Summary Report

Determination of Permissible Chloride Levels in Prestressed Concrete

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SIGNIFICANCE OF FINDINGS

This study demonstrated that development of active corrosion of prestressing tendons depends not only on the presence of chloride ion in the concrete, but also on the environment into which the concrete member is placed. It was found that the threshold water soluble chloride limit above which corrosion of prestressed tendons occurred during and immediately after curing was between 0.11 and 0.17 percent by weight of cement. However, it was also found that under prolonged uniformly moist or dry conditions, active corrosion could not be sustained even in the presence of water soluble chloride contents as high as 0.9 to 1.0 percent by weight of cement.

This study further demonstrated that, with chloride ion present, changes in exposure conditions, such as alternate drying and wetting, and differential or localized drying, can rapidly initiate corrosion. These changes had greater impact on corrosion processes than cement composition, curing method, or

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NOTE: This is a Summary Report of an investigation on Research Project No. 2, "Determination of Permissible Chloride Levels in Prestressed Concrete," sponsored by the Prestressed Concrete Institute. The study was carried out in the Construction Technology Laboratories, a Division of the Portland Cement Association, Skokie, Illinois. The full report (84 pp.) is available from PCI Headquarters upon request at a cost of $30 per copy; $15 to PCI members.

stress level in the steel. Water-cement ratio of the concrete influences corrosion as it affects moisture, oxygen, and chloride diffusion rates.

The above findings can be extended to field structures to explain purported corrosion-free performance of prestressed concrete members made with high levels of chloride ion. In these cases, either drying has increased the electrical resistivity of the concrete sufficiently to prevent flow of galvanic current between potential anodic and cathodic sites on the steel, or, under uniform moist conditions, sufficient dissolved oxygen has not been present to sustain active corrosion. It should be noted that unforeseen changes in these environmental conditions can introduce a high risk of development of active corrosion and should be considered.

To eliminate the risk of active corrosion, it is recommended that the permissible water soluble chloride ion content in prestressed concrete not exceed 0.10 percent by weight of portland cement.

Synopsis

This report describes a laboratory investigation to determine chloride concentrations and exposure conditions required to induce corrosion of prestressed tendons in concrete beams.

Variables included source and concentration of chloride ion, wetting and drying, C_3A content of the cement, water-cement ratio of the concrete, stress level in the steel, and concrete curing method.

Performance was evaluated by electrical potential measurements, visual examination of tendons, and measurement of chloride contents.

Recommendations are made for permissible chloride levels in prestressed concrete as they are affected by exposure conditions.

INTRODUCTION

Under certain exposure conditions, an environment may develop that is conducive to galvanic corrosion of prestressing steel in pretensioned concrete members. This type of corrosion requires moisture, oxygen, and sufficient chloride ion at the surface of the steel to sustain electrochemical corrosion reactions. The required chloride ion level may be reached through the use of chloride-bearing admixtures such as calcium chloride, or by migration through concrete of chloride from external sources such as seawater and deicing salts.

The American Concrete Institute (ACI) states that water soluble chloride in prestressed concrete should not exceed 0.06 percent by weight of cement.[1] Putting this figure into more practical terms, a 2.0 percent calcium chloride ($CaCl_2 \cdot 2H_2O$) addition by weight of cement corresponds to about 1.0 percent total chloride ion by weight of cement.

The ACI limit is based primarily on estimates by George J. Verbeck* and appears to include a "safety factor" because of possible catastrophic results if corrosion occurs.

In view of the uncertain basis for chloride limitations, an investigation was undertaken to address two pertinent questions:

1. What is the permissible chloride level in concrete, above which corrosion of prestressing steel occurs?

2. Under what exposure conditions can calcium chloride admixture in concrete induce corrosion of prestressing steel? Or conversely, under what conditions does it not induce corrosion?

A two-phase program was undertaken to obtain answers to these questions.

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*Personal communication. Mr. Verbeck was formerly Director of Research, Portland Cement Association, Skokie, Illinois.

One phase included the circulation of a questionnaire to members of the Prestressed Concrete Institute, requesting information on the occurrence of corrosion and the use of calcium chloride as an admixture in prestressed concrete. The second phase consisted of a laboratory study to determine the chloride levels and environmental conditions required to develop galvanic corrosion of prestressed tendons in concrete. Results of this work are summarized below.

RESULTS OF QUESTIONNAIRE SURVEY

Very few cases of corrosion of prestressed steel in concrete containing calcium chloride as an admixture were reported. This appears to be related largely to lack of use of this admixture by concrete producers. Corrosion problems that were reported apparently resulted from exposure to chloride solutions in the in-service environment, particularly to chloride deicer solution. None of the producers reported plans to use calcium chloride as an admixture in future production.

LABORATORY PROGRAM

This section describes the details of the experimental program, including test specimens and variables, materials, concrete mix design, specimen fabrication, and corrosive monitoring methods.

