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Seven hundred and ten reinforced concrete blocks were partially submerged in a saturated sodium chloride solution. Based upon the test criterion that a sufficient quantity of concrete absorbed chloride causes the steel to change from a passive to an active or corroding half-cell potential, the test results were (1) increasing the cement factor, and (2) increasing the length of water curing increased the time an active half-cell potential. The steam curing of the concrete resulted in a reduction of the time to an active half-cell potential as well as a reduction in absorption as compared to just water curing. A test procedure used verified capillary action as the primary mechanism of water absorption. The chloride content of the concrete was determined. Of the three tested admixtures and corrosion inhibitors, only pozzolan appeared to result in a significant benefit even though this concrete had the greatest absorption and also the greatest drying shrinkage.

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HIGHWAY RESEARCH REPORT

CONCRETE VARIABLES AND CORROSION TESTING

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STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

NO. M&R HRB 635116-6

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration January, 1972

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STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY

RONALD REAGAN, Governor

DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS AND RESEARCH DEPARTMENT
5900 FOLSOM BLVD., SACRAMENTO 95819

January, 1972

No. M&R HRB 635116-6
FHWA No. D-3-11

Mr. R. J. Datel
State Highway Engineer

Dear Mr. Datel:

Submitted herewith is an interim report titled:

CONCRETE VARIABLES AND CORROSION TESTING

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Sincerely,

JOHN L. BEATON
Materials and Research Engineer

Attachment

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Abstract: Seven hundred and ten reinforced concrete blocks were partially submerged in a saturated sodium chloride solution. Based upon the test criterion that a sufficient quantity of concrete absorbed chloride causes the steel to change from a passive to an active or corroding half-cell potential, the test results were (1) increasing the cement factor, and (2) increasing the length of water curing increased the time to an active half-cell potential. The steam curing of the concrete resulted in a reduction of the time to an active half-cell potential as well as a reduction in absorption as compared to just water curing. A test procedure used verified capillary action as the primary mechanism of water absorption. The chloride content of the concrete was determined. Of the three tested admixtures and corrosion inhibitors, only pozzolan appeared to result in a significant benefit even though this concrete had the greatest absorption and also the greatest drying shrinkage.

Key Words: Corrosion, concrete, steel, admixtures, corrosion inhibitors, cement factor, chlorides, concrete curing, laboratory tests, electrical potential, passive potential, active potential, absorption

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The opinions, findings, and conclusions expressed in this report are those of the authors and are not necessarily those held by the Federal Highway Administration.

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CONCRETE VARIABLES AND CORROSION TESTING

INTRODUCTION

In 1957[1], the California Division of Highways reported on the causes of corrosion of steel in concrete. In 1963, an empirical equation[2] was developed from field and laboratory data for estimating the time to corrosion of embedded steel. This previous work indicated that additional data was required regarding the influence of curing, admixtures, and other concrete design variables when designing a structure for a specific maintenance-free life[2].

Based upon a literature survey, it was found that at least 15 different methods have been used for testing the corrosion of steel in concrete[3]. In general, some of the methods are:

1. Exposure to tidal water[4,5]
2. Normal outdoors[5,6,7,8,9,10]
3. Laboratory, high humidity[6,8,11,12]
4. Laboratory, low humidity[6,13]
5. Alternate immersion[6,12]
6. Alternate but partial immersion[14,15]
7. Variable salt, moisture, temperature[16]
8. Salt spray cabinet[17]
9. Partially covered with a wet towel[13]
10. Flow of water vapor[18]
11. Periodic spraying with salt water[18]
12. Immersed in water[12]
13. Partial immersion[9]
14. Dry cellar[19]
15. Impressed voltages[1]

In effect, the test method, per se, for obtaining precisely reproducible results even by the same investigator[20,21] has not been clearly established.

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In the selected partial immersion corrosion testing of the reinforced concrete blocks, there are two measures of the corrosion phenomenon. One is to measure the half-cell potential of the steel, and the other is to visually inspect the concrete for cracks that result from the rusting of the steel.

In a previous study[21], it was found that one could electrically measure a change from a noncorroding passive half-cell potential (no salt at the steel/concrete interface) to an active half-cell potential which occurs when there are sufficient chlorides present to cause corrosion of the steel. With proper instrumentation, it is less costly to measure the half-cell potential of the steel than to make periodic visual inspections for corrosion-caused concrete cracking, therefore, electrical measurements were used in this study as the sole criterion for the determination of the time to corrosion.

This study is a report on observations which were made on the effect of curing method, curing time, cement factor, admixtures, corrosion inhibitors, and the test method used to determine the influence of these variables on the time to corrosion when the concrete was partially immersed in a saturated sodium chloride solution.

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SUMMARY AND CONCLUSIONS

Absorption

Concrete absorption, per se, does not appear to be a direct measure of ability of concrete to inhibit or prevent corrosion of embedded steel. However, it may be valuable in evaluating similar concrete mixes. That concrete absorption, per se, is not necessarily related to the time to corrosion of the steel is illustrated by two conflicting test results which are (1) concrete absorption is reduced by increasing cement factor which increases the time to corrosion, and (2) concrete absorption is reduced by steam curing with a resulting decrease in the time to corrosion. Roughly, steam curing reduces volumetric concrete absorption by 0.3% (see Figure 4).

