at potentials higher than the pitting potential. One of the few stress corrosion experiments incorporating an actual concrete environment was performed by Treadaway (4). He conducted tests on cold-drawn prestressing steel wires stressed to 70 to 80 percent of the tensile strength in concrete with and without calcium chloride. The specimens were exposed both outdoors in an industrial environment for periods from 2 to 27 months and in hot sodium hydroxide (0.02 N) solutions containing different concentrations of sodium chloride at pH 10.2 to 11.6. No evidence of stress corrosion cracking of the steel either in concrete or in the hot alkaline chloride solution was observed. Tensile testing of the steel wires subsequent to exposure resulted in ductile fracture. When corrosion had occurred, the fracture was initiated at a pit or an area where the wire suffered severe corrosion. However, as pointed out by Slater

(5), no applied potentials were used in these experiments, and the exposure time of 27 months in the concrete environment might have been too short to be conclusive.

Recently, Scannell and Hartt (6) conducted a two-phase experiment to study the susceptibility of prestressing tendons to hydrogen embrittlement when cathodically overprotected. First, a three-point bending test capable of detecting hydrogen embrittlement was developed. In the second-phase experiment, a wrought, ferritic-pearlitic prestressing steel tendon was embedded in concrete and cathodically polarized to $-1,300$ mvolt (SCE) for 36 days. Specimens were then recovered from the concrete, notched, and tested by three-point bending. However, no evidence of hydrogen embrittlement was observed.

On the basis of the above discussion, a comprehensive research plan was developed to investigate the susceptibility of prestressing steel to hydrogen embrittlement under conditions applicable to cathodic protection in concrete. This involved a three-phase program consisting of a phase to characterize and measure hydrogen formation followed by a three part testing phase which included (a) CERT, (b) constant stress testing (CST), and (c) ripple effect testing (RET). The third phase consists of a program to evaluate the findings of the laboratory testing and cathodic protection criteria on full-scale prestressed members; this phase is now in progress.

EXPERIMENTAL

Hydrogen Formation Measurement

The hydrogen embrittlement studies were done in two phases. The first phase was designed to detect the potential at which hydrogen would be generated at the concrete-steel interface. The method used is described by McBreen (7). The method involves electrochemical detection of hydrogen that has passed through a steel membrane as the result of hydrogen production on the other side of the membrane. Figure 1 shows the equipment constructed for this study. It consisted of a carbon steel tube (WE) used as a membrane. The tube dimensions were 2.54 cm (1 in.) in diameter, 0.094 cm (0.037 in.) in wall

thickness, and 14 cm (5.5 in.) in length. The wall thickness of the tube was on the order of the reduced section radius of the test specimen used in the mechanical testing phase—0.064 cm (0.025 in.). The interior of the tube was used as the working surface at which hydrogen would be produced. The exterior of the tube provided the surface for detection of hydrogen passing through the tube wall.

A platinum counter (CE2) electrode was inserted through rubber stoppers in the ends of the tube to permit electrochemical tests, and the tube was filled with test solution (S2) and lined with mortar. The entire working tube was then inserted through rubber stoppers into an outer steel tube (CE1) 5 cm (2 in.) in diameter, which served as a counter electrode and electrolyte chamber for the hydrogen detection cell. Deaerated sodium hydroxide (1 N) (S1) was used as the detector electrolyte. The potential of the inner surface of the tube was monitored by a reference SCE (R2) through a Lugin probe. The potential was controlled with a potentiostat (P2). The potential of the outer detector surface of the tube was monitored with a second reference SCE (R1). A second potentiostat (P1) held the potential of the outer surface of the steel tube (WE) at $+100$ mvolt with respect to reference R1.