Test Specimens

Nineteen pretensioned concrete beams were fabricated for this study. Each beam was 12 ft long, 1 ft wide, and 6 in. deep (3.66 x 0.305 m x 152 mm). Three evenly spaced prestressing tendons were positioned 1 in. (25.4 mm) from the top surface of each beam, while three additional tendons were located 1 in. (25.4 mm) from the bottom surface.

Styrofoam dikes were cemented along the top edge of each beam to help maintain the intended exposure condition. The vertical sides and ends of the beams were sealed with epoxy to minimize effects related to moisture diffusion at those surfaces.

Test Variables

Six variables considered to potentially affect galvanic corrosion processes in concrete were included in this study. Table 1 lists the combinations of variables tested.

Materials

Two Type I cements, conforming to ASTM C150-80 Standard Specifications for Portland Cement, were used to make the test beams. Siliceous coarse and fine aggregate from Eau Claire, Wisconsin was used in all test beams. Total chloride content of the aggregate was only 0.003 to 0.005 percent by weight of the aggregate. Maximum particle size of the aggregate was limited to ⅜ in. (9.5 mm).

All prestressing steel was stress relieved Grade 270K obtained from the same lot. It consisted of ½ in. (12.7 mm) diameter, uncoated seven-wire strand tendon conforming to ASTM A416-80, Standard Specification for Uncoated Seven-Wire Stress-Relieved Steel Strand for Prestressed Concrete.

Tap water containing 10 ppm chloride ion was used as mix water. Commercially available flake calcium chloride ($CaCl_2 \cdot 2H_2O$) was used as a set-accelerating admixture.

Concrete Mix Design

Two concrete mix designs were utilized in this program. Pertinent mix design, curing, and compressive strength data are given in Table 2.

Specimen Fabrication

All test beams were cast and cured at

Table 1. Variable combinations in test program.

Beam	Cement, percent C_3A	Water-cement ratio	Percent $CaCl_2 \cdot 2H_2O$*	Cure	Stress level, ksi	Exposure conditions	
						Initial 10 to 12 months	Final 11 months
1	11	0.35	1.0	Steam	0	Continuous damp	½ beam dry, ½ beam damp
2	11	0.35	2.0	Steam	0	Continuous damp	½ beam dry, ½ beam damp
3	11	0.35	1.0	Steam	80	Continuous damp	Remain as is
4	11	0.35	2.0	Steam	80	Continuous damp	Remain as is
5	11	0.35	1.0	Steam	160	Continuous damp	10 days dry + 4 days damp
6	11	0.35	2.0	Steam	160	Continuous damp	10 days dry + 4 days damp
7	11	0.35	2.0	14 days moist	160	Continuous damp	Remain as is
8	8	0.35	2.0	Steam	160	Continuous damp	10 days dry + 4 days damp
9	11	0.50	2.0	Steam	160	Continuous damp	10 days dry + 4 days damp
10	11	0.50	2.0	14 days moist	160	Continuous damp	Continuous dry†
11	11	0.35	None	Steam	0	Pond — 4 percent NaCl soln.	10 days dry + 4 days 8 percent NaCl
12	11	0.35	None	Steam	80	Pond — 4 percent NaCl soln.	10 days dry + 4 days 8 percent NaCl
13	11	0.35	None	Steam	160	Pond — 4 percent NaCl soln.	10 days dry + 4 days 8 percent NaCl
14	8	0.35	None	Steam	160	Pond — 4 percent NaCl soln.	10 days dry + 4 days 8 percent NaCl
15	11	0.35	2.0	Steam	160	Pond — 4 percent NaCl soln.	Continuous dry†
16	11	0.35	Aggr. sat. 4 percent NaCl	Steam	160	Continuous damp	Remain as is
17	11	0.35	2.0	Steam	160	Continuous dry — 50 percent RH	10 days dry + 4 days 8 percent NaCl
18	8	0.50	0.17	Steam	160	Continuous damp	10 days dry + 4 days 8 percent NaCl
19	11	0.35	None	14 days moist	160	Pond — 4 percent NaCl soln.	10 days dry + 4 days 8 percent NaCl

*Expressed as percent by weight of cement. Metric (SI) convention factor: 1 ksi = 6.895 MPa.

†Two 1½-in. (38 mm) diameter holes were drilled to two tendons and filled with water or 4 percent NaC1 solution for short-term study of localized shifts in potential. Details are given in full report.

Table 2. Summary of concrete mix design and strength data.