Concrete Sorption

A preliminary test of submerging one face of a concrete specimen in water was performed to confirm capillary action as the primary mode for transport of water into concrete. The concrete that had only one face in water absorbed nearly as much water as one that was entirely submerged. Therefore, capillary action must be a large factor in the movement of water into the atmospherically exposed area of concrete. In addition, the gain in weight of the concrete that is simply exposed to high humidity confirms the hygroscopic adsorption properties of concrete[26]. (See Figure 5.) In effect, because all concrete samples were considered water saturated at the beginning of the test, it is considered that the variations in test results due to concrete variables are probably most related to the desorption characteristics of the concrete.

Active/Passive Potential

The total time to that time when the half-cell potential of the steel changes from a passive to an active potential has been related to the total test period that it takes concrete to crack as a result of steel corrosion[21]. In this study, the mean

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passive or noncorroding half-cell potential of the steel was about -0.19 volt to a saturated calomel reference cell. The mean value for the active or corroding potential on the day that the active potential was detected was -0.36 volt, which continued to increase after four weeks of the measuring period to a mean of -0.49 volt. As indicated by this and a previous study[21], the half-cell potential of steel follows a normal statistical distribution, therefore, there will be no absolute value which will precisely define an active or passive potential. However, based upon the two studies, it appears that the values which have a lesser numerical value than about -0.22 volt to the calomel reference cell could empirically indicate a passive potential for about 95% of the measurements. Also, if the potential had a numerical value of greater than about -0.27 volt, then it could indicate an empirical active potential of the steel in approximately 95% of the measurements. The active potential does not indicate a rate of corrosion, merely that sufficient chloride is present to destroy the corrosion inhibiting or passivating effect of the concrete (see Figure 6.).

Cement Factor

In all of the testing, as the cement factor was increased, so was the time to corrosion of the steel. The results of a regression analysis roughly indicates that the addition of one sack of cement per cubic yard to the concrete mix will increase the time to an active potential of the steel by roughly 70% for both the water and the steam-plus-water cured concrete within the cement factor limits of 5 to 8 sacks per cubic yard. (See Figure 7.)

Length of Cure

Within the limits of the test, it was found that the length of water curing of the concrete had a pronounced influence on the time to an active half-cell potential of the steel. The longer the cure, the longer the time to corrosion, or an active potential. However, only a 6-sack concrete mix was tested for this variable. Therefore, the length of concrete curing time may have added or lesser influence on the time to an active potential depending upon the cement factor and even extended times of water curing beyond the test period of 32 days.

The regression analysis of the data indicated that by doubling the water curing time, the time to an active potential increased by 50% for both the water and the water-plus-steam cured concrete (see Figure 8).

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Water and Steam Curing

The steam curing of the concrete reduced the time to corrosion of the steel. With other variables equal, the regression analysis of the data indicated that the steam-plus-water cured concrete had a measured active potential of the steel in about 60% of the length of time for an all water cured concrete (see Figure 9).

Admixture-Inhibitors

In this study, hydrated lime and sodium benzoate were used as corrosion inhibitors, and pozzolan as a concrete admixture. The test results did not clearly indicate that the lime had a significant influence even though there was a small increase in the time to corrosion or active half-cell potential of the steel.

The use of sodium benzoate resulted in a marked increase in the time to corrosion. However, there was a significant reduction in mixing water requirements due to the entrainment and/or entrapment of air. Therefore, the overall benefit of sodium benzoate is questionable until it is compared to a plain concrete made with the same amount of mixing water.

Although there was an increase in mixing water required for a given slump, the addition of a calcined volcanic tuff pozzolan resulted in a significant increase in the time to corrosion. This effect was greatest when the concrete was steam cured. Based on the large coefficient of variation of the test results for the water cured concrete containing pozzolan, it is speculated that the apparent benefits of pozzolan may be increased with longer than the 28 days of water curing used for this particular test; i.e., give the water cured pozzolan and calcium hydroxide chemical reaction a chance to reach the same "maturity" of the steam cured mix (see Figure 10).

Concrete Shrinkage

The major significance in the 14-day drying shrinkage tests was the large increase in shrinkage of the concrete containing pozzolan. Perhaps a reduction of the shrinkage might be achieved by using a coarser sand and reproportioning the mix so as to reduce the mixing water requirements. (See Table 10.)

Chlorides in Concrete

The chemical analysis of the mortar at the interface of the steel

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and concrete showed a calculated concentration of 17.9 and 21.7 pounds of chloride in the mortar portion of a cubic yard of concrete for the water and steam cured concrete respectively. Based upon an assumed concrete absorption of 14% by volume, the evaporable water in the concrete could have contained a salt in solution at a calculated chloride concentration of about 9% by weight at the steel-concrete interface.

Batch Variations

An analysis of variance was calculated between the batches of the 6-sack, 28-day water and the steam-plus-water cured concrete that was batched all in one day versus those that were batched on a weekly basis.