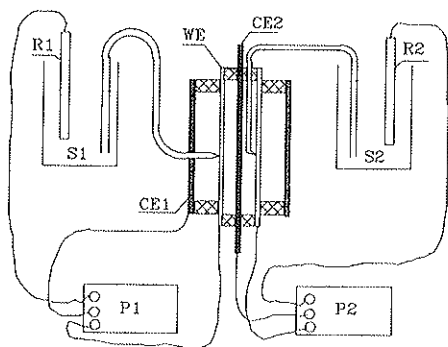
When hydrogen generated on the inside surface is absorbed by the steel and exits the outer surface, the outer surface potential changes, causing the detector potentiostat (P1) to change its output current in an effort to control the preset potential. Detector output current is a measure of the quantity and duration of hydrogen flow through the metal and was continuously measured during the test with a strip chart recorder.

The effects of different potentials such as might be encountered in the presence of corrosion products or carbonated concrete were evaluated. The detector was proven able to detect hydrogen generation at potential and pH values consistent with chemical thermodynamic theory. Tests to determine hydrogen evolution potential were run at pH values of 9.0 and 12.4, and with a tube lined with cement mortar. The effect of pulsed cathodic potentials, such as might be encountered during testing or erroneous operation, were tested using the hydrogen detector.

Mechanical Testing for Hydrogen Embrittlement

The second phase consisted of a series of mechanical tests designed to measure the relative effects of hydrogen on prestressing steel when subjected to various test environments. These tests consisted of CERT, CST, and RET.

All specimens were machined from the central straight strand of 1.5 cm (0.600 in.) 1.86×10^9 Pa (270 ksi) LOLAX prestressing wire conforming to ASTM A416-88B. The diameter of the central strand is 0.508 cm (0.200 in.). Notches were machined into the specimens using two configurations. In one configuration, a 90-degree notch with a 0.013-cm (0.005-in.) radius was used, and in the other a reduced section of 2.54-cm (1-in.) radius was used (smooth specimen configuration). The nominal diameter of the reduced section was 0.127 cm (0.050 in.). Some specimens were prepared so that the notches were encased in portland cement. The mortar used was either chloride free or contained 1×10^4 ppm of chloride and completely encased the notch.



S1	1N Sodium Hydroxide	S2	Test Solution
R1	Sat. Calomel Ref.	R2	Sat. Calomel Ref.
WE	Working Electrode	CE2	Counter Electrode 2
CE1	Counter Electrode 1	P1 & P2	Potentiostats

FIGURE 1 Hydrogen detection test.

TABLE 1 CERT MATRIX

F.C.	Cathodic Protection Potential Level (mV) (SCE)						Test Temperature (°C)				NUMBER OF TESTS	
	-600	-700	-800	-900	-1000	-1100	-1200	0	20	40		60
<u>Laboratory Air Environment:</u>												
X								X				2
X									X			5
X										X		1
X											X	2
<u>Ca (OH)₂ Environment:</u>												
			X					X				1
				X				X				1
					X			X				1
						X		X				2
X									X			4
		X							X			2
			X						X			2
				X					X			2
					X				X			3
						X			X			2
			X					X				3
				X						X		1
					X					X		1
						X				X		1
<u>Cl-Free Cemented Notch:</u>												
X									X			1
		X							X			1
			X						X			1
				X					X			1
					X				X			1
						X			X			1
							X		X			1
<u>10⁴ ppm Cl-Cemented Notch:</u>												
X									X			1
		X							X			1
			X						X			1
				X					X			1
					X				X			1
						X			X			1
<u>Na₂B₄O₇ · 10H₂O Environment:</u>												
									X			3
									X			2
									X			2
									X			2
									X			2
		X							X			3
			X						X			2
<u>CaSO₄ Environment:</u>												
			X						X			3
				X					X			2
					X				X			1

Slow Strain Rate Tests

The CERT method was used to determine the effects of temperature, pH, and cathodic protection level on the hydrogen embrittlement tendency of the prestressing wire. These tests were performed at temperatures of 0°, 20°, 40°, and 60°C in environments of laboratory air and air-saturated solutions of calcium hydroxide (pH 12.4), borax (pH 9.2), and calcium sulfate (pH 6.8). Cathodic protection potentials ranged from freely corroding to -1,200 mvolt (SCE). Additional tests, performed with a nitrogen purge of the solutions, were allowed to stabilize 4 days before testing. Table 1 presents the different conditions of the CERT test. Cathodic potentials were developed after the stabilization period using a custom-designed and custom-built potentiostat, a platinum-coated niobium counter electrode, and a reference SCE.