Beam No.	Cement factor, lb per cu yd	Water-cement ratio	Calcium chloride, percent	Method of cure	Percent air	Compressive strength, psi*	
						1 day	14 days
1	705	0.35	1.0	Steam	5.2	5510	—
2	705	0.35	2.0	Steam	5.5	5240	—
3	705	0.35	1.0	Steam	5.4	3910	—
4	705	0.35	2.0	Steam	6.2	4290	—
5	705	0.35	1.0	Steam	5.0	4790	—
6	705	0.35	2.0	Steam	5.7	4010	—
7	705	0.35	2.0	Moist	5.5	—	5440
8	705	0.35	2.0	Steam	5.5	5910	—
9	493	0.50	2.0	Steam	6.3	3510	—
10	493	0.50	2.0	Moist	6.0	—	4980
11	705	0.35	0	Steam	6.2	4270	—
12	705	0.35	0	Steam	5.6	4300	—
13	705	0.35	0	Steam	5.8	4730	—
14	705	0.35	0	Steam	5.6	5550	—
15	705	0.35	2.0	Steam	6.5	4190	—
16	705	0.35	Sat. Agg.†	Steam	5.0	4290	—
17	705	0.35	2.0	Steam	6.0	4070	—
18	493	0.50	0.17	Steam	5.0	3460	—
19	705	0.35	0	Moist	5.2	—	5830

*Corrected to 6 x 12 in. cylinder strengths. All data are the average of two companion cylinders.
†Aggregate saturated with 4 percent NaCl solution.

Aggregate proportions per cu yd

0.35 W/C mixes — C. Aggregate 1608 lbs
F. Aggregate 1426 lbs

0.50 W/C mixes — C. Aggregate 1660 lbs
F. Aggregate 1460 lbs

Metric (SI) conversion factors: 1 lb per cu yd = 0.5933 kg/m^3; 1 psi = 0.006895 MPa; 1 lb = 4.448 N; 1 in. = 25.4 mm.

Construction Technology Laboratories (CTL). Tendons were degreased with xylene to insure that steel surfaces were clean prior to casting.

The fresh concrete was consolidated in the forms by internal vibration. The top surface of each beam was screeded and finished with a magnesium float. Concrete cylinders [3 x 6 in. (76 x 152 mm)] were cast for later strength determinations and chloride measurements. All mixing and casting was done at 73 ± 3 F (23 ± 1.7 C) and 50 ± 5 percent relative humidity.

Beams scheduled for steam curing were kept under damp burlap and polyethylene sheeting for 4 hours, after which steam curing was initiated. Temperature rise was 15 to 20 deg F (8.3 to 11.1 deg C) per hour during the initial 4-hour period of steam cure. Maximum temperatures were then maintained at 155 to 165 F (68.3 to 73.9 F) for an additional 12 hours. Following this period, the specimens were allowed to cool, in the forms, to room temperature.

For continuously moist curing, the beams were covered with wet burlap and polyethylene for 14 days. Each day during this period, top surfaces of the beams were wetted to minimize desiccation due to cement hydration.

After curing, and following load release and removal of forms, all beams were transferred to a test room maintained at 73 ± 3 F (22.8 ± 1.7 C) and 50 ± 5 percent relative humidity. Steam cured beams were stored under this condition for 27 days, while 14-day moist cured beams were stored under the same condition for 14 days prior to start of the test period.

Monitoring Methods

The following three methods were used to monitor corrosion-related developments:

1. Visual inspections were made for development of corrosion products on tendons extracted from the beams.

2. Electrical potential measurements[2,3] were made following ASTM Designation C876-80 Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete. A copper/copper sulfate (CSE) half cell was used as the reference electrode.

The writer's experience has indicated that potentials more negative than −0.30V reflect high probabilities of corrosion. This criterion was used in this study. Equally significant are differences in potential between different locations on a given prestressed tendon. Differences of about 0.10V, or more, are generally required to sustain corrosion cells for this condition. Potential measurements indicate only the presence of active corrosion and not rate of corrosion or the presence of corrosion products from previously active corrosion cells.

3. Chloride analyses were made to characterize the environment to which the prestressed tendons were subjected. Initial and subsequent total and water soluble chloride ion contents were determined. Initial chloride contents of the concrete were measured on 3 x 6-in. (76 x 152 mm) concrete cylinders that were cast and cured with the beams.

Dry powder samples were obtained from the beams at depths of ¾ to 1¼ in. (19 to 32 mm) from the top surface to determine chloride concentration at about the level of the upper tendons. Chemical analyses were made according to procedures described by Berman.[4] Nonevaporable water contents were measured on each powder sample to correct for nonuniformities in paste-aggregate ratios among the samples.

TEST RESULTS

Results from the three test methods are summarized in this section. Electrical potentials are referenced to the copper/copper sulfate half cell (CSE). All chloride contents, including dosage of calcium chloride admixture, are expressed as percent by weight of cement if not specified otherwise.

Visual Examination of Tendons

Prestressing tendons were removed from eighteen of the nineteen test beams and examined for the presence of steel corrosion products. Observations, summarized in Table 3, show that active corrosion had developed in all nine beams made with 2 percent calcium chloride admixture.

The nature and severity of corrosion ranged from localized pitting in Beams 4 and 15 to numerous areas with films of corrosion product scattered along the entire length of the tendons in Beam 17. Corrosion also occurred in the three beams made with 1 percent calcium chloride admixture. In these beams (Beams 1, 3, and 5) corrosion products occurred as localized films with no evidence of pitting.