For the steam cured concrete, the test results indicated there was no significance that could be related to the two procedures for the casting of the concrete blocks. However, there was a significant difference found for the moist cured concrete. It is speculated that for the moist cured concrete, the difference might be more related to the vagaries of the test itself as the difference between the means was about 22% of the 92-day average test time to active potential. This value of 22% of variation in the means should also be compared to the approximate 30% coefficient of variation of the "normal" testing without regard to batching effect.

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FABRICATION AND TESTING OF BLOCKS

The variables of concrete manufacture as used in this series of tests are shown in Table 1. The river run aggregate was 3/4-inch maximum and the gradation complied with the 1964 Standard Specifications of the California Division of Highways. The cement used was Type II, modified, low-alkali which also complied with the California specifications.

The reinforced concrete specimens were 4-1/2 inches wide, 2-1/2 inches thick, and 15 inches long. The No. 4 reinforcing steel was sandblasted and was cast in the concrete to provide a minimum of 7/8-inch concrete cover at any point. Figure 1 shows a typical corrosion test specimen.

Ten corrosion test specimens, two 6x6-inch cylinders and three 3x3x11-1/4-inch shrinkage bars, were cast from a single batch. Except for the test variations in batching, all concrete was batched in one day for each test variable. The ten corrosion specimens from one-half of each batch were then either water cured or steam-plus-water cured. Water curing was the complete submersion of the block in water at a temperature of approximately 72°F.

Specimens to be steam cured were subjected to approximately 16 hours at 138±5°F of steam curing, and then post cured in water for the length of time that related to that test variable of post water curing time. All steam cured specimens were allowed to stand in their casting mold for a minimum of 4 hours. In all cases, the specimens were steam cured on the day they were cast.

In all cases, the concrete slump was maintained at approximately 3-1/4±1/4 inches by adjusting the amount of mixing water. The vibration of the concrete was accomplished by placing the steel molds on a "Packer" type vibrating table.

After casting, the blocks were subjected to curing variables. In all cases, after the appropriate time of submerged water curing, the blocks were immediately transferred to the partial immersion tanks. Figure 2 shows the blocks in place in the tanks, and Figure 3 shows the data acquisition system that

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automatically obtained the half-cell potentials of the steel and also printed the results on tape.

The corrosion exposure consisted of partially immersing the blocks at an empirically selected depth of 3-1/2 inches on the 15-inch dimension, in a saturated sodium chloride solution, the steel reinforcement rod being in a vertical position.

The absorption tests were made in accordance with Test Method No. Calif. 538-A. Essentially, this test method first requires oven drying at 230±9°F for a minimum of three days and a continuation of drying until the concrete water loss is less than 0.05% by weight. Prior to soaking, the concrete is stored over night at room temperature. For the 6x6-inch absorption cylinders used in this test program, the approximate drying time would be 14 days. In soaking, the concrete is required to be submerged at least one inch below the surface of the water. The weight gain is recorded at approximately 1, 3, 5, 7, and 24 hours, and 2, 3, 8, 16, and 28 days. The weight gain versus time data is then plotted on log-log paper and the "best fit" of the weight gain curve at 28 days is either visually obtained, or calculated by a regression analysis. The weight gain is then computed and reported as percent by volume of the concrete.

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RESULTS

Absorption and Cure Method

The absorption values reported on Tables 2 and 3 were obtained by means of Test Method No. Calif. 538-A dated April 6, 1970. In Table 2, "28-day Concrete Absorption", the results are the values obtained after 28 days of soaking of the initially oven dried 6x6-inch cylinders. The results for three repetitive or cyclic tests are shown on Table 2. In Table 3, "28-day Absorption of Admixture-Inhibitor Concrete", the absorption values shown are the average for three cycles or repetitive tests of concrete absorption.

In Figure 4, "28-day Absorption of Steam versus Water Cure Concrete", the values shown are the average values for three cycles of absorption testing for each batch of concrete of the various cement factors. All concrete had 28 days of water cure prior to the absorption testing of the concrete.

When the data shown in Figure 4 were analyzed by the method of least squares, the following relationship was obtained:

$$A_S = 1.01\ A_W - 0.422 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Wherein: A_S = Absorption of steamed and 28-day water cured concrete, in percent of concrete by volume

A_W = Absorption of 28-day water cured concrete in percent of concrete volume

For this relationship of 20 pairs of values, the correlation coefficient was 0.9175, and the standard error of estimate was found to be 0.33%.

As indicated by the results for plain nonair-entrained concrete containing 5 through 9 sacks of cement per cubic yard, the provess of steam-plus-water curing reduces the 28-day concrete

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absorption value roughly by 0.3% by volume. However, as shown in Table 3, "28-day Absorption of Admixture-Inhibitor Concrete", in the case of the admixture pozzolan, steam curing did not result in a significant reduction in absorption.

Concrete Sorption

As a preliminary confirmation of the means whereby water is absorbed into concrete, 12 concrete blocks of 3x3x11-1/4-inch were cast of 3/4-inch maximum size aggregate. Originally, the blocks were moist cured for 7 days and measured for drying shrinkage. These blocks were on hand for a few years and for the purpose of confirmation, were reused in this test. However, all were subjected to the standard California Division of Highways absorption test, No. 538-A. After oven drying at 230°F, six of the room temperature, oven dried blocks were placed in a closed container so that the blocks were partially but horizontally immersed in water for 1/4-inch of depth. The other six blocks were also placed in the same container, but elevated above the water's surface so that they were only exposed to approximately 100% relative humidity.