The SCE was placed in a separate vessel and joined to the test cell with a salt bridge and Lugin probe. Slow strain rate CERT tests were conducted at a preselected rate of 4.0×10^{-6} cm (1.5748 $\times 10^{-6}$ in.) per second on an electrically powered CERT test machine.

Hartt et al. at Florida Atlantic University (FAU) also performed CERT tests as part of this project. One of the purposes of the FAU testing was to explore the degree of surface roughness that determines whether a specimen behaves as a smooth specimen or a notched specimen. Another objective was to investigate mechanical property recovery after excessive hydrogen generating potentials have been applied and released as might occur during testing or improper cathodic protection application. The tests were conducted using a constant extension rate of 4.7×10^{-6} cm/sec (1.85 $\times 10^{-6}$ in./sec) in a nitrogen-purged saturated calcium hydroxide solution (pH 12.5). The effect of notch severity was studied by determining fracture stress as a function of notch geometry. The geometry considered was specimen diameter, notch diameter, notch angle (45 and 60 degrees) and notch root radius (0.001, 0.020, 0.25, 1, and 2 mm).

Specimens used to determine the effect of notch angle were charged at between -700 and -1,500 mvolt in 200-mvolt steps. Specimens used to evaluate the effect of root radius were charged at -900 and -1,300 mvolt (SCE). Notched specimens tested to determine the effect of precharging time

on embrittlement were charged at -900 mvolt (SCE) for 0 to 16 days. Smooth specimens used to evaluate the effect of rest time were precharged for 9 hr at $-1,300$ mvolt (SCE).

Constant Strain Testing

CST was conducted to determine the effects of short- and long-term exposures to hydrogen-generating cathodic potentials. Both notched and smooth specimens were used. All tests were conducted in a saturated solution of calcium hydroxide at 20°C and all but one test were conducted with a nitrogen purge. The test specimen was strained to a predetermined load before testing. The specimen was exposed to the test solution 4 days before application of the cathodic potential of $-1,200$ mvolt. Table 2 presents the test matrix.

Ripple Effect Testing

RET was performed to determine the relationship between the static-load environment cracking threshold and the corrosion fatigue threshold, and how this relationship is influenced by cathodic protection of the prestressing steel. All tests were performed in a 20°C calcium hydroxide solution.

Table 3 presents the test matrix for the RET. After test specimen stabilization, the specimen was loaded to the mean stress level and cycling commenced at a frequency of 1 Hz and stress amplitude of ± 5 percent. RET was carried out on a computer-controlled servohydraulic mechanical test ma-

chine. Testing continued until the specimen failed or until a total of 10^6 cycles accumulated.

DISCUSSION OF RESULTS

Hydrogen Formation Tests

There was a delay between the time the potential was applied above the hydrogen evolution potential and the time that the detector current began to change, indicating the presence of a depolarizing agent, i.e., hydrogen, on the surface. The delay time is the result of the time it takes the hydrogen to diffuse through the steel membrane. The detector current continued to increase after the hydrogen generating potential was removed and several hours were required before the current returned to initial values. The potential at which hydrogen flow from the cement-coated steel surface was first detected in the detector at pH 12.4 was -974 mvolt (SCE). No hydrogen generation was detected at -900 mv (SCE). Tests at the other pH levels indicated that hydrogen was generated on the steel tube surface and penetrated the tube wall at potential levels consistent with thermodynamic considerations.

