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DETERMINATION OF PERMISSIBLE CHLORIDE LEVELS IN PRESTRESSED CONCRETE

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prestressed concrete institute

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DETERMINATION OF PERMISSIBLE CHLORIDE LEVELS IN PRESTRESSED CONCRETE

by

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Submitted by

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INTRODUCTION

Under certain exposure conditions, an environment may develop which 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 the water soluble chloride limit in prestressed concrete is 0.06% by weight of cement.(1)** For ordinary reinforcing steel the limit is 0.15%. Putting these figures into more practical terms, a 2.0% calcium chloride ($CaCl_2 \cdot 2H_2O$) addition by weight of cement corresponds to about 1.0% chloride ion by weight of cement. This is approximately seventeen times higher than the limit for prestressing steel and seven times higher than the limit for

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**Numbers in parentheses correspond to references listed at the end of this report.

ordinary reinforcing steel. Sea dredged fine aggregate with an absorption of 1.5% would introduce about 0.06% chloride ion, by weight of cement, into a six bag concrete mix. This level is equivalent to the ACI limit for prestressed concrete.

The limit on chloride level for ordinary reinforcing steel is based on laboratory research primarily in South Africa, and the United States.(2,3) Conclusions from this research have been generally substantiated in evaluations of field structures. However, the ACI limit for prestressing steel appears to be based primarily on estimates from limited laboratory work by Verbeck and Monfore.(4)

Because of the uncertain basis for the ACI limit, a need exists to define more clearly the chloride limits for prestressed concrete under various exposure conditions. This investigation therefore addresses itself to two pertinent questions:

1) What is the permissible water soluble 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?

Accordingly, a two phase program was undertaken to obtain answers to these questions. One phase included the circulation of a questionnaire to members of the Prestressed Concrete Institute (PCI), 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 research study to determine the effects of materials and environmental factors on the development of galvanic corrosion of prestressed tendons. The questionnaire is attached to this report as Appendix 1. Results from the questionnaire, and a description and results of the laboratory study, are given below.

QUESTIONNAIRE SURVEY

Sixty-six responses to the questionnaire were received. They indicated that none of the producers had used calcium chloride as an admixture in the past ten years, but that four had used it more than ten years ago. Two of the four used 2% dosages by weight of cement, a third used 1-1/4%, while the fourth couldn't remember the dosage. Two producers listed time of year of production as a factor in its use; two mentioned in-service exposure conditions of the concrete unit as a factor; two listed cement composition as a consideration; and one listed, additionally, stress level in the steel tendons and type of curing as considerations.

Sixteen of the sixty-six responses provided information on circumstances or conditions under which corrosion of prestressed steel had occurred in concrete. Three stated that calcium chloride had been used in the concrete while eight noted that it had not been used. The most commonly reported exposure where corrosion had occurred was alternate drying and wetting outdoors with direct contact with atmospheric precipitation. This was listed ten times. Outdoor exposure with no direct contact with atmospheric precipitation, and indoor exposure with temperature and humidity control, were each listed once. Indoor exposure with high humidities or wetting and drying was also listed once. Three responses stated that corrosion had occurred where concrete was under constant load, while four mentioned that the concrete was under repetitive loading conditions. Four responses also mentioned that corrosion had occurred in steam-cured prestressed concrete.

Exposure to seawater was listed once as a probable source of corrosive salts, while outside sources of chloride other than seawater, such as deicer solutions, were listed fifteen times. Exposure to potash salts was also listed as a corrosive exposure condition. Exposure time elapsed before corrosion was apparent ranged from two to more than 16 years, although these time periods are probably distorted by utilization of different criteria or stages of deterioration to confirm the reported corrosion. It is significant that corrosion was noted in as little as two to three years both in concrete containing calcium chloride as an admixture, and in concrete without calcium chloride.

Regarding future use, none of the sixty-six responses stated that there were plans to use calcium chloride as an admixture in prestressed concrete.

In summary, very few apparent cases of corrosion of prestress steel in concrete containing calcium chloride as an admixture were reported. This appears to be related largely to its lack of use as an admixture by the concrete producer.

Corrosion problems that were reported apparently resulted from exposure to chloride solutions in the in-service environment, particularly chloride deicer solution. None of the producers reported plans to use calcium chloride as an admixture in future production.

LABORATORY STUDY

Test Specimens

Nineteen pretensioned concrete beams were fabricated for this study. Each beam was 12-ft long, 1-ft wide, and 6-in. deep. Three prestressing tendons were positioned one inch from the top surface of the beams, and three additional tendons were located one inch from the bottom surface. Styrofoam dikes were cemented along the top edge of each beam to help maintain the prescribed exposure condition. The vertical sides and ends of the beams were sealed to minimize effects related to moisture diffusion. A schematic diagram of a test beam is shown in Fig. 1.

Test Variables

Six variables considered to potentially affect corrosion processes in concrete were included in this study. Table 1 lists the combinations of variables tested in the nineteen beams. Reasons for the selection of each variable are given below.

C_3A Content of Cement

Two cements, one containing 8% tricalcium aluminate (C_3A), and the other containing 11% C_3A, were used in the test beams. This

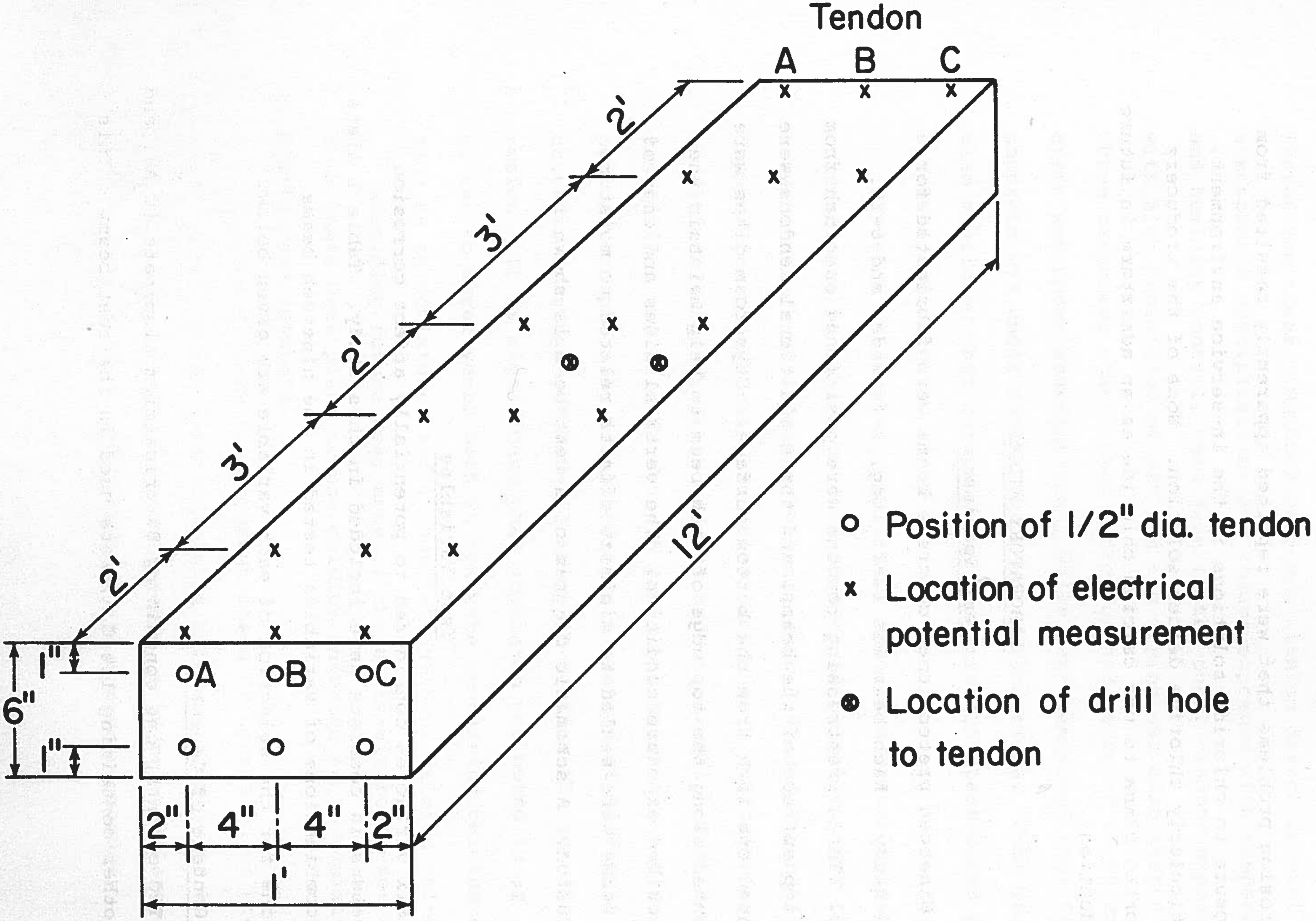

Fig. 1 - Schematic diagram of test beam.

TABLE 1 - VARIABLE COMBINATIONS IN TEST PROGRAM

Beam	Cement $\%C_3A$	Water / Cement	Percent $CaCl_2 \cdot 2H_2O$*	Cure	Stress Level-ksi	Exposure Conditions	
						Initial	Final
1	11	0.35	1.0	Steam	0	Continuous Damp	1/2 Beam Dry, 1/2 Beam Damp
2	11	0.35	2.0	Steam	0	Continuous Damp	1/2 Beam Dry, 1/2 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	14D 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	14D Moist	160	Continuous Damp	2 Holes to Tendons - Water
11	11	0.35	None	Steam	0	Pond - 4% NaCl Soln.	10 Days Dry + 4 days 8% NaCl
12	11	0.35	None	Steam	80	Pond - 4% NaCl Soln.	10 Days Dry + 4 days 8% NaCl
13	11	0.35	None	Steam	160	Pond - 4% NaCl Soln.	10 Days Dry + 4 days 8% NaCl
14	8	0.35	None	Steam	160	Pond - 4% NaCl Soln.	10 Days Dry + 4 days 8% NaCl
15	11	0.35	2.0	Steam	160	Pond - 4% NaCl Soln.	2 holes to tendons - 4% NaCl
16	11	0.35	Aggr. sat. 4% NaCl	Steam	160	Continuous Damp	Remain as is
17	11	0.35	2.0	Steam	160	Continuous Dry - 50% RH	10 Days Dry + 4 Days 8% NaCl
18	8	0.50	0.17	Steam	160	Continuous Damp	10 Days Dry + 4 Days 8% NaCl
19	11	0.35	None	14 D moist	160	Pond - 4% NaCl soln.	10 Days Dry + 4 Days 8% NaCl

*Expressed as percent by weight of cement.

variable was included to determine the relative significance of different amounts of calcium aluminate hydration products in chemically combining with soluble chloride ion, thereby reducing chloride concentration remaining in solution.

Water-Cement Ratio

Two water-cement ratios, 0.35 and 0.50, were used in this study. This variable was selected to determine the effect of concrete permeability on moisture loss during drying, and on penetration of chloride ion. Sixteen beams were made with the 0.35 water-cement ratio, and three with the 0.50 ratio.

Curing Conditions

Both moist curing and steam curing at atmospheric pressure were used in this study. Different curing conditions were included to determine if the nature of cement hydration products was a significant factor in corrosion, and also to provide, with moist curing, a more direct comparison of corrosion resistance of prestressing steel with ordinary reinforcing steel.

Initial Chloride Content of Concrete

Fourteen test beams were made with chloride ion added to the the fresh concrete. Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) was used at rates of 1.0, 2.0, and 0.17% by weight of cement. These rates provide 0.48%, 0.96%, and 0.08% total chloride ion, respectively, by weight of cement. The latter rate was used to provide the ACI water soluble chloride limit of 0.06%, by weight of cement. For one beam, the coarse aggregate was presoaked in

4% sodium chloride (NaCl) solution for three days to simulate the use of seawater-contaminated aggregate. Based on concrete mix proportions and aggregate absorption, the resulting chloride content of the concrete would have corresponded to 0.09% by weight of cement. However, because it was impossible to drain sufficient chloride solution from the presoaked aggregate, actual total chloride content was 0.20% by weight of cement.

Stress Level In Steel

Maximum stress levels of 0, 80, and 160 ksi were applied to prestressing tendons prior to casting the test beams. This variable was included to determine if stress level is a valid basis for prescribing a different permissible chloride level for prestressed steel than for ordinary reinforcing steel. Presently, the lower ACI limit appears to function partly as a safety factor bacause of the greater potential of catastrophic failure should corrosion cause failure of prestressed tendons.

Test Exposure Condition

Three initial exposure conditions were used in this program. Reasons for their selection are described below.

1) Continuous Damp - This condition was initially maintained on the top surface of eleven beams in which chloride ion was intentionally added either as an admixture, or to aggregate during a presoaking period. The purpose of this exposure condition was to prevent drying and to insure that moisture was present in the concrete to serve as electrolyte for any corrosion

cells that might develop. Only a water film covered with polyethylene sheeting was maintained for this purpose so that dilution of chloride in the beams would be held to a minimum.

2) <u>Continuous Ponding with 4% NaCl Solution</u> - This condition was maintained on five beams made without intentionally added chloride, and on one beam which contained 2% calcium chloride admixture by weight of cement. The five beams were to be used to determine threshold corrosion levels for chloride ion introduced from external sources after the concrete had cured. The other beam was ponded with chloride solution to determine susceptibility to corrosion where uniformly high chloride levels were already present in the concrete.

3) <u>Continuous Drying at 50% Relative Humidity (RH)</u> - One beam which contained 2% calcium chloride admixture by weight of cement was continuously exposed to 50% RH to allow freer access of oxygen to the steel where greater than ACI permissible chloride levels were already present. This contrasts with all other beams, in which exposed top surfaces were maintained wet with either chloride solution or water.

These three exposure conditions were initially imposed uniformly on the top surface of each beam for ten to twelve months. Exposures were then changed for fifteen beams to induce differential conditions which might facilitate initiation of corrosion reactions. These latter conditions were maintained for eleven months. Reasons for the changes are described below.

4) <u>Half Beam Continuous Dry, Half Beam Continuous Damp</u> - Two beams containing 1% or 2% calcium chloride by weight of cement were subjected to this exposure following the continuous damp period. This was done to introduce differential oxygen and moisture contents along the top prestressing tendons, thereby possibly initiating or accelerating corrosion reactions.

5) <u>Cycle of Four Days Damp and Ten Days Dry</u> - This cycle was imposed on four beams containing calcium chloride admixture. Each part of the cycle was maintained along the full length of the beam in an effort to periodically allow oxygen to more readily diffuse to the prestressing steel without causing excessive drying of the concrete. In these cases, it was reasoned that sufficient chloride ion was already present at the steel surface to otherwise induce corrosion.

6) <u>Cycle of Four Days Pond with 8% NaCl Solution and Ten Days Dry</u> - This cycle was designed to impose the most extreme conditions favoring corrosion processes, since it provides a more concentrated source of chloride ion, as well as oxygen and moisture. Five of the seven beams subjected to this exposure were made without adding chloride ion to the fresh concrete. Previously, these beams had been exposed to continuous ponding with 4% NaCl solution. The other two beams had 2.0% or

0.17% calcium chloride by weight of cement, added to the fresh concrete mix, and had been exposed to either a continuous damp condition or continuous drying at 50% RH.

Four beams remained under the initial continuous damp exposure condition for the full duration of the test program. These beams contained chloride ion added to the fresh concrete.

A further test variable was imposed on tendons in all of the above beams after approximately one year of testing under initially prescribed conditions. It is well known in galvanic corrosion processes that increases in cathode to anode area ratio increases rate of corrosion. Since the three isolated upper tendons in each beam were being subjected to conditions more favorable to corrosion than those for the three lower tendons, it was believed that electrically connecting the three lower tendons to an upper tendon would increase the cathode to anode ratio, thereby increasing the corrosion rate for the upper tendon. Therefore, a single copper wire was soldered to an exposed end of the lower tendons of each beam, and then similarly connected to upper tendon "A." Theoretically, the three lower tendons would then function as the cathode for a single upper tendon for the duration of testing. The other tendons, "B" and "C", remained isolated for comparison with tendon "A".

In the two remaining beams, Nos. 10 and 15, 1-1/2 in. diameter holes were drilled to two of the three upper tendons and filled with 4% NaCl solution or water. That is, liquid was placed directly in contact with the steel tendons. This was done to determine maximum electrical potential obtainable, and the area affected under localized severe test conditions.

Materials

Two Type I cements, conforming to ASTM C150-80 Standard Specifications for Portland Cement, were used to make the test beams. The compositions of these cements are given in Table 2. Sixteen beams were made using cement with 11% C_3A, while three were made with cement containing 8% C_3A.

Coarse and fine aggregates from Eau Claire, Wisconsin were used in all test beams. Aggregate from this source was selected because it contained only 0.003 to 0.005% chloride ion. The coarse aggregate is a known durable material and consists primarily of granitic to gabbroic rock types with lesser amounts of crystalline volcanics, quartzite, gneiss, and schist. The fine aggregate consists primarily of feldspar and quartz with minor amounts of the rock types present in the coarse aggregate. Because only one inch of cover was provided over the tendons, maximum particle size of the aggregate was limited to 3/8 in.