The results of this test are shown in Figure 5, "Variables in Concrete Absorption of Water". As indicated by this figure, gain in weight by the initially oven dried concrete is neither contingent upon complete immersion, nor even upon being in direct contact with water. These results seem to confirm previous work[2] that indicated that the major control upon the movement of water into saturated concrete which results in a buildup in the concentration of chloride is the continued evaporation of the water from some part of the concrete surface into the atmosphere. Also, this recent work reaffirms previous work[2,22] that demonstrated that the major mechanism that controls the passage of water into good quality concrete is capillary and evaporation and not hydrostatic pressure as related to permeability measurements.

Half-Cell Potentials

The half-cell potential of the steel was referenced to a saturated calomel reference cell, and was normally measured thrice weekly with a data acquisition system of 10 megohms input impedance.

The normal trend of the half-cell potential behavior in this test is shown on Figure 6, "Typical Half-cell Potential of Steel in Concrete". As determined in a previous study[21], the half-cell potential of the steel abruptly changes from a passive to an

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active potential when sufficient chlorides come in contact with the steel to cause corrosion. This change in potential has been measured to have a rate of change of about 0.15 volt in three hours; however, this rate is not known to be an average rate of change.

As indicated in Figure 6, the passive, or noncorroding potential of the steel has a mean value of about -0.19 volt as referenced to the saturated calomel half-cell. In a previous study[21], the mean passive potential of 200 specimens was found to be approximately -0.11 volt and the potentials fall into a normal statistical distribution about the mean.

As shown in Figure 6, the mean change in potential at the time when it was observed, was from -0.19 volt to -0.36 volt to the calomel cell. With increasing time, the mean active potential continues to increase to average value of about -0.49 volt.

The value of an active potential on the day of observed change of -0.36 volt seems to compare fairly well with the previously observed value of -0.33 volt. However, in this study as well as another[21], it has been observed that the steel in about 5% of the test blocks would have the abrupt change from a passive potential of about -0.19 volt to an active potential of about -0.36 volt, and then drop back down to a passive potential. This phenomenon of shifting from passive to active potential for a small percentage of blocks would be repetitive or cyclic and has been observed in this and a previous study[21].

It was previously shown that the time to the active potential of steel in concrete that is partially immersed in a saturated sodium chloride solution is mathematically related to the time to concrete cracking due to corrosion[21]. As a result, this study did not include the test parameter of observing the surface of the concrete for cracks or rust stains. Visual observations not only have a questionable accuracy depending upon the observer, but it is a more time consuming and expensive procedure than is the measuring of half-cell potentials.

Effect of Cement Factor

In order to determine the influence of the cement content on the time to corrosion of the steel, concrete blocks were cast containing cement factors of 5, 6, 7-1/2, and 9 sacks per cubic yard. All concrete was water cured or post water cured for 28 days. The test results for the days to an active half-cell potential for this test variable is shown in Tables 4 and 5, and

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Figure 7, "Effect of Cement Factor on Time to Active Potential".

As shown in Figure 7, there is a significant difference in the time to an active half-cell potential of the steel depending upon the cement content of the concrete.

By the method of least squares, a regression analysis indicated the following relationship between cement factor and time to an active potential for the steam-plus-water cured concrete.

$$P_s = 0.157(C)^{3.34} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Wherein: P_s = days to an active potential, steam plus 28 days of water curing of concrete

C = cement factor in sacks of cement per cubic yard

For this relationship, the correlation coefficient was 0.910 and the standard error of estimate was 0.1306 Log_{10} for the 110 pairs of data.

When analyzing the data for the 28-day water cured concrete, a regression analysis indicated the following relationship:

$$P_w = 0.104(C)^{3.72} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Wherein: P_w = days to an active potential, water cured concrete

C = sacks of cement per cubic yard

For this relationship, the correlation coefficient was 0.8797 and the standard error of estimate was 0.1765 Log_{10} for the 130 pairs of data.

In order to determine the average "fit" between the water and steam-plus-water cured concrete, the data were combined by mathematically equating the water to the steam cured concrete by means of equation[8]. The result of this analysis was:

$$P_{ws} = 0.125(C)^{3.42} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

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Wherein: P_{WS} = days to active potential of mathematically combined water and steam-plus-water cured concrete

C = sacks of cement per cubic yard

For this relationship, the correlation coefficient was 0.8915, and the standard error of the estimate was 0.1504 Log_{10} for the 240 pairs of data.

Concrete Curing Time

In order to study the effect of the length of curing on the time to an active potential of the embedded steel, the concrete was subjected to water curing periods of 2, 4, 8, 16, and 32 days.

As shown in Tables 6 and 7, "Curing Time Study", and also Figure 8, "Effect of Concrete Curing Time on Time to Active Potential", the length of water curing time has a definite influence to the time to corrosion. The longer the curing time, the longer the time to an active potential.

By the method of least squares, a regression analysis was made to determine the effect of water curing time to the time to an active potential. For the concrete that was steam-plus-water cured, results of the analysis were:

$$P_S = 6.23(D)^{0.66} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Wherein: P_S = days to an active potential, steam-plus-water curing

D = days of post underwater curing

For this relationship, the correlation coefficient was 0.8165, and the standard error of estimate was 0.2014 Log_{10} for the 100 pairs of data.