There was no difference in the potential for hydrogen evolution between the pH 12.4 solution adjusted with calcium hydroxide and the pipe coated with cement mortar, except that the response time for the cement-coated steel was slower. This slowness might mean that the concentration of hydrogen entering the metal is lower in alkaline environments; however, it was not explored further.

TABLE 2 CST MATRIX FOR TESTS CONDUCTED IN 20°C $\text{Ca}(\text{OH})_2$ SOLUTION AT CATHODIC PROTECTION POTENTIAL OF $1,200$ mvolt (SCE)

CEMENTED NOTCH	CONSTANT STRAIN 70% UTS	STRAIN 70% NFS (1)	N ₂ PURGE	SOAK TIME (DAYS)	HOLD TIME AFTER PULSE (HOURS)	COMMENTS
	X	X	NO	4	24	
	X		YES	2	24	
		X	YES	4	0	SEE NOTE 2
		X	YES	4	0	SEE NOTE 3
		X	YES	4	24	SEE NOTE 4
		X	YES	4	0	SEE NOTE 5
X		X	YES	4	0	SEE NOTE 2
X		X	YES	4	0	SEE NOTE 3
X		X	YES	4	24	SEE NOTE 4
X		X	YES	4	0	SEE NOTE 5
(6)		X	YES	4	0	SEE NOTE 2
(6)		X	YES	4	0	SEE NOTE 3
(6)		X	YES	4	24	SEE NOTE 4
(6)		X	YES	4	0	SEE NOTE 5

NOTES:

- 1 - NOTCH FRACTURE STRESS BASED ON THE AVERAGE OF THE 20°C AIR TESTS RUN AT 1.5748×10^{-6} INCHES/SECOND)
- 2 - AFTER SOAK PERIOD ESTABLISH -1200mv AND HOLD 3 TO 5 DAYS. AFTER HOLD PERIOD COMMENCE STRAINING AT 1.5748×10^{-6} INCHES/SECOND.
- 3 - COMMENCE STRAINING AT 1.5748×10^{-6} INCHES/SECOND AFTER SOAK PERIOD.
- 4 - COMMENCE STRAINING AT 1.5748×10^{-6} INCHES/SECOND AFTER HOLD PERIOD.
- 5 - COMMENCE STRAINING AT 1.5748×10^{-6} INCHES/SECOND IMMEDIATELY AFTER 60 SECOND CATHODIC PROTECTION PULSE.
- 6 - TEST PERFORMED WITH SMOOTH SPECIMEN CONFIGURATION.

TABLE 3 RET MATRIX

CEMENTED NOTCH	CATHODIC PROTECTION LEVEL (mV) (SCE)	C.P. PULSES AT -1200 (mV) (SCE)	COMMENTS
	FREELY CORRODING		
	-600		
	-1200	YES	SEE NOTE 1
	-600		
X	FREELY CORRODING		
X	-600		
X	-1200		
X	-600	YES	SEE NOTE 1

ALL TESTS CONDUCTED IN N₂ PURGED 20°C Ca (OH)₂ SOLUTION

CYCLIC FREQUENCY - 1 Hz

MEAN STRESS - 70% OF NOTCH FRACTURE STRESS FOR TEST CONDUCTED AT 20°C
IN AIR

ALTERNATING STRESS - ±5% OF MEAN STRESS

CYCLE SPECIMEN TO FAILURE OR TOTAL CYCLE COUNT OF 10⁶

NOTES:

- 1 - SPECIMEN TO BE PULSED TO -1200 mV (SCE) CATHODIC PROTECTION
LEVEL FOR 60 SECONDS EVERY 24 HOURS.

Pulsed-current flow at potential levels sufficient to generate hydrogen resulted in detection of hydrogen passing through the steel. A 60-sec pulse at -1,200 mvolt resulted in measurable hydrogen on the detector side of the steel membrane after about 50 min. The detector current at the steel membrane surface reached a peak after several hours before it began to decline towards initial values. This behavior indicates that even short-duration exposure to cathodic potentials of sufficient magnitude can produce hydrogen in the metal.