All prestressing steel was stress relieved Grade 270K obtained from the same lot. It consisted of half-inch 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. It was reported to

TABLE 2 - SUMMARY OF ANALYSES OF PORTLAND CEMENT

Chemical Analyses - %

Cement	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I.
High C_3A	19.51	5.51	2.01	62.51	2.50	3.50	0.32	1.07	1.38
Low C_3A	21.23	4.61	2.52	66.13	1.00	2.52	0.07	0.21	1.16

L.O.I. - Loss on Ignition

Calculated Compound Composition - %

Cement	C_3S	C_2S	C_3A	C_4AF
High C_3A	57	12	11	6
Low C_3A	66	11	8	8

Chemical analyses and calculations done according to ASTM C 114-80, Standard Methods for Chemical Analysis of Hydraulic Cement.

contain 77 to 80 percent calcium chloride ($CaCl_2$). Neutralized Vinsol resin (NVR), meeting ASTM Designation C260-77 Standard Specification for Air-Entraining Admixtures for Concrete, was used as the air-entraining agent.

Concrete Mix Design

Two concrete mix designs, which are in the range used for commercial production of prestressed concrete members, were utilized in this program. Concrete for sixteen beams was made using a nominal cement factor of 7.5 bags (705 lbs) per cubic yard and a water-cement ratio of 0.35. Concrete for three beams was made using a cement factor of 5.25 bags (495 lbs) per cubic yard and a water-cement ratio of 0.50. Prescribed air contents were 6.0% ± 0.5%. However, for several beams, air contents were only 5.0%. For purposes of this test program, this was not considered to be a significant variation.

The primary requirement for these mixes was that concrete be sufficiently strong to withstand transfer of prestressing load without cracking at the time the tendons were released. Calculations indicated that compressive strengths of about 2700 psi would be sufficient for this requirement. To provide a safety factor, concrete mixes were designed for 4000 psi compressive strength at load release time. To further minimize chances for cracking, loads on the tendons were released slowly and as uniformly as possible. Examination of beams after load release revealed no evidence of cracking.

Table 3 summarizes concrete mix design and strength data for each mix. Measured concrete strengths for several beams were less than 4000 psi at load release time, but this appeared not to have presented any problems for later corrosion testing.

Specimen Fabrication

All test beams were cast and cured at Construction Technology Laboratories (CTL). The prestressing bed used for fabrication could accommodate three 12-ft long test beams for simultaneous casting. Thus, the casting schedule consisted of five days of casting three beams, and two days of casting two beams. All beams cast on a given day necessarily contained prestressing strand held at the same stress level.

All beams were cast in forms made of three-fourths in. thick resin-impregnated plywood. Six holes were cut at the proper positions in the end pieces of the forms so that prestressing strands could extend continuously between anchorages of the prestressing bed. On the day prior to casting, tendons were positioned and stressed to 80 or 160 ksi as required. One hour before casting, tendons were restressed to compensate for relaxation of steel after initial stressing. All tendons were degreased with xylene to insure that steel surfaces were clean prior to casting.

Each beam was made using one concrete batch mixed in a vertically oriented drum-type mixer. Both fine and coarse aggregates were presoaked in water for 18 hours prior to batching. After draining the excess, sufficient water was retained

TABLE 3 - SUMMARY OF CONCRETE MIX DESIGN AND STRENGTH DATA

Beam No.	Cement Factor bags/yd^3	Water-Cement Ratio	Calcium Chloride %	Method of Cure	% Air	Compressive Strength - psi*	
						1 Day	14 Days
1	7.50	0.35	1.0	Steam	5.2	5510	--
2	7.50	0.35	2.0	Steam	5.5	5240	--
3	7.50	0.35	1.0	Steam	5.4	3910	--
4	7.50	0.35	2.0	Steam	6.2	4290	--
5	7.50	0.35	1.0	Steam	5.0	4790	--
6	7.50	0.35	2.0	Steam	5.7	4010	--
7	7.50	0.35	2.0	Moist	5.5	--	5440
8	7.50	0.35	2.0	Steam	5.5	5910	--
9	5.25	0.50	2.0	Steam	6.3	3510	--
10	5.25	0.50	2.0	Moist	6.0	--	4980
11	7.50	0.35	0	Steam	6.2	4270	--
12	7.50	0.35	0	Steam	5.6	4300	--
13	7.50	0.35	0	Steam	5.8	4730	--
14	7.50	0.35	0	Steam	5.6	5550	--
15	7.50	0.35	2.0	Steam	6.5	4190	--
16	7.50	0.35	Sat. Agg.	Steam	5.0	4290	--
17	7.50	0.35	2.0	Steam	6.0	4070	--
18	5.25	0.50	0.17	Steam	5.0	3460	--
19	7.50	0.35	0	Moist	5.2	--	5830

*Corrected to 6"x12" cylinder strengths.
All data are the average of two companion cylinders.

for later addition to bring the mixing water up to the required amount. For beam No. 16, which contained coarse aggregate saturated with sodium chloride solution, fresh tap water was used instead of excess drain water (salt solution) to maintain the net mix water requirement.

Calcium chloride admixture, when specified, was dissolved in the mix water prior to its addition to the batch. This was followed by the addition of neutralized Vinsol resin to the concrete mix. Mixing was done on a 3-3-2 minute, mix-rest-mix cycle, with all admixture and water being added during the initial two minutes of mixing. Slump and air content were measured immediately following the mix cycle.

The fresh concrete was transported to the casting site in two buckets. Upon discharge into the forms, concrete was consolidated by internal vibration. The top surface of each beam was screeded and then finished with a magnesium float. Three by six-inch concrete cylinders were also cast for later strength testing and chloride measurements. All mixing and casting was done at 73±3°F and 45 to 50% relative humidity.

Beams scheduled for steam curing were kept under damp burlap and polyethylene sheeting for four hours following casting. After this period, the coverings were removed and a styrofoam-insulated wooden enclosure was placed over the beams and cylinders for steam curing. Perforated, 1/2 in. diameter, pipes, which extended full length adjacent to each side of the forms, served to supply the steam needed for accelerated curing. Three thermocouples were inserted into the enclosure to monitor temperatures. Steam supply and temperature were controlled manually to insure temperature rise of 15 to 20°F per hour during the initial four hour period of steam cure. Maximum temperatures were then maintained at 155°F to 165°F for an additional twelve hours. Following this period, the steam was turned off, the insulated enclosure was removed, and the specimens were allowed to cool, in the forms, to room temperature.

For continuously moist cured beams, the side and end pieces of the forms were removed after one day, and the concrete was covered with wet burlap and polyethylene, which were kept in place for 14 days. Each day during this period, top surfaces of the beams were wetted to minimize self-desiccation due to cement hydration.

After curing, prestressing tendons were released gradually to prevent the concrete from cracking. Following load release and removal of forms, all beams were transferred to a test room maintained at 73°±3°F and 50±5% RH. Steam cured beams were stored under this condition for 27 days, while 14-day moist cured beams were stored under this condition for 14 days prior to start of the test period. During that time, 2-in. high styrofoam dikes were attached, with silicone-based adhesive, to the top edges of each beam to contain solutions or water ponded on the top surface. Vertical faces of each beam were sealed with two coats of two-component epoxy to minimize or eliminate drying from those surfaces. The exposed ends of the prestressing tendons were heavily greased to prevent corrosion in those areas.

Monitoring Methods

Three methods were used to monitor corrosion related phenomena. These are described below.

Visual Inspection

Periodically, during the test period, the concrete beams were examined for the development of longitudinal cracking over tendons. After testing was completed, prestressing tendons were extracted from eighteen of the nineteen beams and examined for evidence of corrosion.

Electrical Potential Measurements

Electrical potential measurements were made on all beams at one to four week intervals during the test period. Measurements were conducted as described in ASTM Designation C876-80 (Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete). A diagram of the electrical circuitry for this method is shown in Fig. 2. In it, a lead wire from a high impedance voltmeter is attached to the exposed end of the prestressing tendon to be measured. A second lead wire extends from the voltmeter to a copper/copper sulfate reference half cell (CSE) which is placed on the top concrete surface directly above the area of the tendon to be measured. The electric circuit is then completed through concrete between the half cell and the tendon directly below the cell. Prior to measurement, ponded concrete surfaces are sponge dried, and air dried surfaces are locally dampened, to stabilize voltage readings.

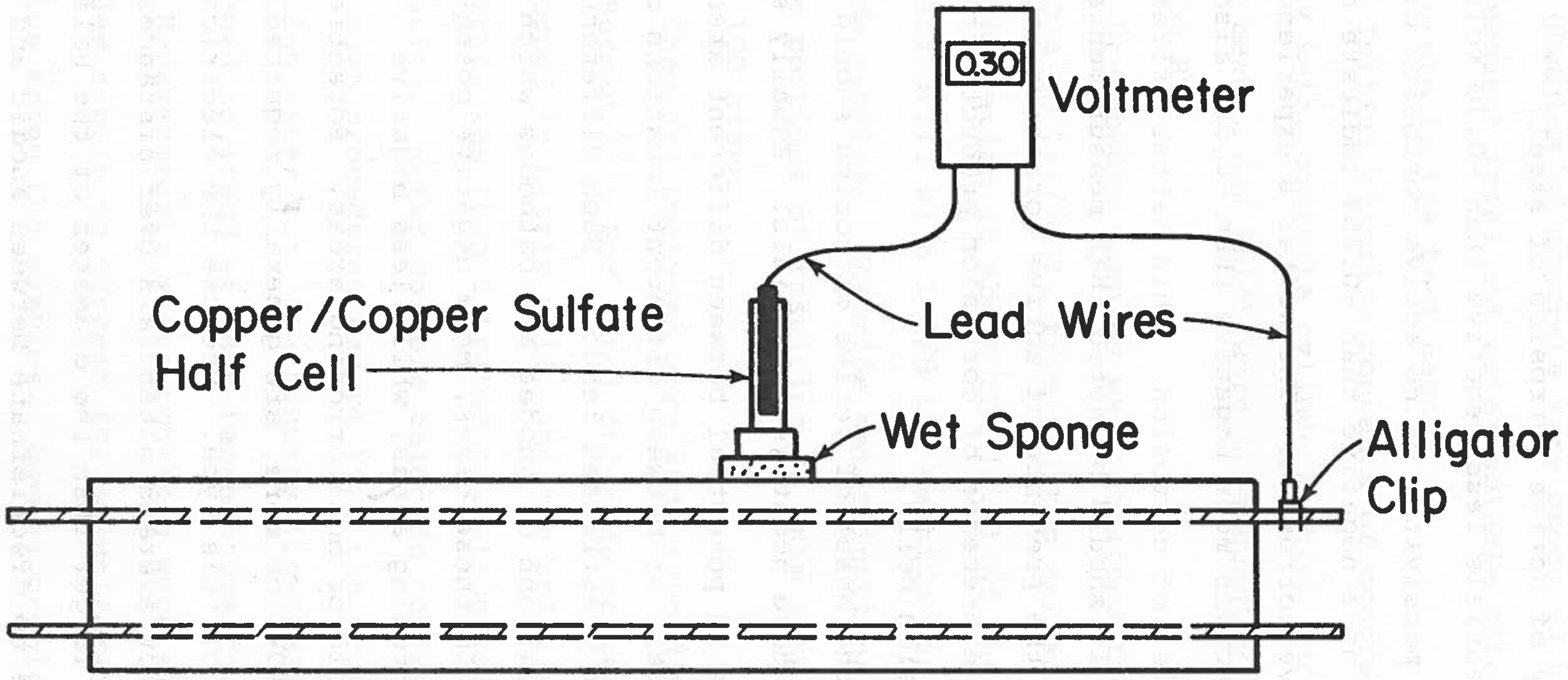

Fig. 2 - Diagram of scheme for measuring electrical potentials.

Electrical potentials determined in this manner can indicate the relative probability of active corrosion of steel.(3,5) It has been found that potentials less negative than -0.30 volts (V) indicate electrical passivity, or no active corrosion of the steel, while potentials more negative than -0.35V indicate about 90% probability of active corrosion. The writer's experience has indicated that potentials more negative than -0.30V also reflect high probabilities of corrosion. This latter criterion is used in this study. It should be noted that measurements of this type indicate only the presence of active corrosion and not rate of corrosion nor the presence of corrosion products from previously active corrosion cells.

It is evident that the onset of active corrosion should be indicated by a shift to more negative potentials. Equally significant are differences in potential between different areas of a mat of reinforcing steel, or between different locations on a given reinforcing bar or prestressed tendon. Such differences in potential reflect locations of anodes and cathodes which drive corrosion cells. In these cases, more negative potentials represent anodic, or corroding areas, while less negative potentials denote cathodic or non-corroding areas. Potential differences of about 0.10V, or more, are generally required to sustain corrosion cells of this type. Because the electrical potential readings reflect average potentials over distances on the steel several times larger than the diameter of the half cell, it is not possible to discriminate between anodic and cathodic areas that are only fractions of an inch apart.

Chloride Analyses

Samples of concrete were procured to determine initial and subsequent total and water soluble chloride ion contents of concrete in the test beams.

Initial chloride contents of concrete were measured on 3 by 6-in. concrete cylinders which were cast and cured with the beams, but which were subsequently stored at 73±3°F and 50±5% RH.

Dry powder samples were obtained from the beams at depths of 3/4 to 1-1/4 in. from the top surface to determine chloride concentration at about the level of the upper tendons. An impact drill with 1-1/8 in. carbide tip bit was used to procure these samples. Chloride determinations were made on representative portions of resulting 30 gram samples ground to pass the No. 100 sieve.

Chemical analyses were made according to procedures described by Berman.(6) For total chloride content, the powder sample was digested in nitric acid, and the solution was filtered. The filtrate was then titrated potentiometrically with silver nitrate solution. Water soluble chloride contents were measured using the same procedures except that the ground sample was placed in boiling water for five minutes (instead of nitric acid) and then allowed to stand at room temperature for 24 hours.

Nonevaporable water contents were also measured on each powder sample to correct for nonuniformities in paste-aggregate ratios among the samples. Nonevaporable water is determined from the weight change which occurs when the sample is heated from 105°C to 525°C, and maintained at the higher temperature for five minutes. Known mix proportions, plus measured unit weights of the concretes, were used as bases for expressing chloride contents as percent by weight of cement.

Test Results

Summaries of results from the three test methods are reported in this section. It should be noted that all potentials are referenced to the copper/copper sulfate half cell. Also, chloride contents, including dosage of calcium chloride admixture, are expressed as percent by weight of cement when not specified otherwise. Discussion of test results is given in a later section of the report.

Examination of Prestressing Tendons

When testing was terminated, prestressing tendons were removed from eighteen of the nineteen test beams and examined for the presence of steel corrosion products. Observations, together with initial chloride content of the concrete and exposure condition, are summarized in Table 4.

Results show that active corrosion had developed in all nine beams made with 2% calcium chloride admixture. The nature and severity of corrosion ranged from localized pitting in beam Nos. 4 and 15 to numerous areas with films of corrosion product scattered along the entire length of the tendons in beam No. 17.

TABLE 4 - SUMMARY OF OBSERVATIONS OF PRESTRESSING TENDONS

Beam No.	$CaCl_2 \cdot 2H_2O$*	Exposure Conditions	Observations of Upper Tendons
1	1%	Continuous damp half dry & half damp	Several localized areas with film of corrosion products.
2	2%	Continuous damp Half dry & 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%	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%	Continuous damp	Localized areas with film of corrosion product. Pitting scattered along entire length on two or three strands of each tendon.
5	1%	Continuous damp 10 days dry + 4 days damp	Film of corrosion product along 1-1/2 ft length on four strands near one end of one tendon. Film on several strands at middle of beam on each tendon.
6	2%	Continuous damp 10 days dry + 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%	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%	Continuous damp 10 days dry + 4 days damp	Few spots, about 1/2 in. long, with film of corrosion product scattered full length on each tendon.

*Expressed as percent by weight of cement

TABLE 4 - SUMMARY OF OBSERVATIONS OF PRESTRESSING TENDONS (Continued)

Beam No.	$CaCl_2 \cdot 2H_2O$*	Exposure Conditions	Observations of Upper Tendons
9	2%	Continuous damp 10 days dry + 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%	Continuous damp Water in drill holes	Few spots, 2 to 4 in. long and 2 ft from one end on each tendon, with film of corrosion product.
11	0	Pond 4% NaCl soln. 10 days dry + 4 days pond 8% 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% NaCl soln. 10 days dry + 4 days pond 8% NaCl soln.	No corrosion observed on tendons.
13	0	Pond 4% NaCl soln. 10 days dry + 4 days pond 8% NaCl soln.	No corrosion observed on tendons.
14	0	Pond 4% NaCl soln. 10 days dry + 4 days pond 8% NaCl soln.	No corrosion observed on tendons.
15	2%	Pond 4% NaCl soln. 4% NaCl soln. in drill holes.	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%NaCl	Continuous damp	Few localized spots on each tendon with corrosion products.

TABLE 4 - SUMMARY OF OBSERVATIONS OF PRESTRESSING TENDONS (Continued)

Beam No.	$CaCl_2 \cdot 2H_2O$*	Exposure Conditions	Observations of Upper Tendons
17	2%	Continuous dry 50% RH 10 days dry + 4 days pond 8% NaCl soln.	Localized areas with layer of corrosion product on all tendons.
18	0.17	Continuous damp 10 days dry + 4 days 8% 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% NaCl soln. 10 days dry & 4 days pond 8% NaCl soln.	Beam held in reserve for possible further testing. Tendons not retrieved for visual inspection.