Tendons from four of the five beams made without added chloride revealed no evidence of corrosion, even after ponding with NaCl solution throughout

Table 3. Summary of observations of prestressing tendons.

Beam No.	$CaCl_2 \cdot 2H_2O$*	Exposure conditions	Observations of upper tendons
1	1 percent	Continuous damp → Half dry and half damp	Several localized areas with film of corrosion products.
2	2 percent	Continuous damp → Half dry and half damp	Few localized deposits of corrosion product scattered along full length of tendons. Extensive, but discontinuous film of corrosion product along tendon in damp half of beam. Minor pitting in this section.
3	1 percent	Continuous damp	Light film of corrosion product in several 2 to 4 in. long areas 2 ft from one end on each tendon.
4	2 percent	Continuous damp	Localized areas with film of corrosion product. Pitting scattered along entire length on two or three strands of each tendon.
5	1 percent	Continuous damp → 10 days dry plus 4 days damp	Film of corrosion product along 1½ ft length on four strands near one end of one tendon. Film on several strands at middle of beam on each tendon.
6	2 percent	Continuous damp → 10 days dry plus 4 days damp	Localized areas with film of corrosion product in 1 to 3 ft length near one end of each tendon. Several areas, 2 to 4 in. long, with corrosion products.
7	2 percent	Continuous damp	Small areas 2 in. long with film of corrosion product scattered along entire length. Film of corrosion product 2 ft long near one end of each tendon.
8	2 percent	Continuous damp → 10 days dry plus 4 days damp	Few spots, about ½ in. long, with film of corrosion product scattered full length on each tendon.
9	2 percent	Continuous damp → 10 days dry plus 4 days damp	Few spots, 2 to 4 in. long and 2 ft from one end of each tendon, with film of corrosion product.
10	2 percent	Continuous damp → Continuous dry†	Few spots, 2 to 4 in. long and 2 ft from one end on each tendon, with film of corrosion product.

See footnotes on opposite page.

the test period. One tendon in Beam 11 displayed corrosion products. In this case, a crack had formed over the tendon prior to indications of active corrosion.

Tendons from Beam 16 which contained coarse aggregate presoaked in 4 percent NaCl solution, displayed localized corrosion after 79 weeks under the continuous damp exposure condition. In Beam 18, which was made with 0.17

Table 3 (cont.). Summary of observations of prestressing tendons.

Beam No.	$CaCl_2 \cdot 2H_2O$*	Exposure conditions	Observations of upper tendons
11	0	Pond 4 percent NaCl soln.→ 10 days dry plus 4 days pond 8 percent NaCl soln.	No corrosion observed on Tendons A and C. Pitting in 2 in. length in 2 strands 1 to 2 ft from one end on Tendon B.
12	0	Pond 4 percent NaCl soln.→ 10 days dry plus 4 days pond 8 percent NaCl soln.	No corrosion observed on tendons.
13	0	Pond 4 percent NaCl soln.→ 10 days dry plus 4 days pond 8 percent NaCl soln.	No corrosion observed on tendons.
14	0	Pond 4 percent NaCl soln.→ 10 days dry plus 4 days pond 8 percent NaCl soln.	No corrosion observed on tendons.
15	2 percent	Pond 4 percent NaCl soln.→ Continuous dry†	Localized areas up to 6 in. long with film of corrosion product 2 ft from one end. Occasional pitting scattered full length of tendons.
16	0 Aggr. sat. 4 percent NaCl	Continuous damp	Few localized spots on each tendon with corrosion products.
17	2 percent	Continuous dry 50 percent RH → 10 days dry plus 4 days pond 8 percent NaCl soln.	Localized areas with layer of corrosion product on all tendons.
18	0.17	Continuous damp → 10 days dry plus 4 days pond 8 percent NaCl soln.	Localized areas, 2 to 4 in. long and 1 to 3 ft from one end, with film of corrosion product on tendons.
19	0	Pond 4 percent NaCl soln.→ 10 days dry plus 4 days pond 8 percent NaCl soln.	Beam held in reserve for possible further testing. Tendons not retrieved for visual inspection.

Metric (SI) conversion factors: 1 ft = 0.305 m; 1 in. = 25.4 mm.

*Expressed as percent by weight of cement.

†Two 1½-in. (38 mm) diameter holes were drilled to two tendons and filled with water or 4 percent NaCl solution for short-term study of localized shifts in potential. Details are given in full report.

percent calcium chloride admixture (which corresponds to the ACI limit of 0.06 percent water soluble chloride ion for prestressed concrete), two of the three tendons displayed localized films of corrosion product in a 2-ft (0.61 m) length near one end of the beam. This condition appeared to develop after ponding with 8 percent NaCl solution.

With the exception of Beam 11, none of the beams displayed cracking. Beam 19 was held for possible further testing.