Hydrogen Embrittlement Tests

CERT

Figures 2-4 show the results of the CERT testing. All normalized notch fracture stress calculations are based on specimen fracture load and the notch diameter at failure. Normalized notch fracture stress is the ratio of the notch fracture stress under the test conditions to the average notch fracture stress in air.

Figure 2 shows the CERT test results for the specimens in calcium hydroxide at 20°C. The figure plots normalized notch fracture stress against potential for plain specimens and specimens with cement encasement (with and without chloride in the cement). These tests indicate that as the potential becomes more negative than the hydrogen evolution potential, the normalized notch fracture stress decreases. There is approximately a 30 percent decrease in the normalized fracture stress over the range of potentials from about -950 to -1,200 mvolt (SCE). For the potential range of -300 through -950 mvolt (SCE), the normalized notch fracture stress remains relatively constant. This effect is consistent with previous research (8,9), which indicated that the effect is a result of hydrogen embrittlement.

Results indicate that the test results for 12.4 pH solution faithfully represent the behavior in cement-encapsulated spec-

imens. There is no apparent additional effect of chloride contamination alone on the environmental cracking behavior of LOLAX steel wire. Corrosion pitting was not observed in the notch area of the cement-encased specimens containing chloride.

The temperature range selected for testing represents typical temperatures to which a bridge structure might be exposed. Data from the current work indicate that temperature has little effect on the normalized notch fracture stress through the potential levels investigated. All tests over the range of temperatures tested, 0°C to 60°C, exhibit similar behavior above and below the hydrogen evolution potential (see Figure 3).

Figure 4 shows the results of testing in pH environments of 12.4, 9.2, and 6.8 in a nitrogen-purged environment. Each plot indicates that there is a corresponding reduction in the normalized notch fracture stress when the potential is more negative than the hydrogen evolution point for the given solution. Hydrogen embrittlement can occur at increasingly positive potentials as the environmental pH decreases below that found in sound cement.

The FAU tests found a strengthening effect in the specimen diameter range 1.27 to 2 mm when comparing specimen diameter to fracture stress at the notch diameter. This was attributed to possible notch strengthening. No discernable change in fracture stress was observed for diameters greater than 2 mm. The notch diameter was held constant for all tests, meaning that those with specimen diameters in the affected range had a rather shallow notch. The unaffected specimens had deeper notches (greater percentage of the cross section). No discernable trend was observed when comparing either notch base diameter or notch radius with fracture stress. Specimens charged at -900 mvolt (SCE) for varying time periods indicated first an increase in fracture strength for short pre-charging times (less than 5 days), then a decrease in strength for longer charging times.