Corrosion also occurred in the three beams made with 1% calcium chloride admixture. In these beams, Nos. 1, 3, and 5, corrosion products occurred as localized films with no evidence of pitting.

Prestressing tendons from four of the five beams made without added chloride were also examined. In beam Nos. 12, 13, and 14, there was no evidence of corrosion, even after ponding with NaCl solution throughout the test period. One tendon in beam No. 11 displayed corrosion product. This development is discussed later.

Tendons were examined from two other beams made with chloride ion added to the fresh concrete. In beam No. 16, which contained coarse aggregate presoaked in 4% NaCl solution, there was minor localized corrosion after 79 weeks under continuous damp exposure conditions. In beam No. 18, which was made with 0.17% calcium chloride admixture (which corresponds to the ACI limit of 0.06% water soluble chloride ion for prestressed concrete), two of the three tendons displayed localized films of corrosion product in a two foot length near one end of the beam. This condition appears to have developed after ponding with 8% NaCl solution, as indicated by potential measurements to be discussed later.

Beam No. 19 is being held for possible further testing. Thus, tendons from this beam were not examined.

Electric Potential Measurements

As stated earlier, electrical potential measurements were made at regular intervals to determine time of active corrosion of prestressed tendons. At each time of measurement, six readings were taken on each of the three upper tendons. Readings were taken at both ends of each beam, and at positions one foot and four feet from the center of each beam as shown in Fig. 1. In this manner, possible effects on corrosion of different stress levels along a given tendon could be evaluated. However, review of data indicated that, at any given age, potential differences between the six positions, with exceptions in beam Nos. 1 and 2 to be discussed later, were less than 0.05V. Differences of this magnitude were not considered significant. Also, with exceptions in beam No. 11, potential differences between tendons at a given age were no greater than 0.05V. Therefore, averages of all eighteen readings were used to characterize corrosion resistance at a given time in all but the noted exceptions. This latter behavior will be mentioned later in the discussion of cathode to anode area ratios.

Figures 3 through 16 summarize results of electrical potential measurements. In these figures, pertinent characteristics of the beams, together with test exposure condition, are given. The 27-day unidentified time period preceding the test period is the air drying interval immediately following curing. For moist cured beams, moist plus dry periods are included.

Results for beam No. 11, presented in Fig. 3, illustrate differences in measured potential between actively corroding prestressing tendons and noncorroding tendons which are in the passive state. This beam was made without calcium chloride admixture but was ponded with sodium chloride solution. From

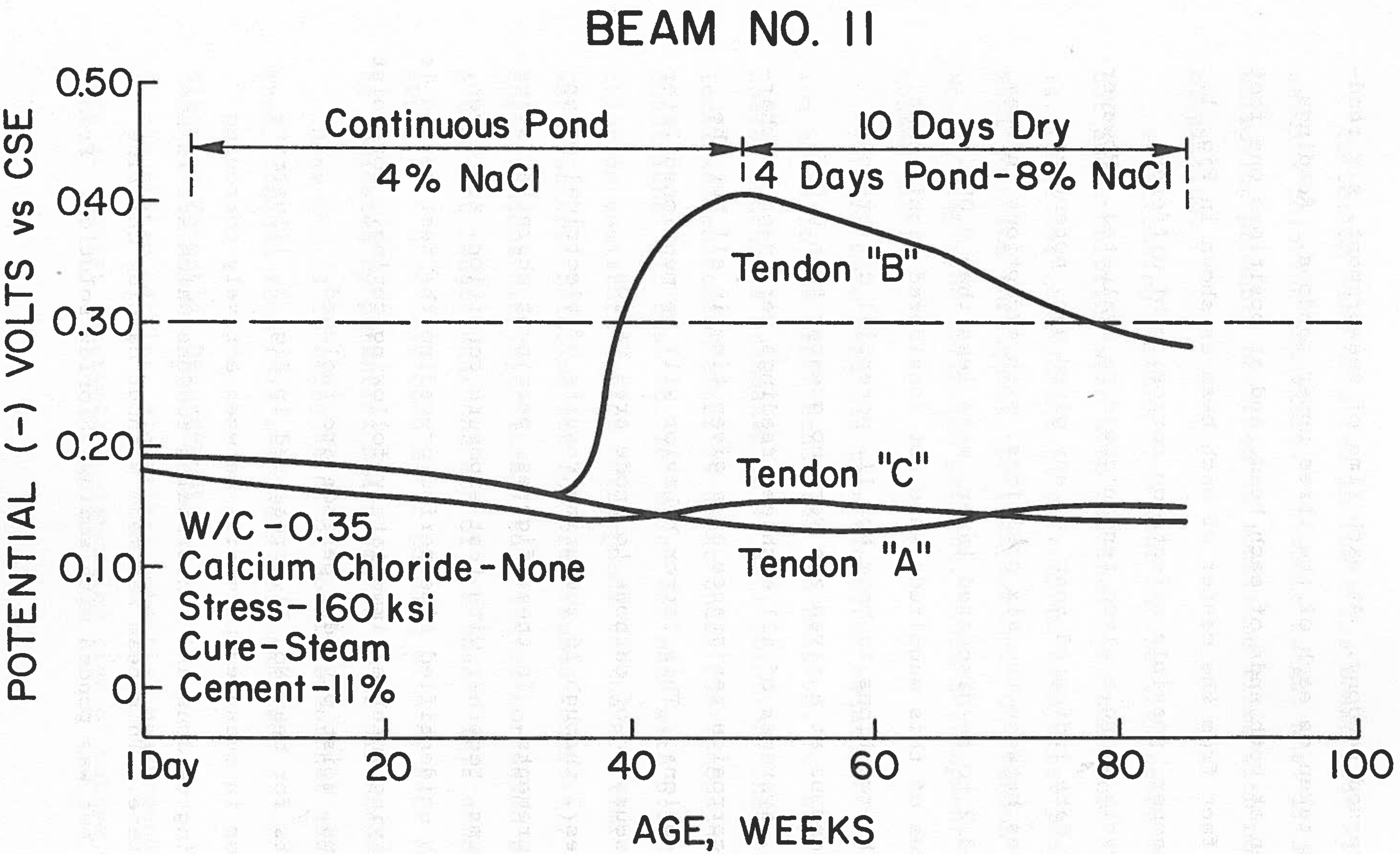

Fig. 3 - Potential curves for individual tendons in beam No. 11.

one day of age (initial measurement) through 35 weeks of ponding, potentials for all three tendons were similar and less negative than -0.30V. At that point, potentials for tendon "B" rapidly shifted from -0.17V to about -0.40V. This shift signifies the initiation of active corrosion. In contrast, potentials for tendons "A" and "C" remained at about -0.16V to -0.19V for the entire 49-week duration of the continuous ponding period, as well as for the subsequent 37-week long period of alternate drying and ponding. This indicates that active corrosion never developed on these two tendons. Potentials for tendon "B" remained at levels more negative than -0.30V for most of the alternate drying and ponding period, but eventually shifted to a potential value of -0.28V at the final test age of 86 weeks. This latter trend indicates termination of active corrosion at some point during the final 10 to 15 weeks of testing when potentials shifted to values less negative than -0.30V. Visual examination of tendons from beam No. 11 confirmed the presence of pitting and corrosion products at one end of tendon "B". No evidence of corrosion was found on tendons "A" and "C".

Development of active corrosion on tendon "B" but not on tendons "A" and "C" appears to have resulted from the presence of a fine crack over tendon "B" at one end of the beam where pitting was observed on the tendon. This crack was first noticed several weeks before the shift in potentials. The exact cause of its development is not known, but it probably was not due to corrosion because, if so, it would not have been seen before the shift in potential.

Comparison of results among the other eighteen beams are given below according to test variable.

C_2A Content of Cement

Figures 4 and 5 summarize results of potential measurements for beams that were made with cements containing 8% or 11% C_3A. In Fig. 4, potential curves are shown for beam Nos. 6 and 8, which were made with 2% calcium chloride admixture. These curves show that initial potentials, measured within two hours after steam curing was completed, were -0.34V and -0.42V for beams containing the 8% and 11% C_3A cements, respectively. Both values are in the range that indicates active corrosion. From this time onward through the 28-day air drying period and subsequent exposure conditions, potentials steadily shifted to final values of -0.02V and -0.24V, both of which indicate termination of active corrosion. For beam No. 6, which contains the 11% C_3A cement, active corrosion appears to have stopped within 20 to 25 weeks of age. For beam No. 8, which contains cement with 8% C_3A, active corrosion appears to have stopped within about eight weeks after casting.

Examination of tendons confirmed that corrosion had occurred in both beams. Potentials are thus taken as evidence that active corrosion developed in both beams within one day of casting. Overall, results indicate that, under these test conditions, C_3A content had no effect on whether active corrosion developed. However, active corrosion appears to have stopped earlier in beam No. 8, which was made with cement with the lower C_3A content.

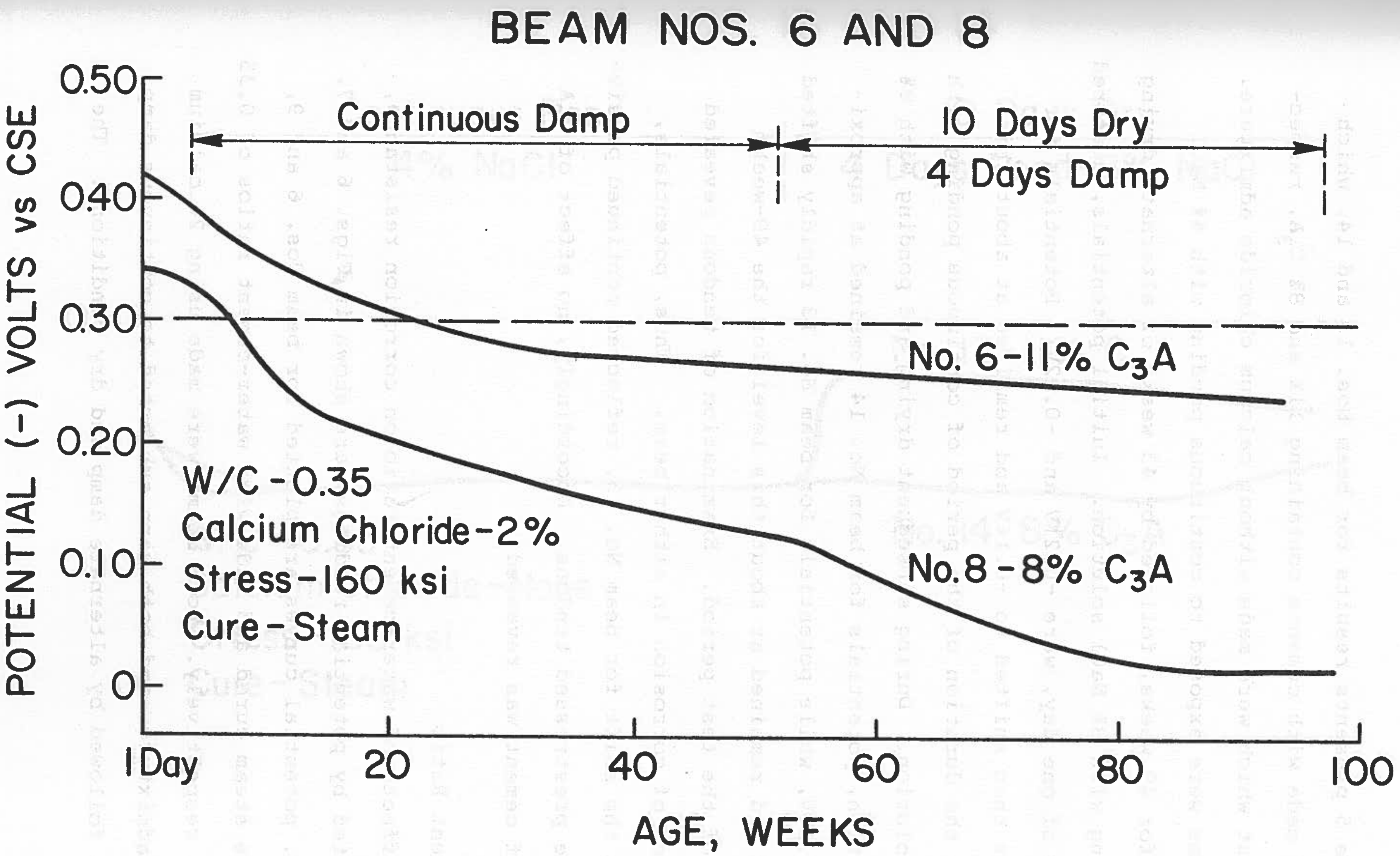

Fig. 4 - Potential curves for beams which contain cements with 8% or 11% C_3A.

Figure 5 presents results for beam Nos. 13 and 14, which also were made with cements containing 11% and 8% C_3A, respectively, but which were made without calcium chloride admixture. These beams were exposed to continuous ponding with 4% NaCl solution for 49 weeks, followed by 43 weeks of alternate drying and ponding with 8% NaCl solution. Initial potentials, measured at an age of one day, were -0.21V and -0.22V. Potentials for both beams then shifted to -0.16V and remained at about this level for the duration of the period of continuous ponding with 4% NaCl solution. During subsequent drying and ponding with 8% NaCl solution, potentials for beam No. 14 remained at approximately -0.16V, while potentials for beam No. 13 rapidly shifted to -0.25V and remained at about this level for the 40-week duration of the test period. Examination of tendons revealed no evidence of corrosion in either beam. Thus, potentials, including the shift for beam No. 13, reflected continued passivity of the prestressed tendons. Accordingly, no effect of C_3A content of cement was revealed.

Water-Cement Ratio

The effects of water-cement ratio on corrosion resistance, as reflected by potential readings, are shown in Figs. 6 and 7. In Fig. 6, potential curves are plotted for beam Nos. 6 and 9, which were steam cured and made with water-cement ratios of 0.35 and 0.50, respectively. Both beams were made using 2% calcium chloride admixture, and both were subjected to continuous damp exposure, followed by alternate damp and dry conditions. The

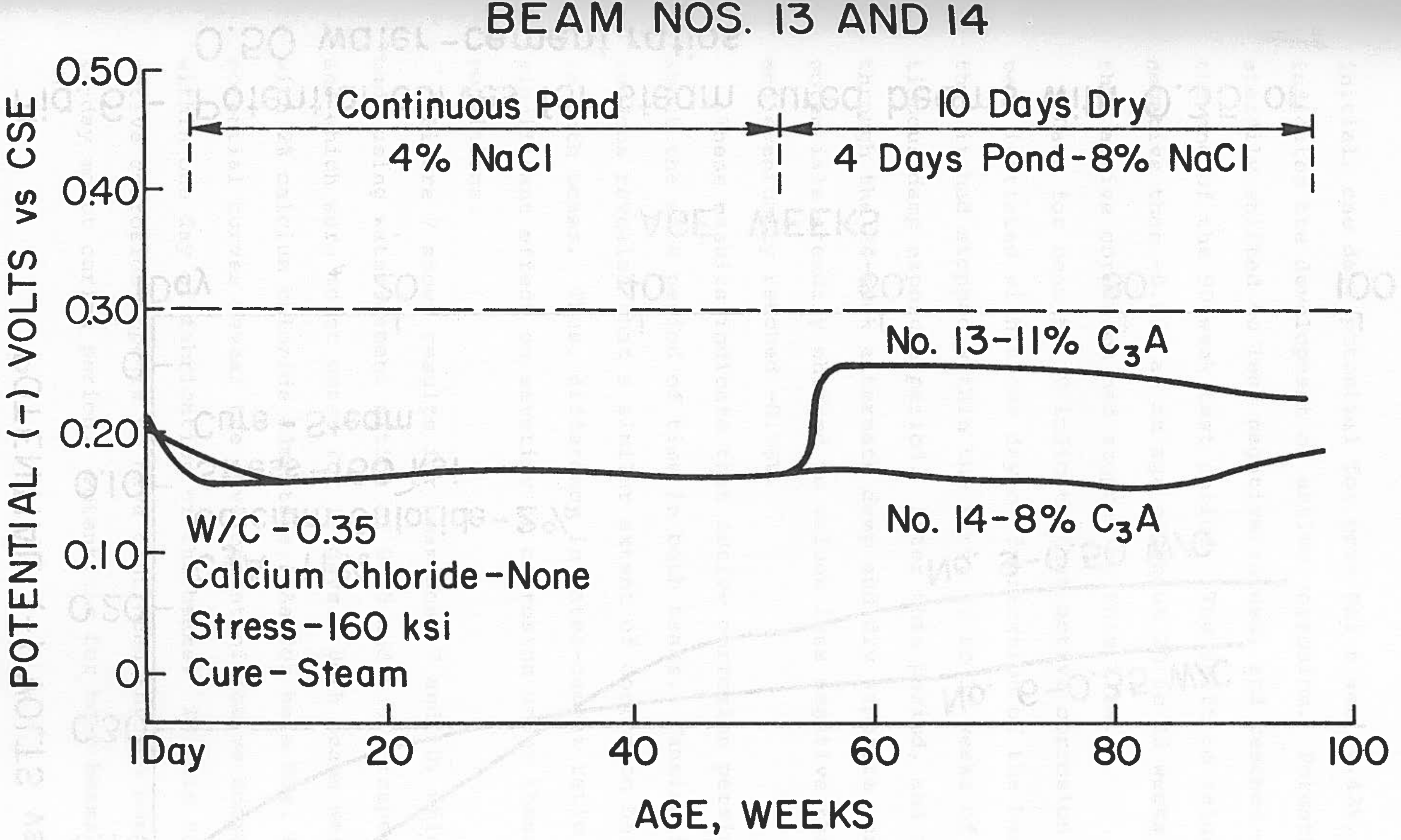

Fig. 5 - Potential curves for beams containing 8% or 11% C_3A cement and exposed to NaCl solutions.