Electrical Potentials

The most significant results of electri-

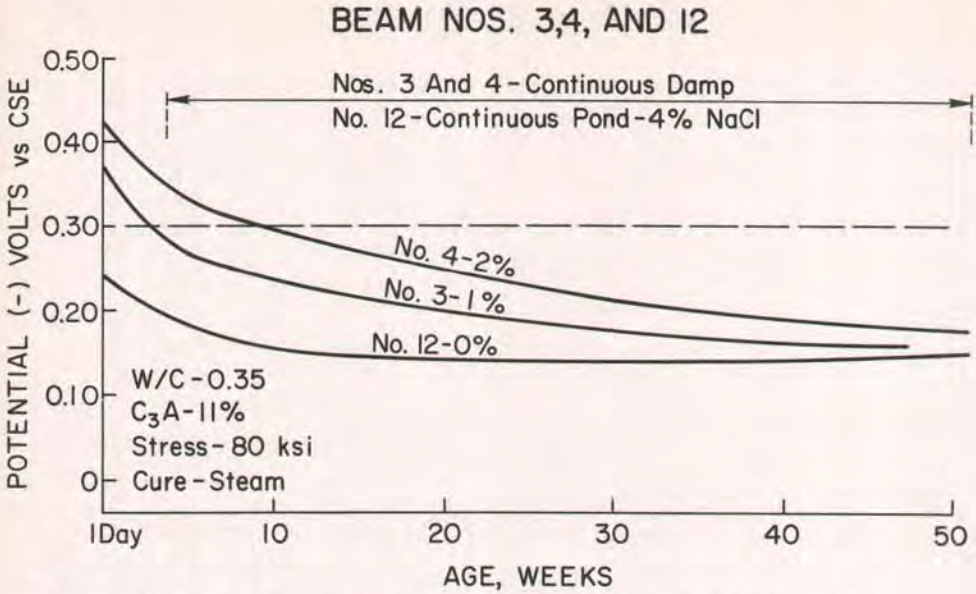

Fig. 1. Potential curves for beams made with 0, 1, or 2 percent calcium chloride admixture.

cal potential measurements are summarized in Figs. 1 to 4. In Fig. 1, comparisons are made for beams made with 0, 1, or 2 percent calcium chloride admixture, by weight of cement. Results indicate that, where 1 or 2 percent calcium chloride was used, active corrosion developed within 1 day of fabrication of the beam. However, it terminated within 3 to 10 weeks. This is indicated by shifts in potential to values less negative than −0.30V.

Potentials for the beam made without calcium chloride remained less negative than −0.30V, thus indicating that active corrosion had not developed during the test period. Results for this beam also indicate that sufficient chloride ion from the solution ponded on the top surface of the beam did not reach the tendons to later initiate active corrosion.

Fig. 2 shows results for Beam 16, which contained 0.20 percent total (0.17 percent water soluble) chloride by weight of cement. Virtually all of the chloride was introduced through presoaking the coarse aggregate in 4 percent NaCl solution to simulate seawater immersion. The potential curve shows the development of an initial period of active corrosion that terminated at about 15 weeks. This illustrates that water soluble chloride as low as 0.17 percent, even though introduced with the aggregate, can initiate active corrosion.

Fig. 2 also shows the potential curve for Beam 18, which was made with 0.13 percent total (0.11 percent water soluble) chloride, by weight of cement. In this case, active corrosion was not initiated until the period of ponding with NaCl solution. Thus, 0.13 percent chloride by weight of cement was not sufficient to initiate corrosion.

The effect of prolonged drying, at 73 ± 3 F (23 ± 1.7 C) and 50 ± 5 percent relative humidity, on corrosion resistance is indicated in Fig. 3 by the potential curve for Beam 17, which was made using 2 percent calcium chloride admixture. Initial potential was −0.48V which indicates the development of ac-

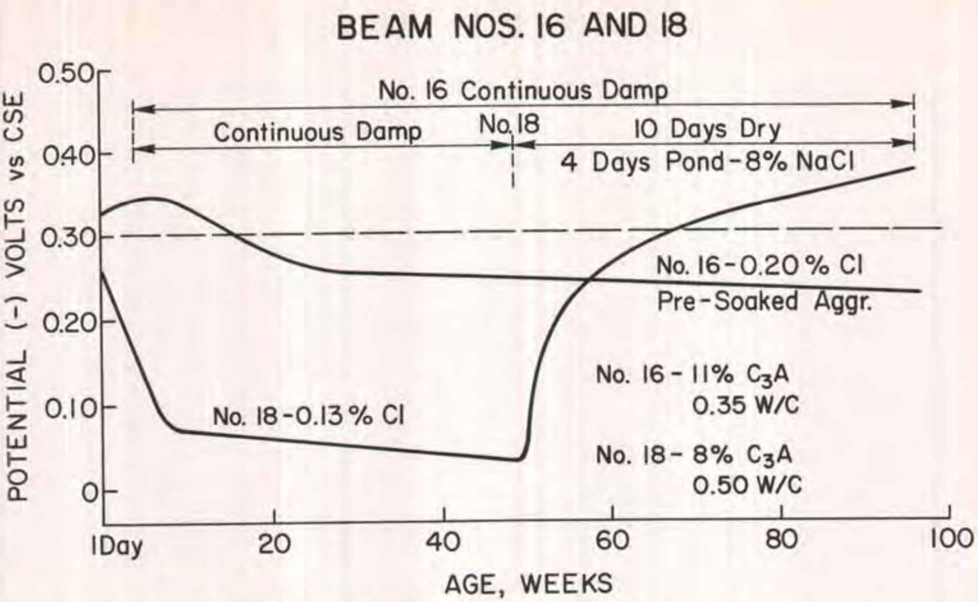

Fig. 2. Potential curves for beams with 0.13 and 0.20 percent total chloride ion.