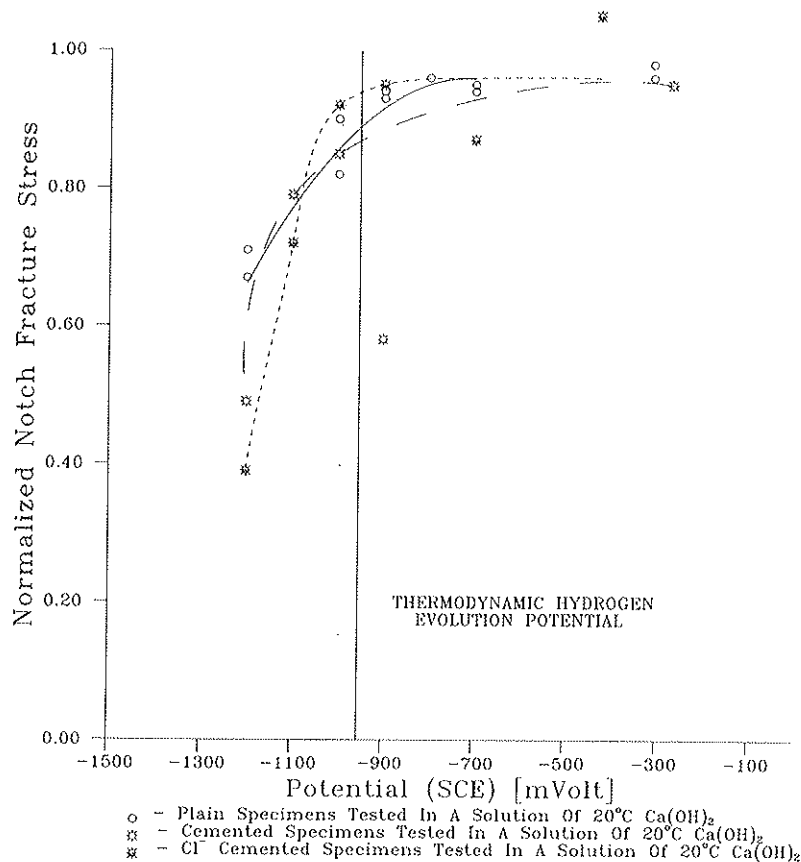


FIGURE 2 Effects of cemented notch on CERT results.

Specimens precharged for 9 hr at $-1,300$ mV, then allowed to rest for varying times before testing, displayed an increase in fracture load initially, followed by a return to lower fracture stress levels. The reduction in area for these specimens displayed a significant decrease for the first 50 hr, then a return to higher values.

CST

CST data indicate that short-term exposures of up to 60 sec to potentials more negative than the hydrogen evolution potential pose no danger to unnotched prestressing steel. Notched specimens did exhibit decreased normalized notch fracture stress when exposed for 2 hr to hydrogen charging. The notch in one of these specimens was encased in cement that might have prevented the hydrogen from escaping, resulting in a shorter time to failure than the nonencased specimen. The smooth specimen did not fail after a 5-day exposure to hydrogen charging and was strained to failure after the 5 days, with no reduction in normalized notch fracture stress. Some of the specimens exposed for 60 sec were held for 24 hr before straining, whereas other specimens were strained immediately. Notched specimens strained immediately exhibited a 20 percent reduction in normalized notch fracture stress, but the smooth specimens exhibited no noticeable reduction in normalized notch fracture stress. All specimens held for the

24-hr period following exposure did not exhibit a reduction in normalized notch fracture stress.

Cement-encased specimens did not exhibit a stress relaxation over the hold period. The unencased specimens did experience a stress relaxation over the hold period that lasted 2 to 5 days. One explanation might be that the bond between the specimen and the cement was sufficient for the cement to carry some of the load; however, the cement used was relatively weak and a strengthening effect of the cement appears unlikely. This effect was not investigated further.

RET

At the time of this paper, only the smooth specimen testing was completed. All of the tested specimens failed as a result of circumstances not related to the conditions. Failures occurred because power line failures caused overload conditions. The specimens were able to withstand the imposed stresses without failure even while being charged at potential levels well above the hydrogen evolution point. On a few occasions, the hydrogen being generated in the test cell displaced the liquid in the salt bridge. When the salt bridge circuit was severed, the reference SCE probe was removed from the control circuit, resulting in an uncontrolled application of cathodic protection at a level more negative than the targeted