The regression analysis for the time of water curing for the nonsteam cured concrete to the time to an active potential of the steel produced the following equation:

$$P_W = 6.0(D)^{0.90} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

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Wherein: P_W = days to active potential, water cured concrete

D = days of water curing

For this relationship, the correlation coefficient was 0.826 with a standard error of the estimate of 0.2651 Log_{10} for the 100 pairs of data.

In order to combine the effect of the two curing methods, the time to an active potential of the water cured concrete was corrected to that of the steam-plus-water cured concrete by the relationship shown in Equation 8.

The results of this analysis indicate that the influence of water curing time to the time of an active potential was:

$$P_{WS} = 6.1(D)^{0.78} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Wherein: P_{WS} = days to active potential, water and also steam-plus-water cured concrete

D = days of water curing

For this relationship, the correlation coefficient was 0.7894 with a standard error of estimate of 0.2603 Log_{10} for the 200 pairs of data.

Curing Method and Time
to Active Potentials

The average time in days to an active potential for the two curing methods is shown on Figure 9, "Water versus Steam Cured Concrete". By the method of least squares, a regression analysis indicated the following relationship between water and steam-plus-water curing to the time to an active potential of the steel:

$$P_S = 0.595\ P_W + 4.21 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Wherein: P_S = days to active potential, steam-plus-water cured concrete

P_W = days to active potential, water cured concrete

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For this relationship, the correlation coefficient was 0.9680, and the standard error of estimate was 18.1 days for the 40 pairs of averaged data points.

Admixture-Inhibitor Study

In a preliminary evaluation of using admixtures in concrete to forestall the time to corrosion of steel in concrete, three admixtures were selected.

Hydrated lime was added to the concrete mix at the rate of 2% and 4% by weight of the cement. Sodium benzoate, a reported corrosion inhibitor for steel in concrete[23], was added to the concrete mix at a dosage of 1% and 2% by weight of the cement, and pozzolan, a material that is reported to enhance some properties of concrete[24], was added at a rate of 15 and 30 pounds per sack of cement.

The pozzolan was a calcined volcanic tuff which was tested under ASTM C-618. All concrete used in the admixture-inhibitor study contained 6 sacks of cement per cubic yard and had a total underwater cure time of 28 days before corrosion testing.

The results of the days to active potential are tabulated in Tables 8 and 9, and shown graphically in Figure 10, "Admixture-Inhibitor Study".

Concrete Shrinkage

At the time the concrete corrosion specimens were batched, three each of 3x3x11-1/4-inch bars were cast to measure the 14-day drying shrinkage at 50% relative humidity and 73°F. As indicated in Table 10, without altering the ratio of coarse and fine aggregate, shrinkage of the concrete increased with increasing cement factor apparently because of the increase in mixing water. Also when pozzolan was added to the mix, there was an increase in drying shrinkage that was associated with an increase in mixing water needed to maintain constant slump.

When hydrated lime was added to the concrete mix, the mixing water and shrinkage was not significantly changed.

The addition of the corrosion inhibitor[23] sodium benzoate, did not result in a highly significant change in shrinkage. However, it is of interest that even with reduction in mixing water, the concrete containing sodium benzoate did not show any significant

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reduction in its drying shrinkage over the nonadmixture concrete. During the mixing of the concrete containing sodium benzoate, the "mix" was observed to have a "frothy" or "bubbly" appearance.

Chloride in Concrete

As an indication of the quantity of salt that could be absorbed by the concrete at the steel/concrete interface, 40 of the 6-sack, 2-day water cure blocks were analyzed for this factor. Half of these blocks were water cured for 2 days and the other half were first steam cured for about 16 hours and then post cured in water for two days.

Within 14 days after the reinforcing steel had a measured active half-cell potential, the blocks were mechanically split so as to expose the concrete mortar interface with the steel. Then the mortar, for a depth of about 1/16-inch, was mechanically removed for about a 3-inch length. This section of mortar would have been in that part of the concrete block which was immersed in the sodium chloride solution.

The concrete mortar was then chemically analyzed for chloride content and reported on the estimated basis that the sand/cement mortar portion of concrete would weigh 2040 pounds per cubic yard.

For the 20 water cured blocks, the absorbed chloride in the concrete at the mortar/steel interface had a calculated mean value of 17.9 pounds per cubic yard, with a standard deviation of 2.38 pounds per cubic yard for the 20 data points. In the case of the steam plus two days of post water curing, the mean chloride content at the mortar/steel interface was 21.7 pounds per cubic yard, and a standard deviation of 3.82 pounds per cubic yard for the 20 data points.

The computed chloride content of the concrete in this test is less than that found in bridge piles that were continuously submerged for about 40 years in sea water[28].

Batch Variations

An attempt was made to determine the influence, if any, of batching procedures on the corrosion test results.

In this test series, as shown in Tables 4 and 5, "Cement Factor Study", the 6-sack concrete was batched as follows:

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Series 1, concrete was batched at a rate of one batch per week; Series 2 concrete was all batched in one day. Each batch contained 10 blocks, of which one-half were water cured for 28 days and the other five were steam-plus-water cured.