tive corrosion. During the ensuing 50-week continuous dry period, potentials progressively shifted to less negative values, and reached −0.18V as drying was terminated.

This long-term shift indicates that active corrosion had stopped within about 20 weeks. The tendons then remained in the passive state for the remaining 30-week duration of the drying period.

Following the period of continuous drying, the beam was subjected to cycles of 10 days drying and 4 days ponding with 8 percent NaCl solution. The curve in Fig. 3 indicates that, within 1 or 2 weeks of this change, potentials shifted to approximately −0.35V. This indicates recurrence of active corrosion. Potentials then remained at about −0.33V for the duration of the 42-week cycling period. This indicates that active corrosion continued throughout this period.

Visual examination revealed the presence of a layer of corrosion product along the entire length of the upper tendons. This observation does not indicate whether corrosion occurred during the first 20 weeks of drying, during the cycling period, or during both periods. However, potentials indicate that active corrosion occurred during two different periods of time.

Fig. 4 reveals the effects of differential drying on corrosion resistance in Beams 1 and 2. Beam 2 was made using a 2 percent calcium chloride admixture. After the initial 50-week period of continuous damp exposure, one-half [6 ft (1.83 m)] of the top surface of the beam was exposed continuously to 50±5 percent relative humidity, while the other half remained in the continuous damp exposure.

Beam 1, which was similar to Beam 2 except that it was made using 1 percent calcium chloride admixture, was subjected to the same change in exposure conditions. No additional chloride was introduced into either beam.

Two potential curves are shown for each beam after the change in exposure

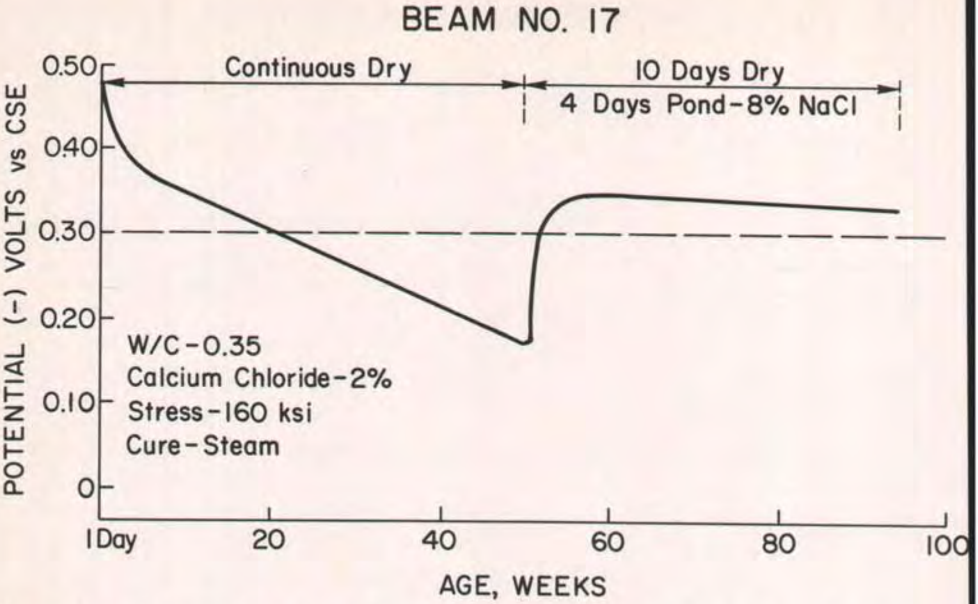

Fig. 3. Potential curve for beam subjected to 50 weeks of drying followed by alternate ponding and drying.