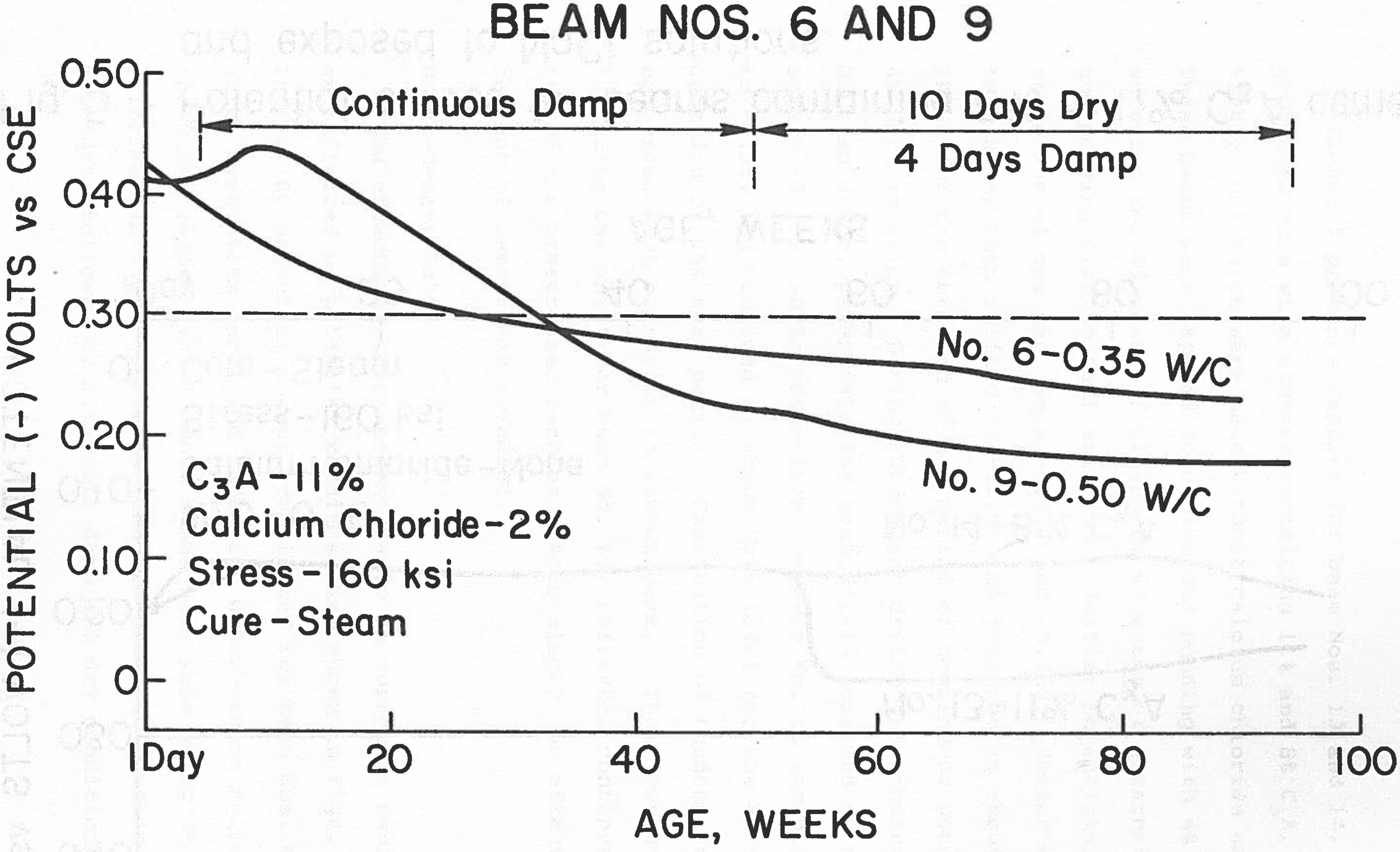

Fig. 6 - Potential curves for steam cured beams with 0.35 or 0.50 water-cement ratios.

initial, one day, potential for beam No. 6 was -0.42V, which indicates the development of active corrosion. Potentials then steadily shifted to less negative values, and reached -0.24V by the end of the 90-week test period. The shift to values less negative than -0.30V at an age of about 20 to 25 weeks indicates that active corrosion had stopped by this time.

Data for beam No. 9 indicate that active corrosion also had been initiated within one day of fabrication of the beam, but that it had stopped within the first 30 to 35 weeks of the continuous damp exposure period. After this period, and continuing through the 44-week alternate damp and dry exposure period, potentials steadily shifted to values less negative than -0.30V, and eventually reached -0.18V.

These results indicate that active corrosion persisted for about the same period of time in both beams. Examination of tendons revealed that a similar extent of corrosion had developed in both beams. Thus, difference in water-cement ratio had no significant effect on severity of corrosion under these exposure conditions.

Figure 7 shows results for beam Nos. 7 and 10, which were made using water-cement ratios of 0.35 and 0.50, respectively, and which were moist cured for 14 days. Both beams were made with 2% calcium chloride admixture. As for beam Nos. 6 and 9, potential curves reveal the development of active corrosion within one day of fabrication of the beams. In this case, active corrosion appears to have continued through most of the 14-day moist curing period. Potentials for both beams then

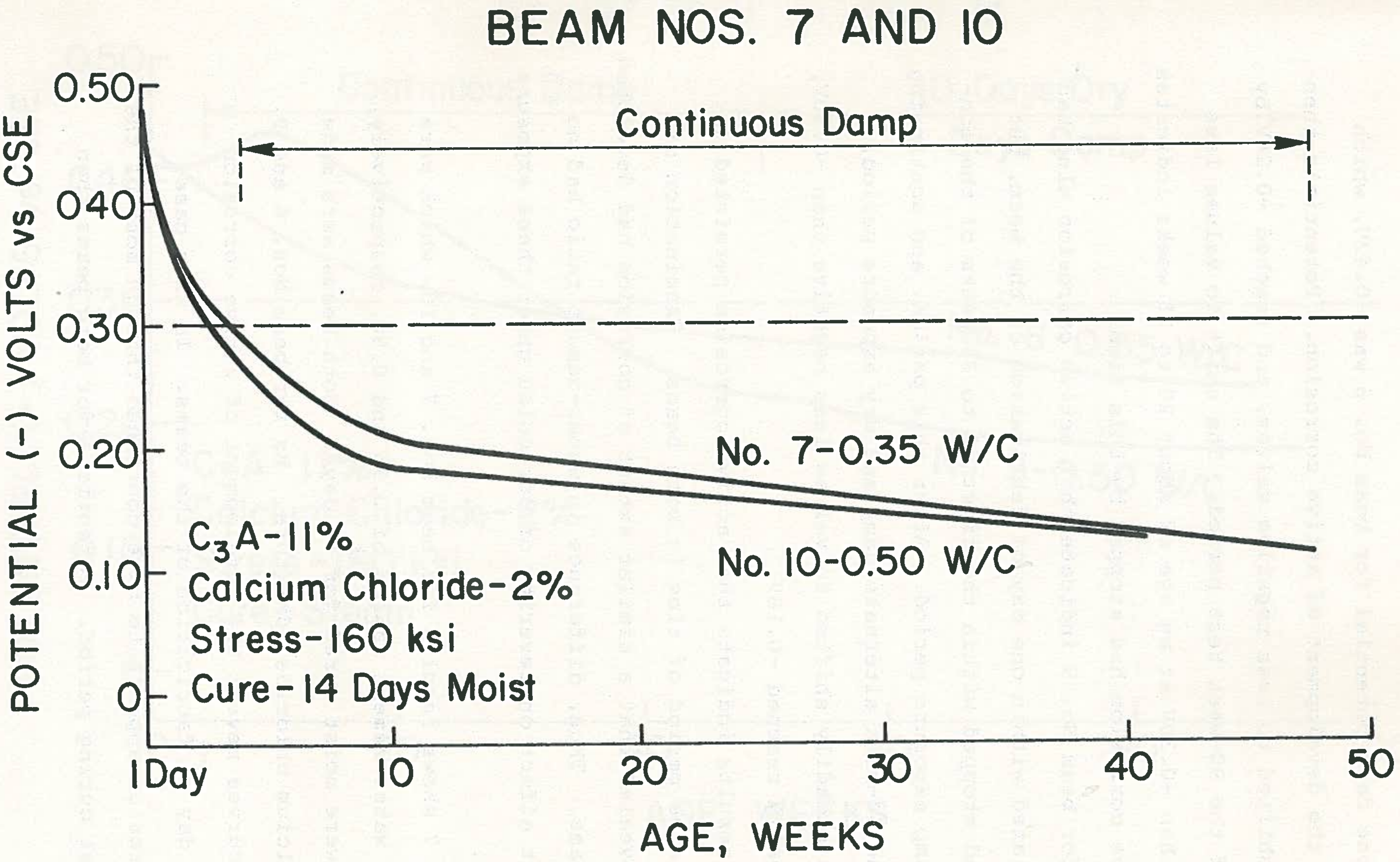

Fig. 7 - Potential curves for moist cured beams with 0.35 and 0.50 water-cement ratios.

shifted to values less negative than -0.30V during the subsequent 14-day air drying period, and then gradually shifted to potentials of about -0.12V at the end of the 44-week continuous damp exposure period. These results indicate that active corrosion had stopped during the 14-day air dry period following moist curing. Examination of tendons revealed similar development of corrosion products in the two beams.

Based on these results, difference in water-cement ratio had little effect on corrosion resistance where 2% calcium chloride admixture had been used.

Curing Method

Relative effects of steam curing and 14-day moist curing on corrosion resistance are shown in Figs. 8 and 9. In Fig. 8, curves are shown for beam Nos. 6 and 7, both of which were made with 2% calcium chloride admixture. One day after fabrication, potentials were -0.42V and -0.43V, which indicates the development of active corrosion. During the subsequent 78-week period of continuous damp, and alternate damp and dry exposures, potentials for the moist cured beam, No. 7, steadily shifted to a final potential of -0.10V. The curve indicates that active corrosion had stopped during the two week air drying period immediately following curing. The curve for beam No. 6, which was steam cured, follows a similar trend, except that potentials remained at more negative values during this period, and shifted to values less negative than -0.30V at the later ages of 20 to

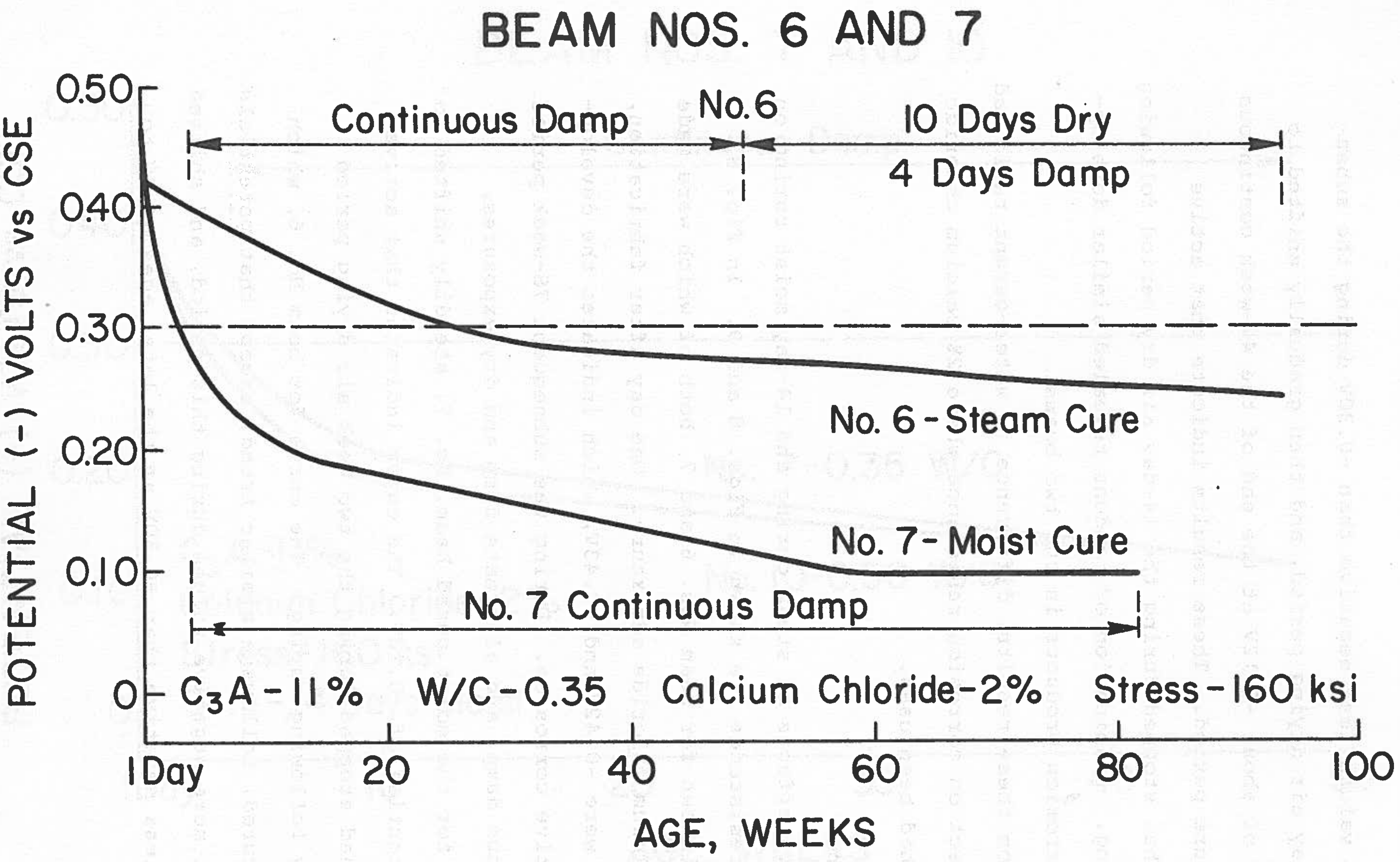

Fig. 8 - Potential curves for steam and moist cured beams.

30 weeks. This would reflect a longer period of active corrosion than for beam No. 7. Examination confirmed the presence of corrosion products on tendons in both beams.

Figure 9 presents potential curves for beam Nos. 13 and 19, both of which were made without calcium chloride admixture, but which were ponded with NaCl solution for most of the 92-week test period. Curves for both beams are confined entirely to a potential range of -0.12V to -0.26V, which is in the passive range where active corrosion is not indicated. The slight shift to more negative potentials at the time of change in exposure condition was not considered to indicate the onset of active corrosion. Examination of tendons from beam No. 13, which was steam cured, confirmed that corrosion had not developed. Tendons were not removed from beam No. 19. However, because potentials for this beam, which was moist cured, are similar to, but generally less negative than, those for beam No. 13, it is presumed that active corrosion also did not develop in beam No. 19.

Results thus indicate that method of curing had little or no significant effect on the development of corrosion in these beams.