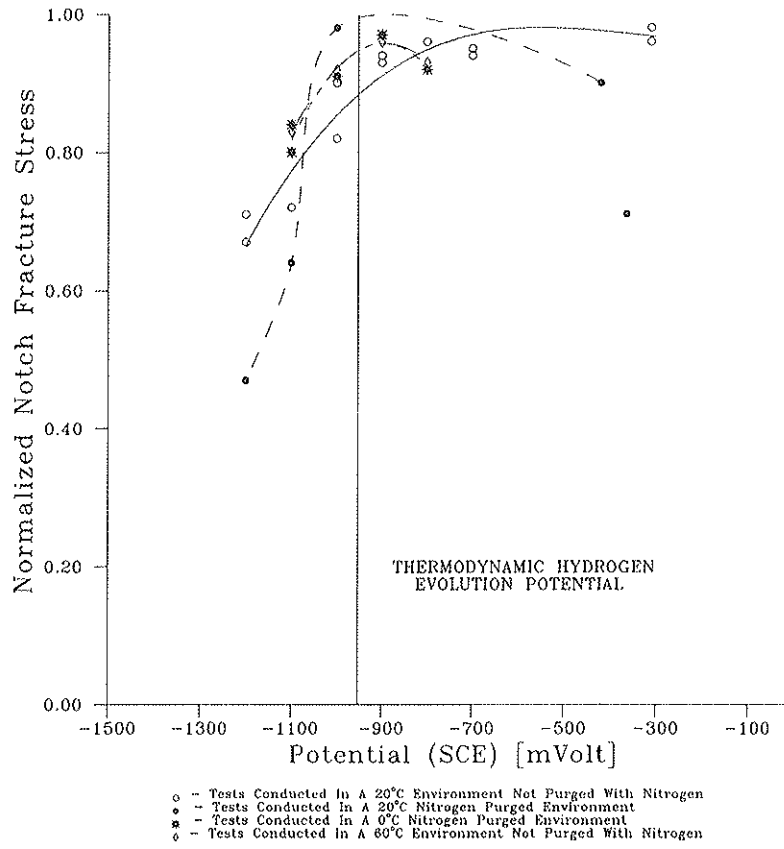


FIGURE 3 Temperature effects on CERT results.

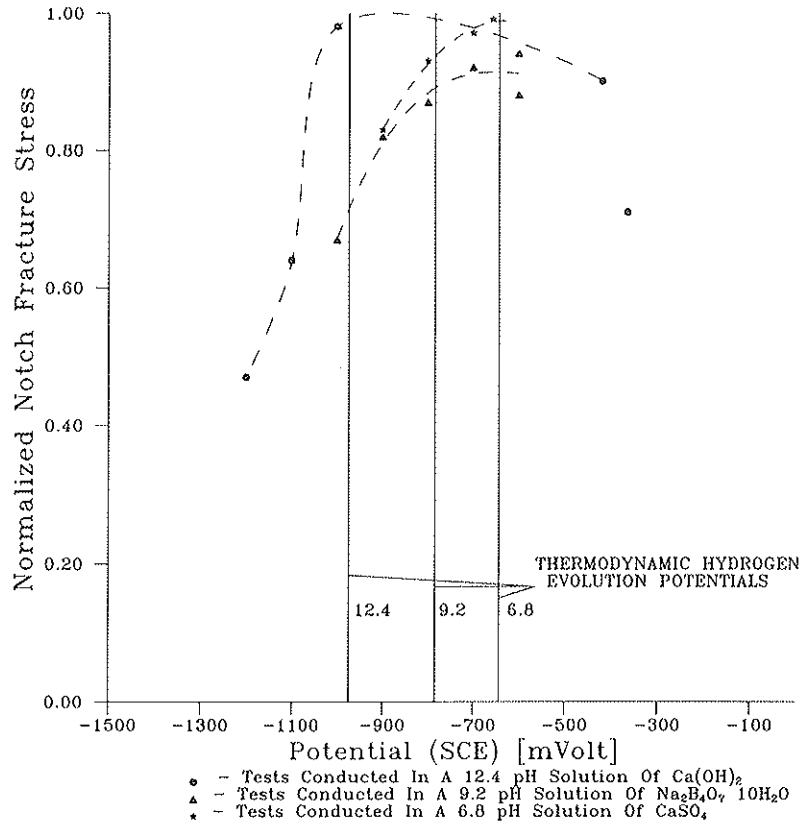


FIGURE 4 Effects of pH and N_2 purging on CERT results.

–1,200-mvolt value. No apparent decrease in cracking resistance was observed, even under these conditions.