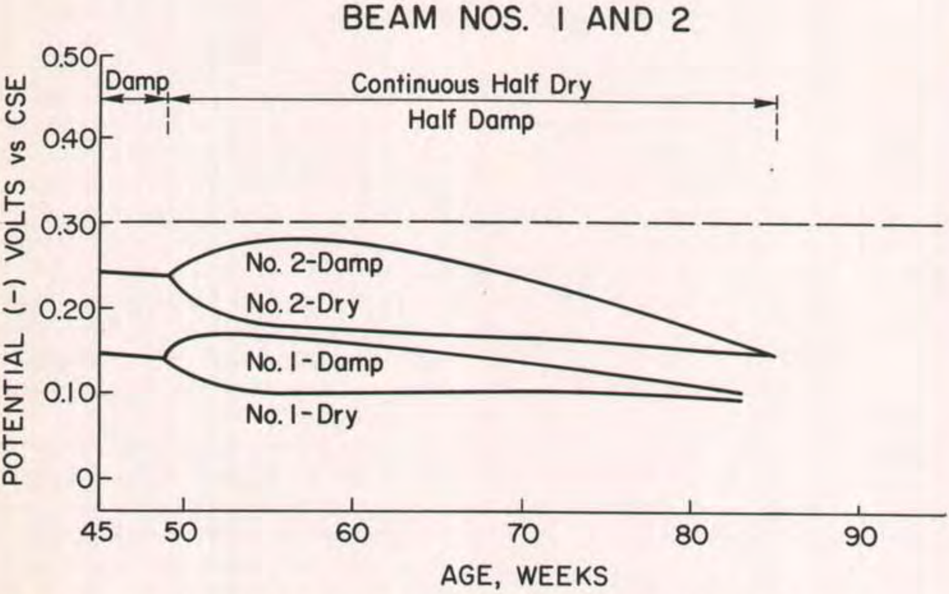

Fig. 4. Potential curves for two beams subjected to continuous half dry-half damp exposure conditions.

condition; one for the dry half of each beam, and one for the damp half. Unlike the similarity of potentials measured along tendons under uniform exposure conditions, differences in potential between the two halves of each beam developed soon after the change in exposure condition. In Beam 2, maximum potential differences reached 0.10V (−0.28V vs −0.18V) in 5 to 10 weeks. A similar pattern developed for Beam 1, except that maximum potential differences reached only 0.06V.

Visual examination of tendons from these two beams revealed, in addition to the few localized deposits of corrosion product present along the full length of tendons from the two beams, a heavier, continuous film of corrosion product along only the 6-ft (1.83 m) length of tendons embedded in concrete exposed continuously to the damp condition in Beam 2. This was not seen along the tendons from Beam 1.

Thus, when 2 percent calcium chloride admixture was used, prolonged periods of damp exposure followed by differential drying of the concrete induced corrosion of prestressed tendons.

Potential curves (not shown) for other beams reveal that C_3A content of the cement, stress level in the steel, water-cement ratio of the concrete, and curing method, had little effect on initial corrosion resistance where 1 or 2 percent calcium chloride admixture had been used. In all cases, only initial periods of active corrosion, similar to those shown in Figs. 1 and 2, developed, which were terminated in less than 30 weeks.

Chloride Contents

Table 4 summarizes the results of initial and final chloride content measurements. Values are expressed as percent by weight of cement, and have been corrected for differences in paste-aggregate ratios by averaging nonevaporable water contents. Measured concrete unit weights of 3950 and 3915 lbs per cu yd (2342 and 2322 kg/m^3) were used to convert percent chloride by weight of concrete to percent by weight of cement for the 0.35 and 0.50 water-cement ratios, respectively.

From these data, an estimate can be made of minimum chloride concentrations required to induce corrosion of prestressed tendons during and immediately following curing. The lowest water soluble chloride level measured at which corrosion was initiated during this period was 0.17 percent by weight of cement. In this case, chloride ion was introduced into the fresh concrete through prior absorption by the coarse aggregate.

In contrast, corrosion did not develop initially when measured water soluble chloride levels were 0.11 percent by weight of cement. Thus, the water soluble chloride level required to induce corrosion of prestressed tendons during and immediately following curing was in the range of 0.11 to 0.17 percent by weight of cement. Respective total chloride concentrations were 0.13 percent and 0.20 by weight of cement.

The data also indicate that chloride levels required to induce corrosion at later ages were strongly dependent upon type of exposure condition. For example, under uniform drying conditions of 50 percent relative humidity at 70 to 75 F (21 to 24C), corrosion failed to develop in concrete containing 0.87 percent water soluble chloride ion by weight of cement. Most of this chloride was introduced into the concrete through use of 2 percent calcium chloride admixture. Continuous exposure of companion concrete beams to uniformly damp conditions following curing and 1 month of drying also failed to sustain active corrosion.

In contrast, exposure to nonuniform drying conditions permitted development of corrosion. In this instance, 2 percent calcium chloride admixture, by weight of cement, had been utilized. Corrosion did not develop under similar

Table 4. Results of chloride content determinations.