Stress Level in Steel

Figures 10 and 11 show potential curves for beams containing tendons held at different stress levels during placement of the concrete. In Fig. 10, curves are given for beam Nos. 1, 3, and 5, all of which were made with 1% calcium chloride admixture,

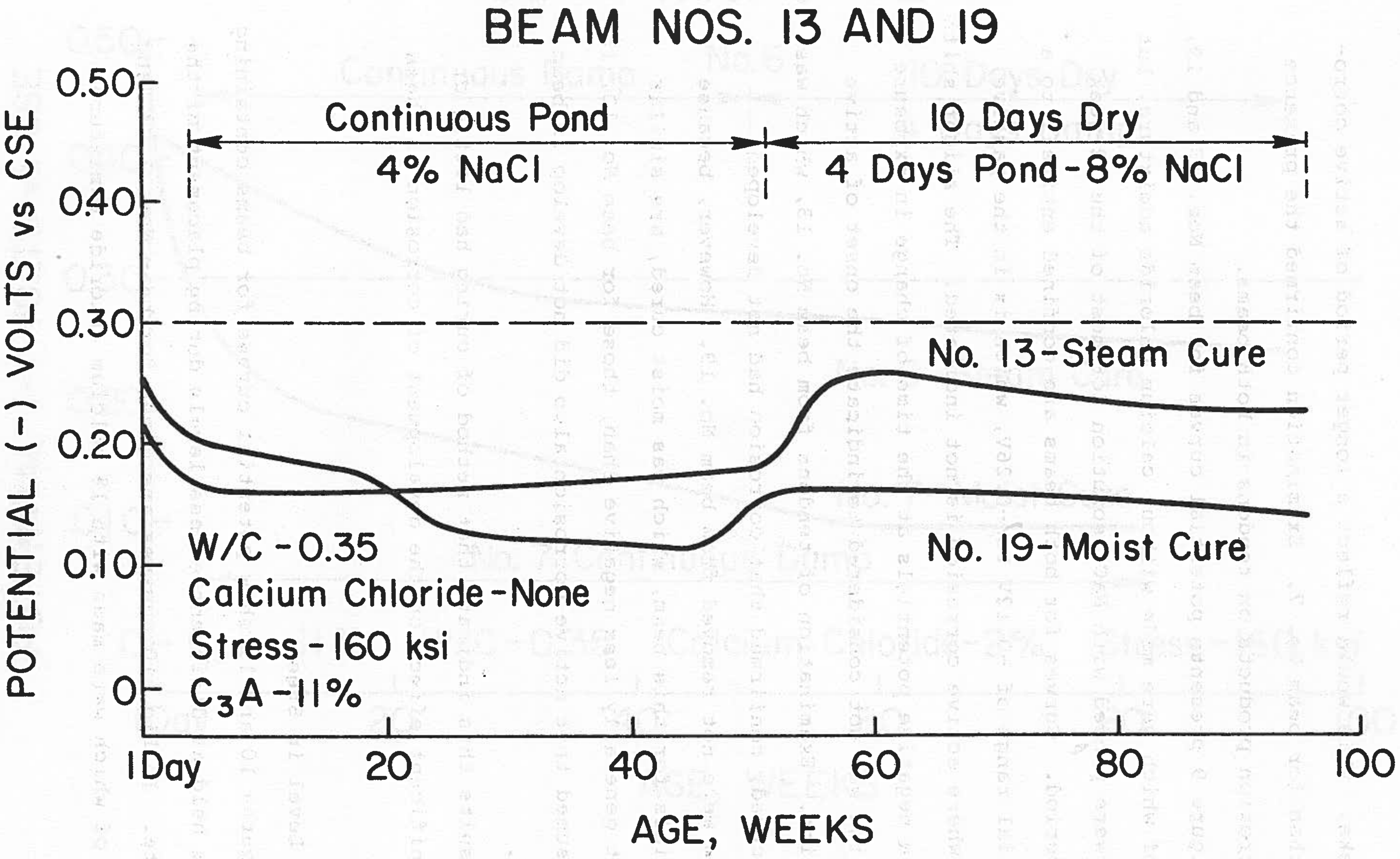

Fig. 9 - Potential curves for steam and moist cured beams ponded with NaCl solution.

with NaCl solution.

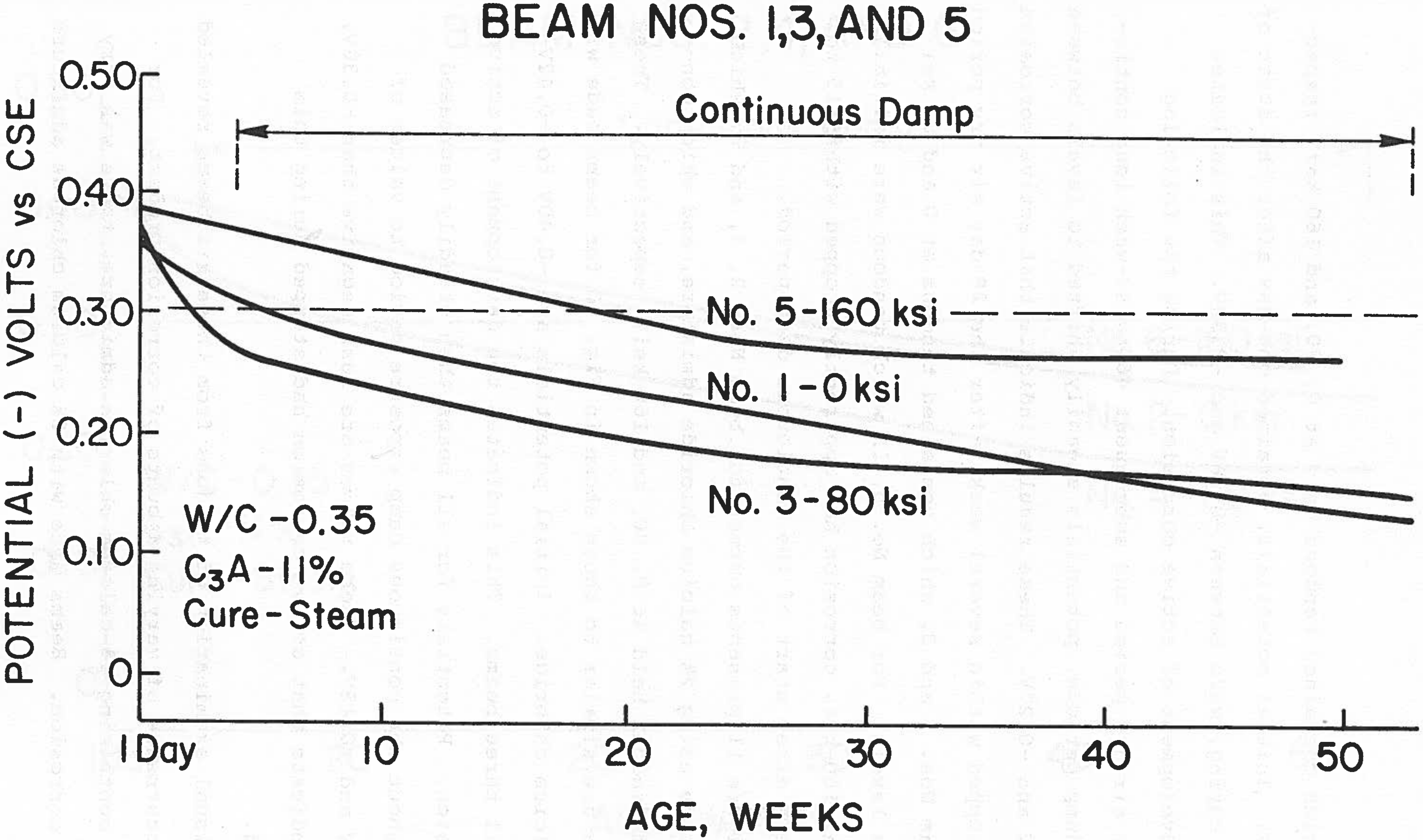

Fig. 10 - Potential curves for beams made with 1% calcium chloride admixture and containing steel at different stress levels.

and which contained tendons held at 0, 80, and 160 ksi, respectively. Initial potentials, obtained one day after the start of steam curing, were between -0.36V and -0.39V. This indicates the development of active corrosion. During the following 28-day air dry period and subsequent 46 to 49-week long continuous damp periods, potentials steadily shifted to levels between -0.14V and -0.27V. These results indicate that active corrosion had stopped within several weeks after the 28-day air dry period in beam Nos. 1 and 3, which contained tendons at 0 and 80 ksi stress levels. For beam No. 5, in which tendons were initially held at 160 ksi, corrosion had apparently stopped within 15 to 20 weeks after start of the continuous damp period.

Figure 11 presents curves for beam Nos. 2, 4, and 6, which were made using 2% calcium chloride admixture, and which contained tendons held at 0, 80, and 160 ksi, respectively. These curves are similar to those shown in Fig. 10 for beams made with 1% calcium chloride. Initial potentials are -0.40V to -0.42V for all three beams. This indicates the development of active corrosion. Potentials for all beams then steadily decreased throughout the continuous damp exposure period to values of -0.24V and -0.18V. These values are less negative than -0.30V, and indicate that active corrosion had stopped during this period.

Visual examination of tendons from these six beams revealed the occurrence of varying amounts of corrosion product. For beams containing 1% calcium chloride admixture, there was very minor corrosion. Beams made with 2% calcium chloride admixture

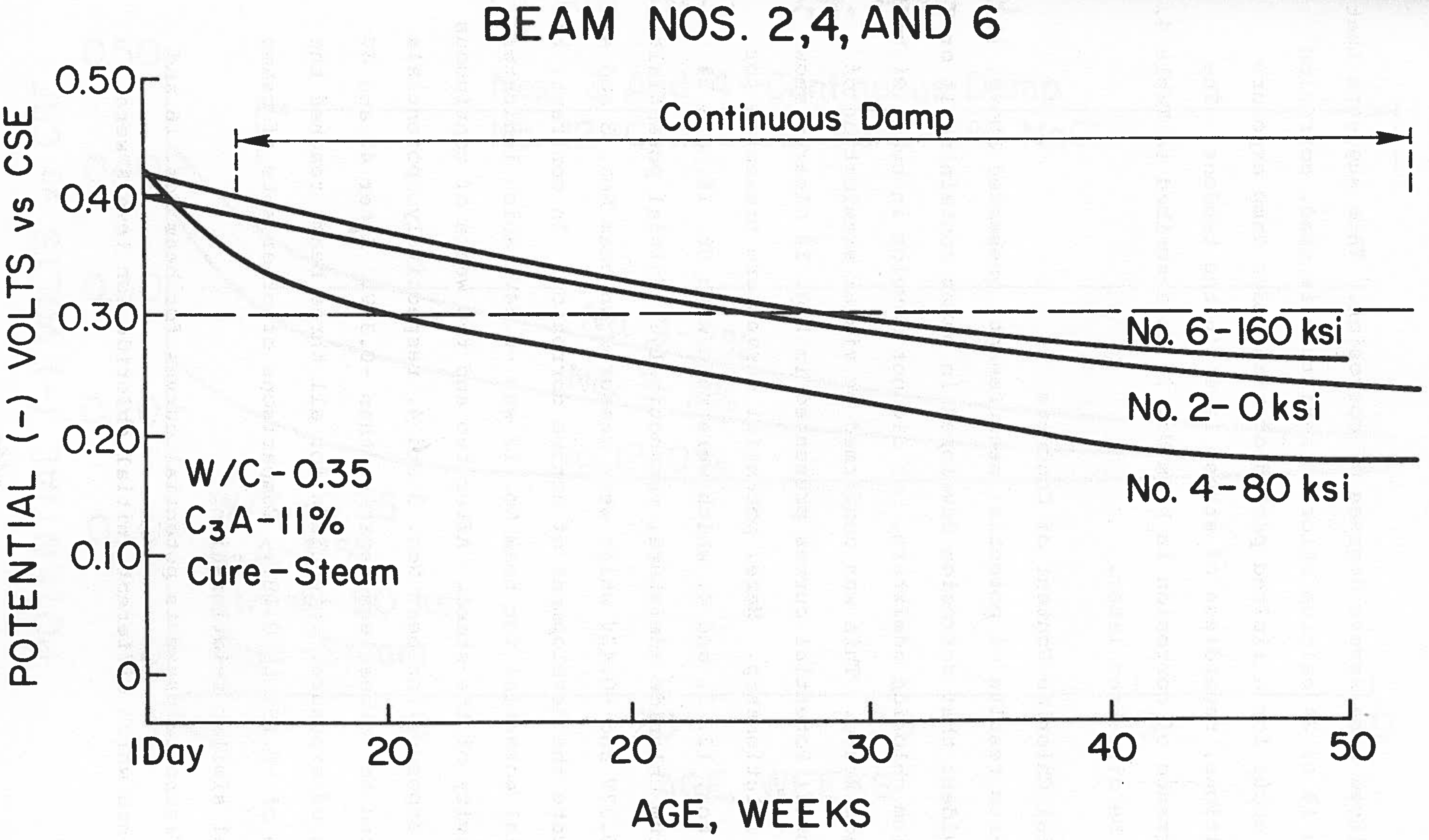

Fig. 11 - Potential curves for beams made with 2% calcium chloride admixture and containing steel at different stress levels.

displayed more severe degrees of corrosion. This suggests that, where 1% or 2% calcium chloride admixture is used, corrosion will occur for a limited period of time under damp exposure conditions, regardless of stress level in the tendons. The occurrence of corrosion in beam No. 2, as described in Table 4, will be discussed later.

Initial Chloride Content of Concrete

From results of potential measurements presented above, it is evident that corrosion developed in beams containing 1% or 2% calcium chloride admixture, but did not develop in beams without the admixture. This was confirmed by visual examination of tendons. Potential curves presented in Fig. 12 clearly show this relationship. Here, potential curves are presented for beam Nos. 12, 3, and 4, which were made with 0%, 1%, and 2% calcium chloride admixture, respectively. Initial potentials of -0.37V and -0.42V which were measured on beam Nos. 3 and 4, indicate the development of active corrosion. In contrast, the initial potential for beam No. 12 was -0.24V, which indicates passivity of the steel. After two and ten weeks of continuous damp exposure for beam Nos. 3 and 4, respectively, potentials shifted to values less negative than -0.30V. After 43 and 47 weeks of exposure, potentials for all three beams reached the range of -0.15V to 0.18V. Comparisons of other sets of beams reveal similar relationships.

Figure 13 presents potential curves for beam Nos. 16 and 18, into which different initial chloride ion levels were

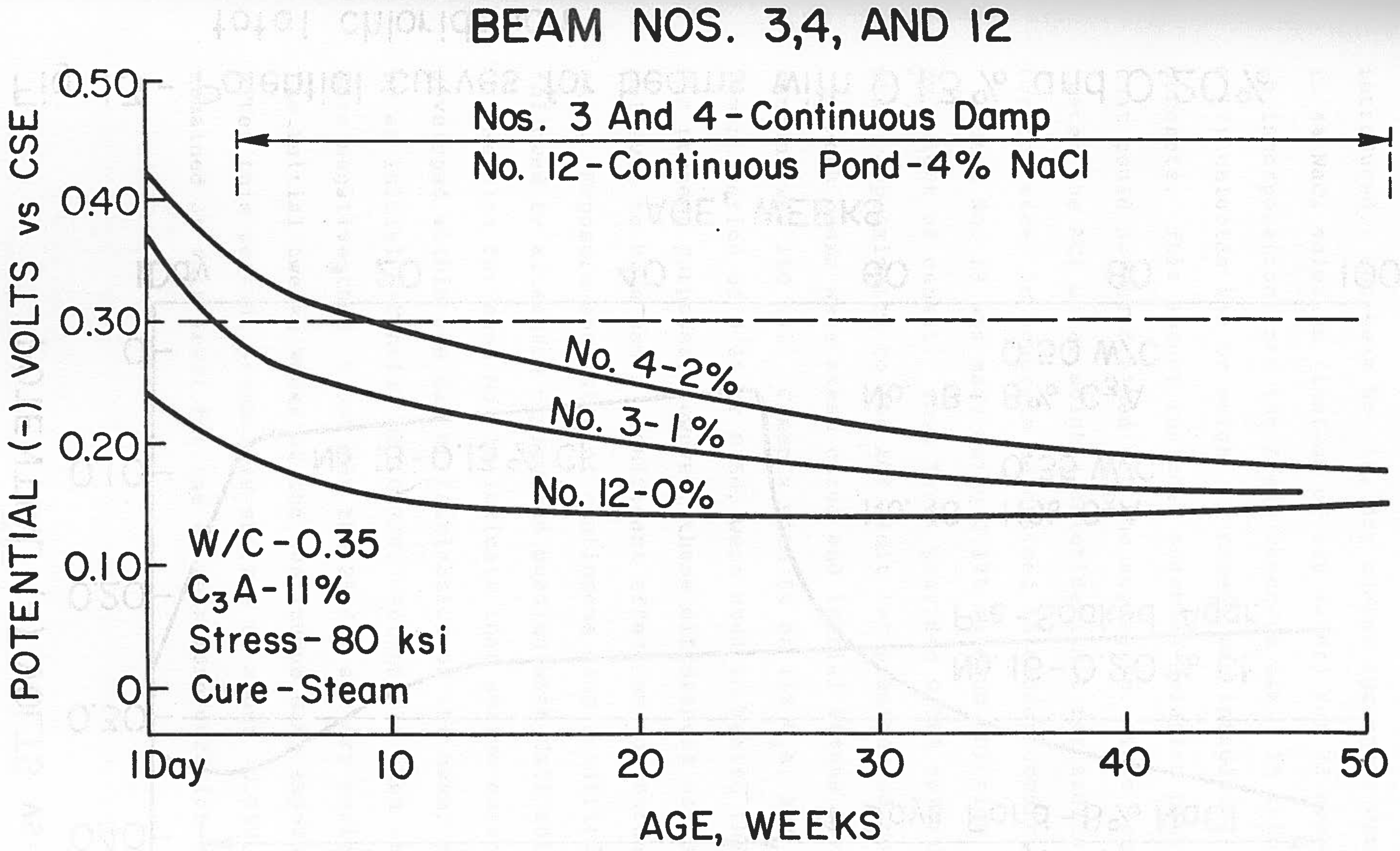

Fig. 12 - Potential curves for beams made with 0, 1, or 2% calcium chloride admixture.