By an analysis of variance[25], it was determined that for the steam cured concrete, there was an "F" ratio (for an "n" of 50) of 0.0671, which does not indicate there was any significance between the test results for the different batching procedures.

For the moist cured concrete, the analysis of variance was calculated to have an "F" ratio of 10.01 (for the 50 observations) whic is considered to represent a significant difference at the 95% confidence level as a result of the methods of batching.

In effect, the data show that batching methods both do and do not affect the results.

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DISCUSSION

Corrosion Testing

Although 15 different test methods have been identified, it might be well to discuss the differences in results that have been obtained in three separate tests with approximately the same 6-sack concrete mix and test method by the same laboratory[20,21].

In Study No. 1[20], the 6-sack nonair-entrained concrete blocks were fog cured for 14 days and then air dried by laboratory storage for 60 days, prior to partially immersing them in saturated salt solution. The average days to corrosion-caused cracking of these concrete blocks was 22 days.

In Study No. 2[21], the 6-sack concrete blocks were moist cured in a fog room for 7 days, stored in the laboratory under controlled conditions of about 72°F and 50% relative humidity for 10.5 months. These blocks were then subjected to varying depths of partial immersion in fresh water for about 5-1/2 months before being partially immersed in the saturated salt solution.

In Study No. 1, concrete cracking was observed after 22 days, while in Study No. 2, the time was 309 days -- a time ratio of 14 to 1 for about the same quality of concrete.

In comparing the two previous test results, it is apparent that the moisture content of the concrete immediately prior to partial immersion of the blocks in the salt solution was of great significance. In Test No. 1, the concrete had air dried for 60 days, and in Test No. 2, the concrete was saturated with fresh water immediately prior to the partial immersion of blocks. It is obvious that the partially air dried blocks could almost immediately absorb the salt solution, while the fresh water saturated blocks in Test No. 2 had to transpire some of the absorbed water before the salt water could enter the concrete by means of absorption. Also, as shown by this study, the influence of concrete curing time prior to testing was also of probable significance.

In this latest, or third test series, even though the concrete was saturated with fresh water immediately prior to the salt

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water exposure, the days to an active potential of the steel of the 6-sack water cured concrete varied from an average of 10 to 115 days, depending upon the length of water curing.

In addition to the variables of curing time and the initial moisture content of the concrete, in Study No. 1 it was observed that when the atmosphere was about 54% relative humidity, the length of time to corrosion-caused cracking of a 7-sack concrete increased by approximately 50% when the relative humidity of the atmosphere was increased to 95% - 97%. Therefore, it is apparent that corrosion testing of steel in concrete can revolve about two basic concrete parameters which are (1) absorption by a "dry" concrete, and (2) the combination of desorption by evaporation and absorption by capillary action of the aggressive water. Also, when considering desorption as a test parameter, it is obvious that the relative humidity of the atmosphere should be of significance.

Variation in Results

In Study No. 2, and even in this third study, the coefficient of variation in the time to corrosion is roughly 30 to 35%. A coefficient of variation of this magnitude has a great bearing on the number of samples that must be tested in order to determine if the test results are real or accidental. For example, at the 95% confidence level and a coefficient of variation of 35%, it could be expected that the average test value for two blocks could have a maximum error of the mean of about 55%. Therefore, if two samples were used for testing a variable, a difference in 50% in the average test time would look good on a chart, but it could just as well be an accident.

Chloride Accumulation

It is acknowledged that when the chloride-ion is either mixed with[1,11,18], or absorbed by the concrete[2,16,17,20, 27], this ion is primarily responsible for the overhwelming majority of the reported cases of corrosion of steel.

Although this study has directed a maximum amount of attention toward the influence of concrete variables on the time to corrosion of steel, only a minor amount of attention was directed toward the actual mechanism of chloride accumulations by absorption or desorption of water in the concrete.

For example, this study shows that concrete absorption per se, is not the single controlling mechanism for the time to corrosion. However, absorption seems to relate to concrete cement factor

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in this test which does relate to the time to corrosion. In a previous study[2], it was empirically determined that the quantity of water that evaporated out of concrete could be related not only to concrete composition, but also to the time to corrosion of the steel. It was assumed that chlorides which accumulated in the concrete by the process of water evaporation would leave a residual of salts.

In this regard, it was reported[28] that the computed concentration of chloride in concrete piling that was continuously submerged for approximately 40 years, was greater than that found in the sea water.

If this accumulation of chloride is by absorption and desorption by water vapor, then it would imply that water vapor can travel within a seemingly water saturated pile for the longitudinal distance of at least 10 feet[28]. Apparently there could be voids in concrete where there is free passage of water vapor even though the capillary pores are filled with water.

If the indicated mechanism of chloride accumulation in concrete can be confirmed, then laboratory corrosion testing can be directed toward controlling those variables which can cause misleading test results. And most importantly, the solution to economically preventing or forestalling the time to corrosion of steel in concrete can be determined in the laboratory rather than by viewing the cost of maintenance of structures.