Beam No.	Source of initial chloride*	Initial and final exposure conditions		Initial chloride content		Final chloride content	
				Total	Water soluble	Total	Water soluble
1†	1 percent $CaCl_2$	Cont. damp →	½ beam dry, ½ beam damp	0.51	0.45	0.53 0.54	0.41 0.50
2*	2 percent $CaCl_2$	Cont. damp →	½ beam dry, ½ beam damp	0.99	0.93	0.93 0.87	0.58 0.70
3	1 percent $CaCl_2$	Cont. damp →	Remain as is	0.51	0.44	0.44	0.22
4	2 percent $CaCl_2$	Cont. damp →	Remain as is	0.99	0.92	0.86	0.65
5	1 percent $CaCl_2$	Cont. damp →	10 days dry plus 4 days damp	0.51	0.42	0.57	0.46
6	2 percent $CaCl_2$	Cont. damp →	10 days dry plus 4 days damp	0.99	0.88	0.85	0.67
7	2 percent $CaCl_2$	Cont. damp →	Remain as is	0.99	0.87	0.81	0.75
8	2 percent $CaCl_2$	Cont. damp →	10 days dry plus 4 days damp	0.99	0.83	0.81	0.54
9	2 percent $CaCl_2$	Cont. damp →	10 days dry plus 4 days damp	1.00	0.86	0.67	0.41
10	2 percent $CaCl_2$	Cont. damp →	Continuous dry‡	1.00	0.88	0.66	0.54
11	None	Pond 4 percent NaCl →	10 days dry plus 4 days 8 percent NaCl	0.05	0.04	0.31	0.13
12	None	Pond 4 percent NaCl →	10 days dry plus 4 days 8 percent NaCl	0.05	0.04	0.17	0.09
13	None	Pond 4 percent NaCl →	10 days dry plus 4 days 8 percent NaCl	0.05	0.01	0.26	0.25
14	None	Pond 4 percent NaCl →	10 days dry plus 4 days 8 percent NaCl	0.05	0.05	0.43	0.36
15	2 percent $CaCl_2$	Pond 4 percent NaCl →	Continuous dry‡	0.99	0.91	1.26	1.07
16	Aggr. sat.	Cont. damp →	Remain as is	0.20	0.17	0.17	0.13
17	2 percent $CaCl_2$	Cont. dry 50 percent RH →	10 days dry plus 4 days 8 percent NaCl	0.99	0.87	1.27	1.19
18	0.17 percent $CaCl_2$	Cont. damp →	10 days dry plus 4 days 8 percent NaCl	0.13	0.11	0.29	0.29
19	None	Pond 4 percent NaCl →	10 days dry plus 4 days 8 percent NaCl	0.05	0.05	0.17	0.12

*$CaCl_2$ refers to $CaCl_2 \cdot 2H_2O$ by weight of cement. Total and water soluble chloride contents are expressed as percent by weight of cement.

†The first figure for final chloride content is for the dry end of the beam.

‡Two 1½-in. (38 mm) diameter holes were drilled to two tendons and filled with water or 4 percent NaCl solution for short term study of localized shifts in potential. Details are given in full report.

exposures where 1 percent calcium chloride admixture had been used.

In beams made without calcium chloride admixture, ponding with 4 or 8 percent NaCl solution failed to induce corrosion, even though up to 0.36 percent water soluble chloride ion was measured at the level of the upper tendons. Absence of active corrosion in these beams appeared to have been due to lack of dissolved oxygen, high electrical resistivity of concrete, and uniformity of environment along individual tendons.

Thus, the data indicate that a single permissible chloride level in concrete, above which corrosion is initiated, does not apply for all environments. Relative lengths of wetting and drying periods, diffusion rates of chloride ion and dissolved oxygen, and moisture condition of the concrete all are significant factors determining the corrosion resistance of prestressing tendons in concrete.

CONCLUSIONS

Based on results developed in this study, the following conclusions are drawn:

1. A survey of prestressed concrete producers indicates that most occurrences of corrosion of prestressing tendons have developed under conditions where concrete had been exposed to external sources of chloride ion.

2. Based on laboratory tests conducted in this program, the threshold water soluble chloride limit above which corrosion of prestressing tendons occurred during and immediately after curing was between 0.11 and 0.17 percent by weight of cement.

3. Based on laboratory tests conducted in this program, the threshold water soluble chloride level above which corrosion occurred at later ages depended on environmental conditions to which the concrete beams were exposed.

4. The laboratory tests indicated that, under certain uniform wetting or drying conditions, corrosion of prestressed tendons was not sustained in concrete made with up to 2 percent calcium chloride admixture by weight of cement.

5. Tests indicated cyclic wetting and drying, or differential drying, induced corrosion where 2 percent calcium chloride admixture had been used.

6. Laboratory tests also indicated that stress levels in prestressing tendons, C_3A content of cement, water-cement ratio of the concrete, and method of curing had little effect on development of corrosion.

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REFERENCES

1. ACI Committee 201, "Guide to Durable Concrete," *ACI Journal,* Proceedings V. 74, No. 12, December 1977, p. 594.
2. Clear, K. C., and Hay, R. E., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs," Report No. FHWA-RD-73-32, Federal Highway Administration, April 1973.
3. Stratfull, Richard F., "Half-Cell Potentials and the Corrosion of Steel in Concrete," Highway Research Record No. 433, Highway Research Board, 1973, pp. 12-21.
4. Berman, H. A., "Determination of Chloride in Hardened Portland Cement Paste, Mortar and Concrete," Report No. FHWA-RD-72-12, Federal Highway Administration, September 1972.

NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by March 1, 1985.