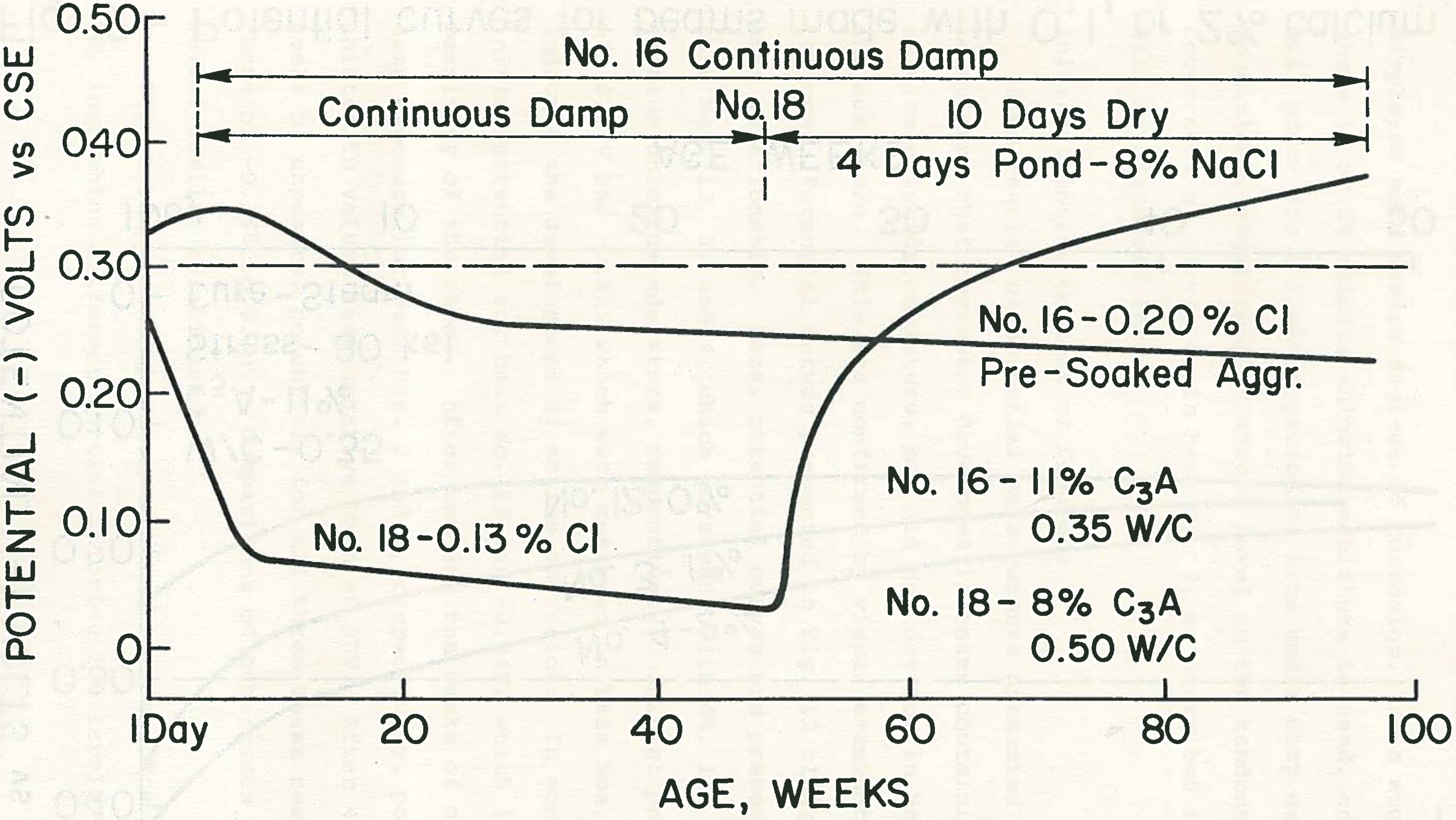
BEAM NOS. 16 AND 18

Fig. 13 - Potential curves for beams with 0.13% and 0.20% total chloride ion.

introduced. For beam No. 16, dry coarse aggregate was immersed in 4% NaCl solution (instead of tap water) for 72 hours prior to incorporation into the fresh concrete mix. In this manner, 0.17% chloride ion by weight of cement was introduced into the concrete. This amount includes absorbed solution plus excess that could not be drained off the aggregate. This level approximates the ACI water soluble chloride limit for ordinary reinforcing steel in concrete maintained in a damp condition.

Beam No. 18 was made using 0.17% calcium chloride admixture by weight of cement. This level provided 0.08% chloride ion, which approximates to the ACI limit for prestressed concrete.

Both beams were steam cured and initial stress level in the tendons was 160 ksi. Cements with 8% or 11% C_3A, and water-cement ratios of 0.35 or 0.50, were used in making the beams. For present purposes, however, these differences are not believed to have had a significant effect on corrosion resistance. Exposure consisted of continuous damp conditions, followed by alternate drying and ponding with NaCl solution.

Results for beam No. 16 indicate that active corrosion developed within one day of fabrication of the beam, as revealed by an initial potential of -0.33V. Potentials then remained more negative than -0.30V for the 28-day air dry period, and for the initial twelve weeks of the continuous damp exposure period. After this period, potentials shifted to about -0.25V, and remained at this level for the 80-week long duration of testing.

This shift indicates that active corrosion had stopped and that tendons remained in a passive condition. Examination of tendons from this beam confirmed that active corrosion, albeit very slight, occurred in this beam. Thus, it is seen that, at about the ACI limit for ordinary reinforcing steel, chloride ion absorbed by the coarse aggregate, plus some excess, can induce active corrosion of prestressing tendons in concrete.

The curve for beam No 18, also shown in Fig. 13, indicates that active corrosion did not develop either during the steam curing period or during the subsequent 28-day air dry and 46-week continuous damp periods. This is indicated by the initial potential of -0.26V, followed by the shift to a potential of -0.03V. Thus, these data indicate that an initial total chloride ion content of 0.08%, which corresponded to the ACI water soluble chloride limit of 0.06% by weight of cement, did not induce active corrosion of tendons in this beam. Results during subsequent exposure of this beam will be discussed in the following section.

Test Exposure Conditions

Several different exposure conditions have already been described in the above discussion of materials variables in this program. Thus, with few exceptions, data shown in Figs. 3 through 13 will not be described again to specifically evaluate the effects of exposure conditions on corrosion. However, effects of selected conditions are described below.

The effect of prolonged drying, at 73±3°F and 50±5 of RH, on corrosion of prestressing tendons is indicated in Fig. 14 by

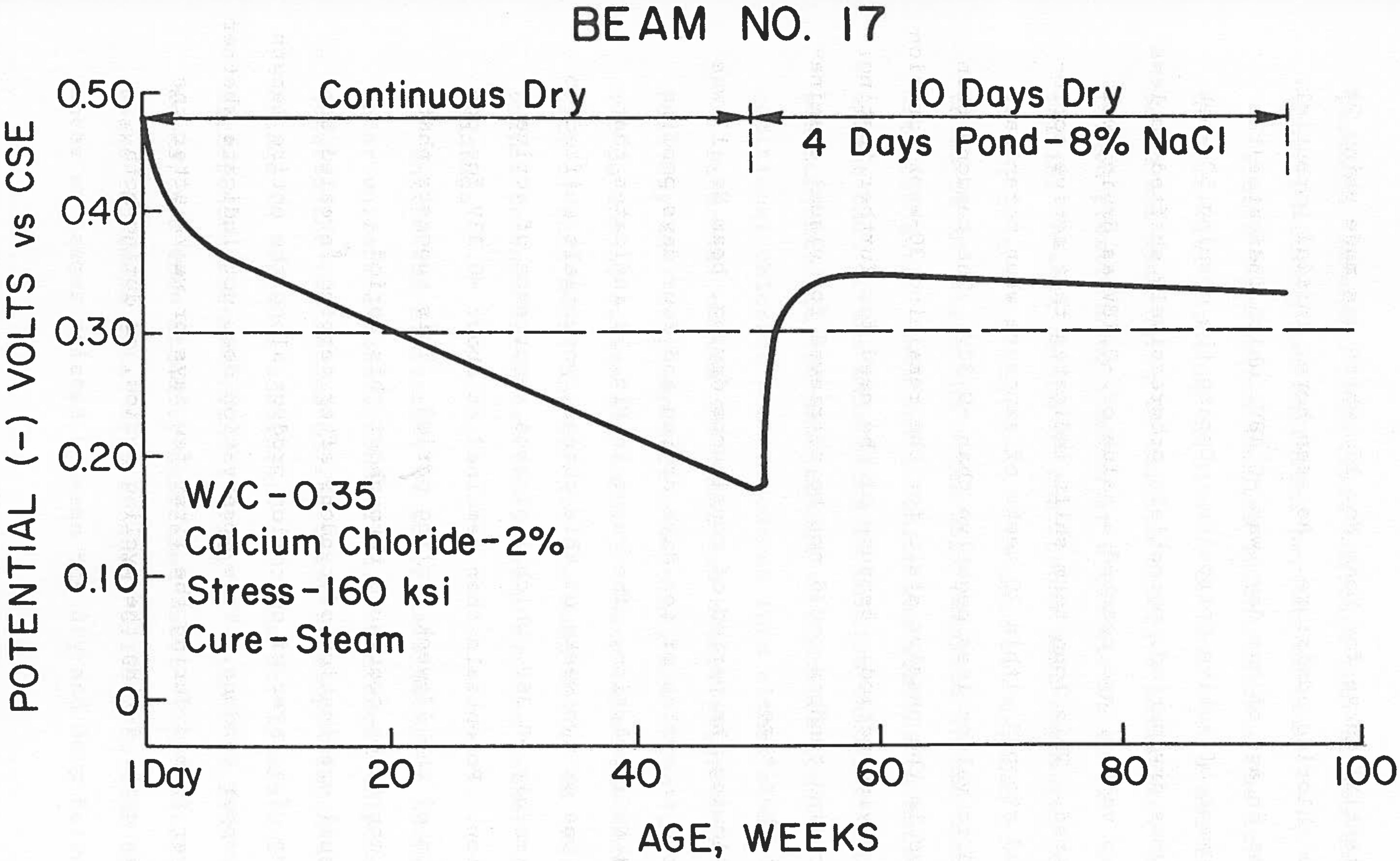

Fig. 14 - Potential curve for beam subjected to 50 weeks of drying followed by alternate ponding and drying.

the potential curve for beam No. 17, which was made using 2% calcium chloride admixture. As seen here, initial potential, taken at an age of one day, was -0.48V, which indicates the development of active corrosion. During the ensuing 50-week continuous dry period, potentials progressively shifted to less negative values, and reached a value of -0.18V as drying was terminated. This long term shift indicates that active corrosion had stopped within 20 weeks of exposure when potentials dropped to values less negative than -0.30V. The tendons then remained in the passive state for the remaining 30-week duration of the drying period. Because of the need for further testing, prestressing tendons could not be retrieved for visual examination at that time.

Following the period of continuous drying, beam No. 17 was subjected to cycles of ten days drying and four days ponding with 8% NaCl solution. The curve in Fig. 14 indicates that within one or two weeks of this change, potentials shifted to approximately -0.35V, which indicates recurrence of active corrosion. Potentials then remained at about -0.33V for the duration of the 42-week cycling period. This suggests that active corrosion continued throughout this period.

Visual examination of tendons after testing revealed the presence of a layer of corrosion product along the entire length of the upper tendons. This observation does not indicate whether the layer formed during the first few days or weeks after the beam was cast, during the cycling period, or during both periods. However, potentials indicate that active corrosion occurred during two different periods of time.

Figure 15 presents results which indicate the influence of differential exposure conditions on beam Nos. 1 and 2. Beam No. 2 was made using 2% calcium chloride admixture, and contained prestressing tendons at 0 ksi stress level. After the initial 50-week period of continuous damp exposure, one half (6 ft) of the top surface of the beam was exposed continuously to 50±5% RH, while the other half remained in the continuous damp exposure. Beam No. 1, which was similar to beam No. 2, except that it was made using 1% calcium chloride admixture, was subjected to the same change in exposure conditions. No additional chloride was introduced into either beam.

Potential curves for these two beams, after change to the half dry-half damp exposure condition, are shown in Fig. 15. Two potential curves are shown for each beam; one for the dry half of each beam, and one for the damp half. In this figure, points on each curve are the average of nine rather than 18 readings.

Unlike the similarity of potentials measured along tendons under uniform exposure conditions, differences in potential between the two halves of the beams developed immediately after change in exposure condition. In beam No. 2, maximum potential differences reached 0.10V (-0.28V vs -0.18V) in five to ten weeks, and then steadily decreased until final potentials at 36 weeks (85 weeks total age) reached -0.15V. At that age, differences no longer existed between the dry and damp halves of the

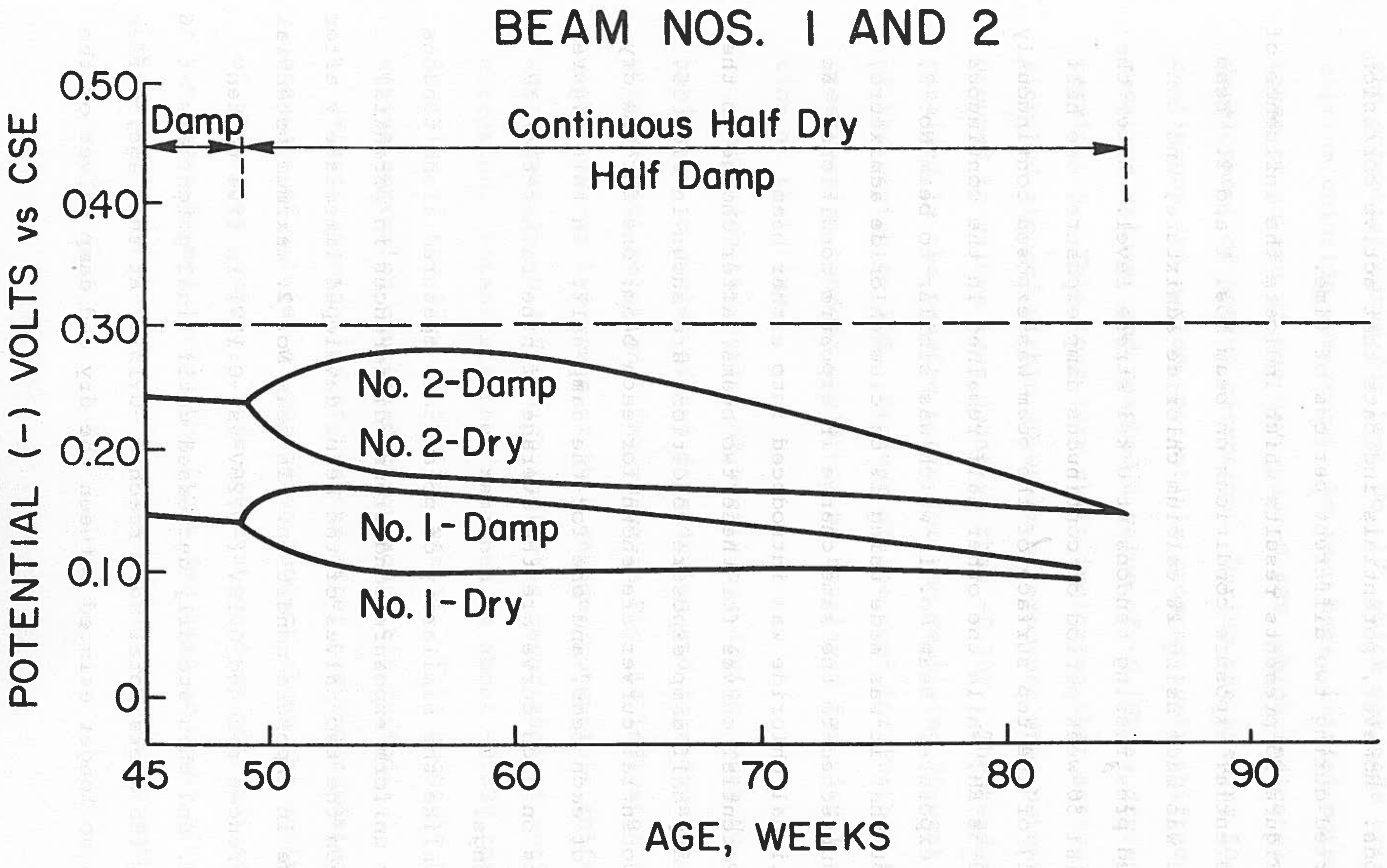

Fig. 15 - Potential curves for two beams subjected to continuous half dry-half damp exposure conditions.

beam. A similar pattern developed for beam No. 1, as shown in Fig. 15, except that maximum potential differences reached only 0.06V before decreasing to negligible differences after 34 weeks (83 weeks total age).

The meaning of these potential differences was found in visual examination of tendons from these beams. In addition to the few localized deposits of corrosion product present along the full length of tendons from beam No. 2, a heavier, continuous film of corrosion product was observed along only the six-foot lengths of tendon embedded in concrete exposed to the continuous damp condition. A similar layer of corrosion product was not seen along one half the lengths of tendons from beam No. 1.

Thus, it appears that when 2% calcium chloride admixture is used, prolonged periods of damp exposure followed by differential drying of the concrete can induce corrosion of prestressed tendons.

The effect, on development of corrosion in beams made with 2% calcium chloride admixture, of continuous damp exposure compared with continuous ponding with 4% NaCl solution immediately following the 28-day air day period is indicated in Fig. 16. Here, potential curves are shown for beam Nos. 6 and 15. After the initiation of corrosion within one day of fabrication, potentials for beam No. 6 steadily shifted to values less negative than -0.30V at an age of about 25 weeks, and reached a final value of -0.26V at 48 weeks. This curve indicates that active corrosion had stopped at least by the age of 25 weeks.