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Table 1

Concrete Mix Variables

Cement Factor	Slump, Ins.	Air, %	Unit Wt., Lbs./C.F.	Mixing Water, Lbs./Cu. Yd. Gross	Mixing Water, Lbs./Cu. Yd. Net	Admixture Type & Dosage
6.00	3-1/4	1.9	153.1	329	286	None
5.99	3-1/4	1.7	152.1	339	298	Pozzolan, 15 lbs./sk.
5.99	3-1/4	1.7	150.4	363	325	Pozzolan, 30 lbs./sk.
6.00	3-1/8	1.8	153.3	324	282	Hydrated Lime 1.89 lbs./sk. (2%)
5.98	3	1.8	153.1	326	283	Hydrated Lime 3.76 lbs./sk. (4%)
5.96	3-1/4	4.9	149.4	301	269	Na Benzoate 0.94 lbs./sk. (1%)
6.04	3-1/2	4.9	149.1	302	260	Na Benzoate 1.88 lbs./sk. (2%)
5.02	3	2.3	151.5	333	289	None
7.51	3-1/4	1.7	154.4	322	282	None
9.01	3	1.6	154.7	334	297	None

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Table 2

28-day Concrete Absorption[1]

Batch	Cycle	Water Cure Sacks per Cubic yard 5	6	7-1/2	9	Steam and Water Cure Sacks per Cubic Yard 5	6	7-1/2	9
1	I	14.63	13.66	12.79	13.13	14.20	13.53	12.41	12.87
	II	14.74	13.79	12.80	12.95	12.34	13.66	12.57	12.92
	III	14.82	13.68	12.79	13.01	14.36	13.70	12.56	12.94
2	I	14.69	13.95	12.94	12.84	14.71	13.24	12.29	12.51
	II	14.84	14.12	13.09	12.84	14.86	13.48	12.52	12.68
	III	14.89	14.09	13.13	12.85	14.99	13.42	12.62	12.71
3	I	14.19	13.58	13.17	13.10	14.41	13.49	12.70	12.65
	II	14.31	13.68	13.11	13.08	14.53	13.63	12.81	12.73
	III	14.37	13.60	13.22	13.03	14.70	13.67	12.92	12.85
4	I	14.87	14.18	13.13	13.15	14.97	13.55	12.87	12.64
	II	14.77	14.15	12.98	12.95	14.81	13.55	12.84	12.66
	III	14.94	14.22	13.02	12.96	15.01	13.57	12.94	13.06
5	I	14.81	13.89	13.48	13.01	14.50	13.63	12.48	12.61
	II	14.81	13.93	13.38	12.89	14.67	13.76	12.68	12.80
	III	14.81	13.89	13.35	12.89	14.75	13.72	12.72	12.83
$\overline{X}$		14.700	13.894	13.092	12.979	14.654	13.573	12.662	12.764
σ		0.228	0.222	0.213	0.103	0.255	0.133	0.193	0.148
V		1.55%	1.60%	1.63%	0.79%	1.74%	0.98%	1.52%	1.16%

$\overline{X}$ - Mean, σ - Standard Deviation, V - Coefficient of Variation

Note: (1) Absorption is in percent of concrete volume

(2) All concrete cured under water for 28 days prior to absorption study

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Table 3

28-day Absorption[4] of Admixture-Inhibitor Concrete

	Pozzolan				Sodium Benzoate				Hydrated Lime			
	15 Lbs./Sk.		30 Lbs./Sk.		1%/Sk.		2%/Sk.		2%/Sk.		4%/Sk.	
Batch	Water	Steam	Water	Steam	Water	Steam	Water	Steam	Water	Steam	Water	Steam
1	14.97	14.94	16.86	16.97	12.66	12.56	13.05	13.23	13.77	13.33	13.97	13.77
2	15.40	15.14	17.25	17.15	13.09	12.37	13.36	12.61	14.07	13.88	14.13	13.69
3	14.99	15.11	17.11	17.60	12.59	12.18	12.74	12.47	13.73	13.64	13.90	13.51
4	14.94	15.03	17.14	17.10	13.39	13.06	12.39	12.01	13.63	13.75	14.23	13.87
5	15.11	14.95	17.08	17.13	12.46	11.81	13.47	12.87	13.75	13.79	13.95	14.20
$\bar{X}$, %	15.08	15.03	17.09	17.19	12.84	12.40	13.00	12.64	13.79	13.68	14.04	13.81
σ, %	0.189	0.091	0.143	0.240	0.389	0.463	0.445	0.455	0.166	0.213	0.138	0.256
V, %	1.25	0.60	0.84	1.39	3.03	3.74	3.42	3.60	1.20	1.56	0.99	1.85

$\bar{X}$ - Mean σ - Standard Deviation V - Coefficient of Variation

Notes:
1. All concrete contains 6 sacks of cement per cubic yard
2. All concrete cured under water for 28 days
3. Steam curing for 16 hours plus 28-day underwater curing
4. Absorption values are in percent of concrete volume

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Table 4

Cement Factor Study
Water Cure[3]