The data indicate that there is no short-term reduction in the resistance of prestressing steel to environmental cracking as a result of small cyclic stresses and cathodic protection.

INTERIM CONCLUSIONS

1. Hydrogen is generated at the surface of highly stressed steel members embedded in concrete at potential levels consistent with thermodynamic considerations. That is, the potential at which hydrogen is generated can be predicted from the pH of the environment through the use of Pourbaix diagrams. The potential at which hydrogen flow from the cement-coated steel surface was first detected in the detector at pH 12.4 was –974 mvolt (SCE). No hydrogen generation was detected at –900 mvolt (SCE).

2. Lower pH values surrounding steel embedded in concrete are possible in areas where carbonation has occurred, at cracks in the concrete, and beneath corrosion products. This effect means that hydrogen can be generated at potentials less negative than –974 mvolt (SCE). At a pH of 9.0, the potential for hydrogen generation is –750 mvolt (SCE). Lower pH results in embrittlement at less negative potentials than required in sound cement.

3. There was no difference in the potential for hydrogen evolution between the pH 12.4 adjusted with calcium hydroxide and the cement mortar coating, except that the response time for the cement-coated steel was slower.

4. Pulsed-current flow at potential levels capable of generating hydrogen was sufficient to produce detectable hydrogen passing through the steel. This effect indicates that even short-duration exposure to cathodic potentials of sufficient magnitude can produce hydrogen in the metal.

5. Cathodic potentials more negative than the hydrogen evolution potential sustained for durations greater than 2 hr will result in a reduction in the dynamic load-carrying capabilities of notched steel tendons. There was approximately a 30 percent decrease in the normalized notch fracture stress over the range of cathodic potential levels from about –950 to –1,200 mvolt (SCE). The normalized notch fracture stress in the range –300 to –950 mvolt (SCE) remained relatively constant. These potentials are consistent with the laboratory hydrogen detection experiments.

6. Smooth specimens did not exhibit increased susceptibility to environmentally assisted cracking (hydrogen embrittlement) when subjected to cyclic or static stresses. These specimens retained their machined finish throughout the test period; there was no pitting.

7. The notch severity necessary to cause an increase in cracking susceptibility is not evident from the data collected so far. The data are too scattered.

8. Temperatures in the range 0°C to 60°C and the presence of chloride ions alone do not significantly affect the material's susceptibility to environmental cracking from hydrogen embrittlement.

9. Effects of short-term exposures (less than 60 sec) were as follows:

- Potential levels more negative than the hydrogen evolution potential should not result in a reduction in the static load-carrying capability of unnotched prestressing tendons.

- Potential levels more negative than the hydrogen evolution potential result in a reduction in the dynamic load-carrying capability of severely notched prestressing steel tendons.

- Severely notched prestressing tendons exposed to short-term potential levels more negative than the hydrogen evolution potential should be held in a static stress condition for at least 24 hr, to permit some hydrogen to dissipate and to allow a restoration of ductility.

WORK IN PROGRESS

The following work is being conducted:

1. Three different cathodic protection criteria are being evaluated on three full-sized prestressed beams. The 14- × 18-in. × 30-ft-long beams were specially fabricated and instrumented. The criteria are 100-mvolt depolarization, $E \text{ Log } I$, and potential control to the most anodic potential [–700 mvolt (SCE)]. Each beam has salt-contaminated concrete in known areas of the prestressing wire and each of the strands can be included or excluded from the cathodic protection system. The beams will be destructively evaluated for the effectiveness of the criteria after the test period. Cathodic protection is being supplied by potentially controlled rectifiers feeding current to conductive paint anodes on one surface.

2. The three criteria are below the hydrogen evolution potential at the normal pH of the concrete encasement. A fourth beam will be overprotected at –1,200 mvolt (SCE). The beam will be destructively examined at the end of the test period. All four beams are located in a marine environment, are sprayed with seawater daily, and are being flexed in a bending mode at 1 Hz to a peak load of 4 kips.

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