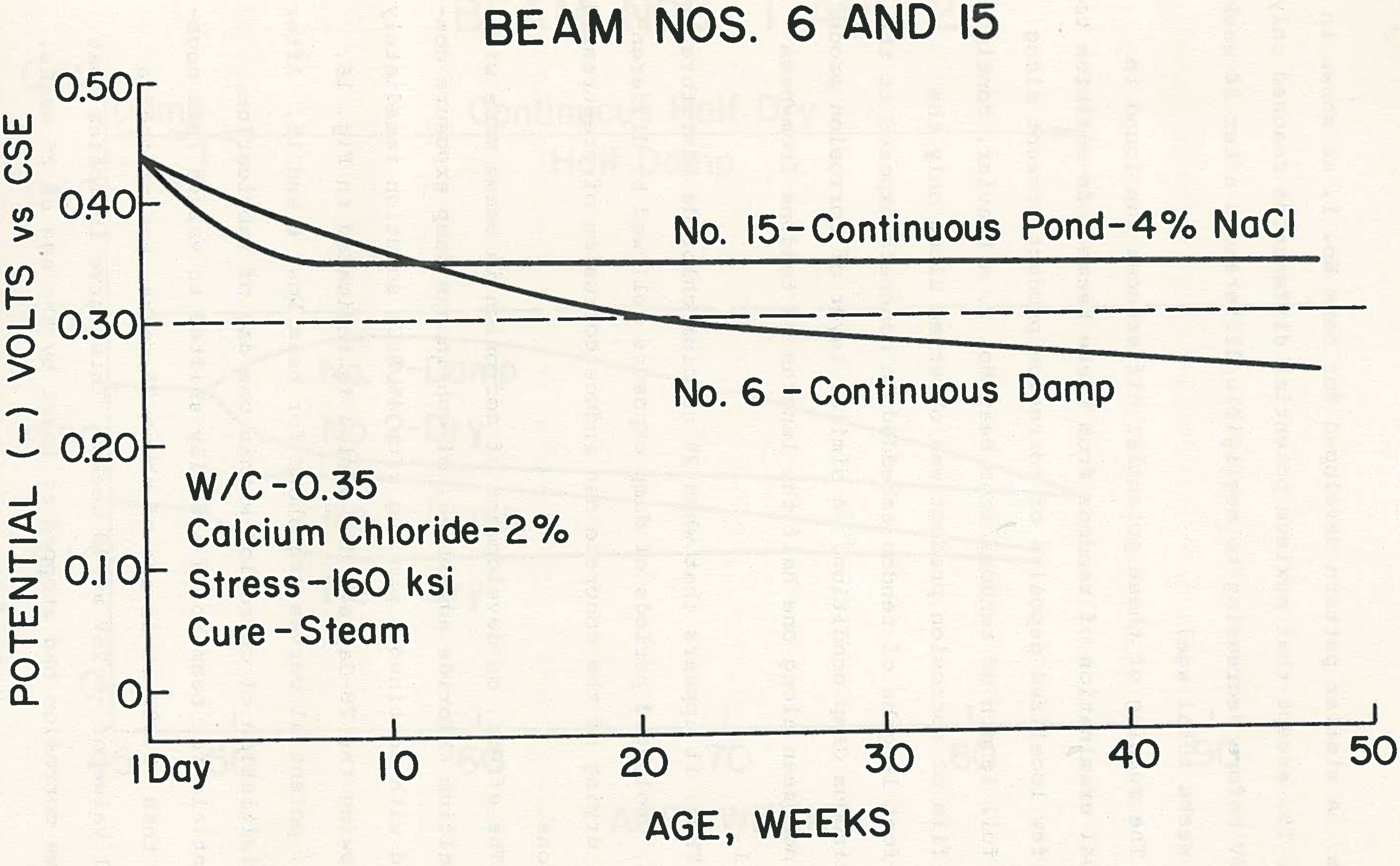

Fig. 16 - Potential curves for beams immediately exposed to moisture or ponded NaCl solution.

The potential curve for beam No. 15 indicates that active corrosion persisted for the duration of the 44-week ponding period. After an initial potential of -0.43V at one day, values shifted only to -0.33V at about seven weeks, and then remained at this level for the remaining 40 weeks of the ponding period. Visual examination of tendons revealed that more severe corrosion had occurred in beam No. 15 than in beam No. 6. This confirms the indications from differences in potentials for the two beams.

Additional exposure conditions, which have not yet been discussed, were imposed on all beams. As described earlier, direct metallic connections between the three lower tendons and upper tendon "A" were made in all beams except Nos. 10 and 15. This was done with the intention of increasing corrosion rates by increasing cathode to anode area ratios.

Review of the test data indicated that no differences developed between potentials for tendon "A" and for isolated tendons "B" and "C" that could be attributed to the change in cathode to anode area ratio. Any minor potential differences noted after the change were also present before the change. Thus, this change had no effect on corrosion rates in the upper tendons. Possible reasons for this behavior are discussed later.

After initial exposure, 1-1/2 in. diameter holes were drilled to tendons "B" and "C" at the midpoint of beam Nos. 10 and 15. These holes were temporarily filled with tap water and 4% NaCl solution, respectively, in the two beams. Electrical potentials were then read at 5-minute to 3-day intervals for ten days to determine maximum (most negative) potentials that could be reached, and the distances along the tendons which were affected by this localized ponding condition. Concrete cover over tendon "A" was left undisturbed.

Results for beam No. 15, on which NaCl solution was ponded, indicated that, within one foot of the holes, potentials on tendons "B" and "C" shifted from -0.33V to -0.44V in 30 minutes, and reached the extreme of -0.53V in two days. Once the solution was removed, potentials shifted to values in the range of -0.35V to -0.42V . With additional air drying, potentials shifted to values of -0.26V to -0.30V. During the period when potentials one foot from the drilled holes reached values more negative than -0.45V, maximum potential differences were 0.10V to 0.15V on tendons "B" and "C" between points five feet apart. As noted in data shown earlier for beam No. 2, potential differences of this magnitude appear to be sufficient to establish galvanic corrosion cells where there is sufficient chloride ion.

Although concrete cover over tendon "A" in beam No. 15 was not disturbed, potentials on this tendon also shifted to more negative values during the period in which NaCl solution filled the drilled holes. For this tendon the most negative value reached was -0.44V, which occurred on the second day. Potential differences reached a maximum of 0.12V. Thus, it appears that direct access of chloride solution to a given tendon resulted in potential differences of sufficient magnitude to initiate active corrosion on adjacent tendons not directly exposed to the chloride solution.

A similar test procedure was utilized in beam No. 10 to determine the effect on potential of direct access of deionized water to exposed tendons. Beam No. 10 was made with 2% calcium chloride admixture, and previously had been stored under continuous damp conditions. Again, concrete cover over tendon "A" was left undisturbed. Fifteen minutes after the drilled holes were filled with water, potentials on tendons "B" and "C" shifted from about -0.14V to -0.29V one foot away from the holes. This was the extreme reached during the ten days the holes were filled with water. Potentials on these tendons, at the ends of the beams, shifted only to about -0.17V, which resulted in potential differences, between points five feet apart, of up to 0.13V. Even though this difference existed between potentials less negative than -0.30V, similar results, shown in Fig. 15 for beam No. 2, indicate that such differences can be sufficient to drive corrosion cells where sufficient chloride ion is available. Thus, it appears that active corrosion could have redeveloped in beam No. 10 when water had direct access to the tendons, and sufficient chloride ion was present in the concrete.

Potentials for tendon "A" also shifted to more negative values during this 10 day test period. For this tendon, the extreme potential reached one foot from the drilled holes was -0.26V. Maximum potential difference between this point and the ends of the beam was 0.12V. Thus, about the same magnitude of potential difference developed on tendon "A", for which concrete cover was not disturbed, as on tendons "B" and "C". After the water was removed from the holes, potentials returned to the same levels that existed prior to the 10-day test period.

Thus, results for beam No. 10 also indicate that if sufficient chloride ion is present, localized direct access of water to the tendons can induce active corrosion, even in adjacent tendons where similar access is prevented.

The effects of exposure condition on development of corrosion, which were discussed in previous sections of this report, are summarized here as follows:

(1) Where 1% or 2% calcium chloride admixture was used, continuous damp exposure conditions did not sustain active corrosion which had developed within one day of fabrication of the beams.

(2) Damp and dry exposure cycles which followed continuous damp exposures did not reinitiate active corrosion which had developed during the steam or moist curing periods.

(3) With the exception of one tendon, continuous ponding with 4% NaCl solution following the curing period did not induce corrosion when calcium chloride admixture was not used.

(4) Alternate drying and ponding with 8% NaCl solution following continuous damp exposure, or ponding with 4% NaCl solution, did not induce corrosion when no chloride ion was added to the fresh concrete.

Chloride Content Measurements

Measurements of chloride ion content were also used to characterize performance of specimens during the test program. Of particular significance was chloride content at the level of the upper tendons. Both total and water soluble chloride contents were measured. Procedures used for these two determinations were described earlier.

The initial total chloride content of each concrete was determined from mix design calculations, and from measurements of chloride content of the aggregate, cement, and water prior to their use in making the concretes. Initial water soluble chloride contents were determined on representative powdered samples of concrete taken from 3-in. by 6-in. cylinders cast and cured with each beam. These cylinders were stored at 73±3°F and 50±5% R.H. for five to six months before they were sampled. Powder samples also were taken from the beams after testing was completed.

Table 5 summarizes results of initial and final chloride measurements. Data included are source of initial chloride added to the concrete mix, exposure conditions, and total and water soluble chloride contents before and after the period of testing. All chloride contents are expressed as percent chloride ion by weight of cement. Ratios of water soluble to total chloride contents are also shown in Table 5. In all cases, values have been corrected for differences in paste-aggregate ratios by averaging nonevaporable water contents. Measured concrete unit weights of 3950 and 3915 lbs per yd were used to

TABLE 5 - 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	$\frac{\text{Water}}{\text{Total}}$	Total	Water Soluble	$\frac{\text{Water}}{\text{Total}}$
1**	1%$CaCl_2$	Cont. Damp ⟶ 1/2 Beam Dry, 1/2 Beam Damp	0.51	0.45	0.89	0.53 0.54	0.41 0.50	0.76 0.92
2**	2%$CaCl_2$	Cont. Damp ⟶ 1/2 Beam Dry, 1/2 Beam Damp	0.99	0.93	0.94	0.93 0.87	0.58 0.70	0.62 0.81
3	1%$CaCl_2$	Continuous Damp	0.51	0.44	0.87	0.44	0.22	0.50
4	2%$CaCl_2$	Continuous Damp	0.99	0.92	0.93	0.86	0.65	0.76
5	1%$CaCl_2$	Cont. Damp ⟶ 10 Days Dry + 4 Days Damp	0.51	0.42	0.82	0.57	0.46	0.80
6	2%$CaCl_2$	Cont. Damp ⟶ 10 Days Dry + 4 Days Damp	0.99	0.88	0.89	0.85	0.67	0.79
7	2%$CaCl_2$	Continuous Damp	0.99	0.87	0.88	0.81	0.75	0.93
8	2%$CaCl_2$	Cont. Damp ⟶ 10 Days Dry + 4 Days Damp	0.99	0.83	0.84	0.81	0.54	0.67
9	2%$CaCl_2$	Cont. Damp ⟶ 10 Days Dry + 4 Days Damp	1.00	0.86	0.86	0.67	0.41	0.61
10	2%$CaCl_2$	Cont. Damp ⟶ Holes to Tendons + Water	1.00	0.88	0.88	0.66	0.54	0.82
11	None	Pond 4%NaCl ⟶ 10 Days Dry + 4 Days 8% NaCl	0.05	0.04	0.80	0.31	0.13	0.41
12	None	Pond 4%NaCl ⟶ 10 Days Dry + 4 Days 8% NaCl	0.05	0.04	0.80	0.17	0.09	0.55
13	None	Pond 4%NaCl ⟶ 10 Days Dry + 4 Days 8% NaCl	0.05	0.01	0.20	0.26	0.25	0.96
14	None	Pond 4%NaCl ⟶ 10 Days Dry + 4 Days 8% NaCl	0.05	0.05	1.00	0.43	0.36	0.83
15	2%$CaCl_2$	Pond 4%NaCl ⟶ Holes to Tendons + 4% NaCl	0.99	0.91	0.92	1.26	1.07	0.85
16	Aggr. Sat	Continuous Damp	0.20	0.17	0.85	0.17	0.13	0.75
17	2%$CaCl_2$	Cont. Dry 50% RH ⟶ 10 Days Dry + 4 Days 8% NaCl	0.99	0.87	0.88	1.27	1.19	0.94
18	0.17%$CaCl_2$	Cont. Damp ⟶ 10 Days Dry + 4 Days 8% NaCl	0.13	0.11	0.82	0.29	0.29	1.00
19	None	Pond 4%NaCl ⟶ 10 Days Dry + 4 Days 8% NaCl	0.05	0.05	1.00	0.17	0.12	0.69

* $CaCl_2$ refers to $CaCl_2 \cdot 2H_2O$.

**The first figure for final chloride content is for the dry end of the beam.
Total and water soluble chloride contents are expressed as precent by weight of cement.

convert percent chloride by weight of concrete sample to percent by weight of cement for the 0.35 and 0.50 water-cement ratios, respectively.

Data in this table reveal that there was an increase in chloride content of concrete at the level of the upper tendons in beams ponded with NaCl solution, as would be expected. Also, there was, with the unexplained exception of beam No. 5, a general decrease in chloride concentration in beams that had been maintained totally or partially in a dampened condition. This suggests that chloride ion migrated to the dampened surfaces of the beams, despite special efforts to maintain only a moisture film on this surface. Nevertheless, chloride contents in these beams remained well above levels considered necessary to induce corrosion.

Results in Table 5 also indicate that, initially, 85% to 95% of the total chloride in beams where calcium chloride admixture had been used was water soluble. Final chloride measurements, following the test periods, revealed that the percentage of chloride ion that was water soluble varied from 40% to 96%. In this case there was no consistent relationship between total chloride content and proportion of chloride that was water soluble. Also, there was no particular relationship between proportion of chloride that was water soluble and whether chloride was derived from calcium chloride admixture or ponded sodium chloride solution. Among beams that were made with calcium chloride admixture, all but one, No. 18, contained initial water soluble chloride ion contents greater than 0.40% by weight of cement.

Table 5 also presents separate data for the dry and damp halves of beam Nos. 1 and 2 after they were maintained under the two conditions. For beam No. 1, which was made with 1% calcium chloride admixture, 0.09 percentage points more water soluble chloride was measured in the damp end than in the dry end. For beam No. 2, the difference was 0.12 percentage points. However, it is believed that differences measured within these beams had little effect on corrosion. This was confirmed because differences were similar in the two beams, but corrosion appeared to have developed only in beam No. 2 under this condition.

Overall, data in Table 5 suggest that chloride content, by itself, may not necessarily determine whether active corrosion will occur on prestressing tendons in concrete.

Discussion of Results

Relationships summarized above can be explained by accepted electrochemical phenomena, and by factors known to affect corrosion processes. Pertinent background information and test results are discussed below.

Background Information

Anodic and cathodic electrochemical reactions must occur simultaneously at the surface of prestressing tendons to cause galvanic corrosion. Anodic reactions cause oxidation of metallic iron, while cathodic reactions result in reduction of dissolved oxygen to form hydroxyl ion. Sites of anodic reactions are visually recognizable by pitting of steel and by in-situ deposits of dark green, black, or rust colored corrosion products.

Oxidation of metallic iron at anodic sites is controlled by availability of oxygen for reduction at cathodic sites. Rate of corrosion is also partially determined by the size ratio of cathode area to anode area. Other things being equal, larger ratios result in higher corrosion rates.

The two electrochemical reactions must be coupled electrically before they can form a viable corrosion cell. Metallic prestressing steel serves as one link between electrodes of the electric circuit. The other is provided by moist concrete of relatively low resistivity which is present in the vicinity of the steel tendon. High moisture contents and dissolved substances in the concrete, such as chloride ion, reduce resistivity and more readily permit current flow between electrodes.

When prestressing steel is embedded in fresh concrete, a protective iron oxide film immediately forms on steel surfaces which inhibits further corrosion in high pH environments. Chloride ion can penetrate this film and disrupt its protective action. Anodic reactions at these sites can be viewed, statistically, as competition between chloride ion and hydroxyl ion. Once a certain threshold concentration of chloride ion is reached, corrosion cells can be sustained provided moisture and oxygen requirements are satisfied. Calcium chloride admixture, used in amounts sufficient to accelerate cement hydration reactions, and seawater contaminated aggregate, both supply chloride ion in amounts greater than the threshold concentrations.

As stated earlier, moisture and oxygen as well as chloride ion must be available to sustain corrosion processes. Both may be available either through their initial presence in the fresh concrete or through later diffusion from external sources through hardened concrete. In dry concrete, oxygen gas can readily diffuse into the concrete, and to prestressed steel, and upon rewetting of the concrete, dissolve into solution and be immediately available for cathodic reactions. In wet concrete, oxygen gas must dissolve into solution at the surface of the concrete and then slowly migrate inward to the steel under the driving force of a concentration gradient. Oxygen solubility is greatly reduced if chloride ion is present in solution, and may in fact become so low as to result in early termination of cathodic reactions.

Likewise, chloride solution can rapidly migrate into dry concrete by absorption through emptied capillary (and gel) pores in the concrete. In wet concrete, dissolved chloride must slowly diffuse through solution under the driving force of a concentration gradient. Differential oxygen and chloride concentration cells may be established at the surface of the steel and increase the probability of corrosion. The presence of a crack in concrete would promote such nonuniform concentration.

Sufficient moisture (solution) is also required in concrete to sustain electrochemical reactions. Moisture serves not only as a medium affecting transport of chloride ion and dissolved oxygen to the reaction site on the steel, but it also functions as the electrolyte in the corrosion cell. Drying of concrete therefore, removes electrolyte and increases the electrical resistivity of the concrete. Sufficient increase in resistivity may inhibit current flow to the extent of stopping corrosion.

Test Results

Most of the phenomena described above appear to have affected the corrosion resistance of prestressing tendons in the test beams. With this background information, results for specific beams can be more readily understood.

Electrical potential data for beam Nos. 1 to 10 indicated that active corrosion which developed within one day after casting was terminated during the subsequent damp exposure period. This suggests that sufficient chloride ion and dissolved oxygen were initially present in the fresh concrete to initiate active corrosion. Drying for 14 or 27 days immediately following curing would have increased the electrical resistivity of concrete, thus tending to inhibit corrosion. The subsequent presence of a moisture film and polyethylene sheeting on the top concrete surface then apparently prevented, or greatly inhibited, migration of additional oxygen to cathodic reaction sites on the steel. Thus, active corrosion could not be sustained under these exposure conditions, despite the presence of 0.80 to 0.90%, by weight of cement, of water soluble chloride ion at the level of the steel. The shift to less negative potentials indicates that increased resistivity was the predominant factor inhibiting corrosion.

With the minor exception noted earlier, corrosion also did not develop in beam Nos. 11 through 14, even after prolonged ponding with 4% and 8% NaCl solution. Results of analyses shown in Table 5 indicate that up to 0.36% water soluble chloride ion, by weight of cement, had reached the level of the upper tendons during the periods of ponding. If, indeed, sufficient chloride did penetrate to the tendon to otherwise induce corrosion, other factors must have served to inhibit it. These would include lack of dissolved oxygen in the concrete, high concrete resistivity, unusually uniform conditions along the tendons, or, most likely, combinations of the above factors. In any case, these results indicate that, under some circumstances, this level of water soluble chloride ion can be tolerated by prestressed tendons without development of active corrosion.

Results for beam No. 17 illustrate the effects of prolonged air drying followed by ponding with chloride solution. This beam was made using 2% calcium chloride admixture and, after steam curing, was exposed to 51 weeks of continuous drying at 50% RH. Active corrosion developed within one day of fabrication of the beam. This reflects immediate availability of moisture, chloride ion, and dissolved oxygen to sustain corrosion reactions. During the subsequent drying period, corrosion stopped, partially because of an initial lack of oxygen at the steel, but more importantly, because of loss of electrolyte, which would significantly increase electrical resistivity. With further drying, however, oxygen gas could more readily diffuse to the level of the steel so that upon rewetting, conditions, including high chloride ion levels already present, would be favorable for reinitiation of active corrosion. This was apparently the case when potentials shifted to values more negative than -0.30V within two weeks after ponding with chloride solution was begun.

Further evidence of the importance of environmental conditions can be seen in data for beam No. 2, which was made using 2% calcium chloride admixture. Again, active corrosion developed within one day of fabrication of the beam, but stopped during the following 49-week long continuous damp exposure period. Following this damp period, one half of the beam was allowed to air dry at 50% RH for 36 weeks while the other half remained in the continuous damp exposure condition. Visual examination of tendons revealed that corrosion recurred at this time because localized but extensive films of corrosion product had formed only along the portion embedded in the 6-ft long section of beam that was maintained under the continuously damp condition.

From these results, it appears that active corrosion could not be reestablished until additional oxygen became available to participate in cathodic reactions. Apparently, this could occur only after drying facilitated diffusion of dissolved oxygen to the steel tendons. Once this occurred, a corrosion cell developed in which the damp half of the beam became the anode and the dry half became the cathode.

The implication of this result is that differential moisture or drying conditions along prestressing tendons can induce active corrosion, provided sufficient chloride ion is also present.

In this regard, it should be noted that beam No. 1 which was made using 1% instead of 2% calcium chloride admixture, and was subjected to the same exposure condition, did not show similar recurrence of active corrosion.

Beams made with 1% or 2% calcium chloride admixture were also tested under cyclic drying and either wetting or ponding with sodium chloride solution following the continuous damp period. Neither of these conditions reinitiated corrosion even though relatively high levels of chloride ion were present at the level of the upper tendons. Apparently, increased electrical resistivity of the concrete and reduced availability of dissolved oxygen at the steel, inhibited further corrosion.

One beam, No. 18, was made using 0.17% calcium chloride admixture, which corresponded to the 0.06% water soluble chloride ion limit specified by ACI for prestressed concrete. Half-cell potential data indicated that corrosion did not occur during either fabrication and steam curing, or during the continuous damp period. In this case sufficient chloride ion was not present to initiate corrosion even though dissolved oxygen would have been initially present. After 45 weeks of damp exposure, the beam was alternately ponded with chloride solution and dried. At this time, potentials rapidly shifted to values more negative than -0.30V, which would indicate the onset of active corrosion. This shift was probably due to the rapid ingress of chloride ion since a 0.50 water-cement ratio, which would result in relatively higher permeability concrete, was used to make this beam. It is probable that dissolved oxygen was already available to react once sufficient chloride ion became available to induce corrosion. It is also possible that, because of relatively higher concrete permeability, additional oxygen could diffuse to the steel during intermittent drying periods.

Data for beam No. 16, for which coarse aggregate was presoaked in NaCl solution, are similar to those for beams made with 1% or 2% calcium chloride admixture. That is, an initial period of active corrosion developed, but stopped under drying followed by continuous damp exposure. This would again appear to reflect increased resistivity of the concrete and, to a lesser extent, depletion of dissolved oxygen at cathodic reaction sites. Thus, aggregate saturated with chloride solution of about the same concentration as seawater can introduce sufficient chloride to induce corrosion.

Moist curing for 14 days had little effect on the development of corrosion, compared with steam curing. As indicated by potentials for beam Nos. 13 and 19, corrosion failed to develop in either beam. Although twice as much chloride ion reached the level of the steel in the steam cured concrete, this amount apparently was not enough to initiate corrosion. Other factors may also have affected this result, as noted in other discussions.

Increasing the cathode to anode area ratio in 17 of the 19 beams appeared not to have any effect on corrosion, as indicated by potential readings and visual inspection of tendons. This was apparently due to the similiarity in concrete between and immediately surrounding upper and lower tendons. Where calcium chloride admixture was used, there was no "chloride-free" concrete such that lower tendons would be cathodic to upper tendons. Where ponding with NaCl solution was maintained on otherwise chloride-free concrete, sufficient chloride did not penetrate to the upper tendons to induce corrosion, thus precluding establishment of anodic sites, relative to lower tendons, for corrosion to occur. Only under differential conditions in the concrete would increased cathode to anode area ratios be expected to accelerate corrosion.

The remaining variables in this study had little or no effect on corrosion resistance. These include C_3A content of the cement and stress level in the steel. Also, water-cement ratio had little effect on initial corrosion resistance of tendons in moist and steam cured beams where 2% calcium chloride admixture was used.

From this work, an estimate can be made of minimum chloride concentration required to induce corrosion of prestressed tendons during and immediately following curing. The lowest water soluble chloride level measured which initiated corrosion during this period was 0.17% 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% or 0.06% by weight of cement. The latter concentration corresponds to the level permitted by ACI. Thus, the threshold level required to induce corrosion during and immediately following curing was about the same as the ACI permissible level of 0.15% for ordinary reinforcing steel in concrete subjected to a moist environment.

Further testing revealed that chloride levels required to induce corrosion at later ages were strongly dependent upon type of exposure condition. Under uniform drying conditions of 50% RH and 70 to 75°F, corrosion failed to develop in concrete containing 0.87% water soluble chloride ion by weight of cement. Most of this amount was introduced into the concrete through use of 2% calcium chloride admixture. Continuous exposure of companion concrete beams to uniformly damp conditions following curing and one month of drying also failed to sustain active corrosion. In contrast, exposure to non-uniform conditions, in which one portion of the concrete was exposed to drying and the other to moisture permitted development of corrosion. In this instance, 2% calcium chloride admixture had been utilized. Corrosion did not develop under similar exposure where 1% calcium chloride admixture had been used.

In beams made without calcium chloride admixture, ponding with 4% or 8% NaCl solution failed to induce corrosion, even though up to 0.36% water soluble chloride ion was present at the level of the upper tendons. Absence of active corrosion in these cases may have been due to a combination of several factors, including lack of dissolved oxygen, high electrical resistivity of concrete, and uniformity of environment along individual tendons. In any case, this chloride level is more than twice the minimum amount required to induce early corrosion when chloride ion was introduced into the fresh concrete with the aggregate.

Thus, it appears that a single permissible chloride level in concrete, above which corrosion is initiated, cannot be justified for all environments. In addition, concrete quality with particular emphasis on water-cement ratio, would appear to be a significant factor determining the corrosion resistance of prestressed tendons in concrete exposed to different in-service environments.

In this regard, it should be especially noted that 16 of the 19 beams in this program were made using 0.35 water-cement ratio. Concrete of this quality would inherently provide greater protection from corrosion than higher water-cement ratio concretes because of reduced permeability and increased electrical resistivity. Undoubtedly, prestressing tendons in concrete made with higher water-cement ratios would have revealed greater evidence of active corrosion under exposure conditions where none developed in the beams tested in this program.

SUMMARY

This research program consisted of a two-phase investigation into factors which affect the corrosion resistance of prestressing tendons in concrete. In one phase, responses to a questionnaire survey of producers of prestressed concrete disclosed very few apparent cases of corrosion of prestressing steel in concrete where calcium chloride had been used as an admixture. Most corrosion problems that were reported apparently resulted from exposure to chloride solution in the in-service environment. None of the responses indicated plans to use calcium chloride as an admixture in future production.

The second phase consisted of laboratory evaluation of corrosion resistance of prestressing tendons in 12 ft-long concrete beams containing different chloride levels and subjected to different exposure conditions.

Results of this work reflected the importance of the combined availability of chloride ion, moisture, and dissolved oxygen in initiating and sustaining active corrosion of prestressing tendons in concrete. Chloride ion introduced by the use of 1% or more calcium chloride admixture invariably led to development of active corrosion by the end of the steam curing period. Chloride introduced with coarse aggregate saturated with sodium chloride solution at the concentration equivalent of seawater also induced corrosion in that time period. However, corrosion failed to develop when 0.11% water soluble chloride ion was introduced into the fresh concrete. This is higher than the permissible level specified by ACI. Corrosion also failed to develop where ponding introduced as much as 0.36% water soluble chloride ion, by weight of cement, at the level of the tendons in the concrete.

Drying immediately following curing appeared to have been a primary factor inhibiting corrosion. This was evidenced by shifts in potentials to values less negative than -0.30V where 1% or 2% calcium chloride admixture had been used. Potentials remained in this less negative range during the subsequent damp exposure periods, thus indicating that concrete resistivity remained sufficiently high to inhibit corrosion for the duration of those periods.

Availability of dissolved oxygen at cathodic reaction sites also determined the time of initiation of active corrosion. This was particularly evident where 2% calcium chloride admixture had been used, and active corrosion developed only after different portions of the same tendon were subjected to continued drying at 50±5% RH, or to continued damp exposures. This being the case, oxygen depletion may also have been a factor, together with increased concrete resistivity, in inhibiting corrosion during prolonged periods of damp exposure over the full length of the beams.

Several other variables in this test program had little or no apparent effect on corrosion resistance. Increasing the cathode to anode area ratio by using direct metallic connections between upper and lower tendons did not increase severity of corrosion, as noted during visual inspection of tendons. This was probably due to the uniform condition of the concrete between these tendons, particularly with respect to distribution of chloride ion. Stress level in the tendon, C_3A content of the cement, and method of curing, also had little or no apparent effect on corrosion resistance.

It should be noted that most of these findings are based on tests of concrete beams made with low, 0.35, water-cement ratios. Concrete of this high quality will provide greater corrosion resistance for embedded prestressed tendons, primarily because of inherently lower permeability and higher electrical resistivity. Undoubtedly, corrosion would have been more severe under the same test conditions had higher water-cement ratios been used. However, low water-cement ratio concretes are commonly used in the prestressing industry because of the need for high strengths at early ages.

Test results indicate that a water soluble chloride level of 0.11% to 0.17% by weight of cement was required to induce corrosion during and immediately after curing. However, at later ages, type of exposure condition to which the concrete is subjected is decisive in determining whether galvanic corrosion will occur, even in concrete where 2% calcium chloride admixture, by weight of cement, had been utilized.

CONCLUSIONS

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

1. Calcium chloride is not used today as an admixture in making prestressed concrete members.
2. Most occurrences of corrosion of prestressing tendons were reported to have developed under conditions where the concrete was exposed to external sources of chloride ion.
3. 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%, by weight of cement.

4. The threshold water soluble chloride level above which corrosion occurs at later ages depends on environmental conditions to which prestressed concrete members are exposed.
5. Under certain uniform wetting or drying conditions, corrosion of prestressing tendons did not occur in high quality concrete made with up to 2%, by weight of cement, of calcium chloride admixture.
6. Wetting and drying cycles, and differential drying within a prestressed concrete member, induced corrosion where 2%, by weight of cement, of calcium chloride admixture was used.
7. Lower water-cement ratios, as they influence moisture, chloride, and oxygen diffusion through concrete, provide greater corrosion resistance under differential or cyclic exposure conditions than higher water-cement ratios.
8. Stress levels in prestressing tendons, C_3A content of cement, method of curing, and increased cathode to anode area ratios had little or no effect on corrosion processes.
9. Additional research is needed to more precisely define threshold chloride levels, above which corrosion occurs in different water-cement ratio concretes exposed to different wetting and drying environments.

SIGNIFICANCE OF FINDINGS

This study demonstrated that development of active corrosion of prestressed 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% 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% 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 have greater impact on corrosion processes than cement composition, curing method, or 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, on the basis of this study, that the permissible water soluble chloride ion content in prestressed concrete not exceed 0.10% by weight of portland cement.

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APPENDIX

QUESTIONNAIRE

Past Manufacturing Operations

1) Have you used calcium chloride as an admixture in prestressed concrete during the following time periods:
   a) Past 1 to 5 years? Yes _____ No _____
   b) Past 6 to 10 years? Yes _____ No _____
   c) More than 10 years ago? Yes _____ No _____

2) Which of the following factors were considered in whether to use calcium chloride?
   a) Stress level in steel tendons Yes _____ No _____
   b) Type of curing Yes _____ No _____
   c) Time of year concrete unit was manufactured Yes _____ No _____
   d) Cement composition or ASTM type Yes _____ No _____
   e) In-service exposure conditions of concrete unit Yes _____ No _____
   f) Other - list

   List combinations, if any, of above factors that might have been considerations for use of calcium chloride.

3) At what dosage rates (e.g. percent by weight of cement) was calcium chloride added?

Exposure and Performance

1) Have you encountered instances where corrosion of prestressing steel in concrete has occurred;
   a) In concrete containing calcium chloride as an admixture? Yes _____ No _____
   b) In concrete that does not contain calcium chloride as an admixture? Yes _____ No _____

2) Indicate with the appropriate combination of letters the conditions present under which corrosion of prestressing steel has occurred in concrete, if at all, which was brought firsthand to your attention. (Example: AEG - calcium chloride in concrete mix, indoor exposure with humidity and temperature controls, concrete under constant load. This could represent exposed concrete elements in an office building.)

A) Calcium chloride in concrete mix.
B) No calcium chloride in concrete mix.
C) Outdoor exposure of concrete with alternate drying and direct contact with atmospheric precipitation.
D) Outdoor exposure of concrete with no direct contact with atmospheric precipitation.
E) Indoor exposure only, with humidity and temperature controls for human comfort (e.g. office).
F) Indoor exposures with alternate drying and high humidity (steam) conditions, or with no drying (e.g. industrial manufacturing).
G) Concrete under constant load.
H) Concrete under repetitive load.
I) Concrete steam-cured.
J) Seawater exposure.
K) Concrete exposed to outside source of chloride solution, other than seawater.

3) Refer to letter combination in No. 2 above and, where possible, list age of concrete when corrosion problem became apparent.

4) What was the evidence for corrosion in the above concrete units?

Present and Future Manufacturing Operations

1) Are you using, or do you plan to use calcium chloride in manufacturing prestressed concrete units?
Yes _____ No _____

2) Are there any types of exposure conditions where you are not permitted to use calcium chloride, in any dosage, as an admixture? Explain.

3) Are you using, or do you plan to use corrosion inhibitors, tendon coatings, or other means in your manufacturing operation to minimize or eliminate corrosion of prestressed steel in concrete? Explain.

pci

prestressed concrete institute

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