Batch	Days to Active Potential				
		6 sks./cu.yd.			
	5 sks/cy	Series 1*	Series 2*	7-1/2 sks/cy	9 sks/cy
1	49	104	107	287	394
	71	78	118	287	406
	39	32	98	369	362
	34	18	100	317	518
	56	67	77	53	394
2	38	55	63	132	416
	64	70	135	251	367
	62	80	152	276	388
	45	111	128	223	351
	35	146	128	199	388
3	56	62	93	201	553
	34	79	89	177	322
	41	62	40	177	488
	40	56	70	177	504
	56	79	55	208	399
4	54	54	114	316	316
	54	48	98	316	396
	26	48	131	176	512
	57	35	121	109	405
	54	61	61	232	316
5	29	118	110	213	307
	35	85	75	204	385
	35	84	30	206	276
	27	77	112	171	449
	31	97	91	66	68
6			137		
			110		
			96		
			77		
			103		
$\overline{X}$	44.9	72.2	97.3	213.7	387.2
σ	12.7	28.5	29.5	77.8	97.3
V	28.4	39.5	30.3	36.4	25.1

$\overline{X}$ - Mean σ - Standard Deviation V - Coef. Variation

Notes:
*1. Series 1, cast at one batch per week
*2. Series 2, all batches cast in one day
3. Concrete cured under water for 28 days

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Table 5

Cement Factor Study
Steam Plus Water Cure

Batch	Days to Active Potential				
		6 sks./cu.yd.			
	5 sks/cy	Series 1*	Series 2*	7-1/2 sks/cy	9 sks/cy
1	42	56	82	158	151
	41	71	77	326	393
	29	71	61	139	270
	48	64	91	174	286
	28	61	103	146	403
2	44	73	68	174	237
	20	62	49	129	181
	34	45	55	70	185
	31	50	61	120	185
	24	64	44	118	185
3	29	37	55	145	390
	33	44	61	166	210
	33	72	61	124	56
	40	58	68	135	194
	26	72	48	112	320
4	25	104	57	207	270
	54	64	70	124	253
	43	71	55	162	165
	33	39	55	188	272
	32	71	63	125	272
5			77		
			77		
			44		
			77		
			77		
6			34		
			72		
			48		
			51		
			65		
$\overline{X}$	34.5	62.5	63.5	152.1	243.9
σ	8.8	15.2	15.0	51.2	88.2
V	25.5	24.3	23.7	33.6	36.1

$\overline{X}$ - Mean, σ - Standard Deviation, V - Coef. Variation

Notes: *Series 1, cast at one batch per week
*Series 2, all batches cast in one day
After 16 hours of steam curing, concrete post cured under water for 28 days

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Table 6

Curing Time Study
Water Cure

Batch	Days to Active Potential				
	2 days*	4 days*	8 days*	16 days*	32 days*
1	9	21	29	58	115
	5	18	47	63	60
	23	41	83	47	129
	12	19	68	84	117
	8	24	50	72	103
2	5	3	26	47	101
	21	38	76	61	129
	12	31	48	63	138
	6	21	65	84	183
	26	24	65	69	80
3	5	59	42	86	117
	2	63	44	112	140
	22	74	48	55	154
	5	59	49	75	143
	55	59	48	91	109
4	19	40	38	44	122
	2	63	44	86	119
	5	38	55	91	61
	2	38	52	149	75
	5	27	52	84	109
$\bar{X}$	10.0	38	51.5	76.1	115.2
σ	7.8	19.2	14.2	24.7	30.5
V	78.8	50.5	27.7	32.4	26.5

$\bar{X}$ - Mean, σ - Standard Deviation, V - Coef. Variation

Note: 1. Moist cure is continuous submersion in water
2. All concrete contained 6 sacks cement per cubic yard

*Days of under water curing

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Table 7

Curing Time Study
Steam Plus Water Cure

Batch	Days to Active Potential				
	2 days*	4 days*	8 days*	16 days*	32 days*
1	23	56	23	55	94
	9	6	8	34	49
	6	10	28	22	53
	23	19	37	30	49
	7	4	12	29	56
2	13	10	29	61	53
	19	27	19	54	62
	12	21	33	28	72
	8	38	37	26	80
	8	14	33	23	89
3	5	18	20	40	70
	13	17	20	35	70
	9	11	28	33	63
	5	12	16	47	61
	5	35	28	34	59
4	19	10	21	51	52
	26	7	34	36	75
	13	7	16	55	59
	5	31	34	68	101
	13	19	29	55	52
$\overline{X}$	12	19	25	41	66
σ	6.7	13.1	8.5	13.7	15.3
V	55.4	70.5	33.5	15.3	23.2

*Days of under water curing

$\overline{X}$ - Mean σ - Standard Deviation V - Coef. of Variation

Note: 1. Concrete steam cure for 16 hours, then under water cure

2. All concrete contains 6 sacks of cement per cubic yard

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Table 8

Admixture-Inhibitor Study
Water Cure

	Days to Active Potential					
Batch	15 Lbs. Pozzolan	30 Lbs. Pozzolan	2% Lime	4% Lime	1% Sodium Benzoate	2% Sodium Benzoate=
1	387	67	90	120	193	174
	130	137	106	137	169	197
	485	139	82	69	151	172
	134	64	82	116	69	75
	61	67	67	75	71	145
2	55	62	143	87	141	185
	62	62	66	106	146	162
	66	561	77	70	188	181
	146	62	99	104	136	118
	174	62	77	62	176	92
3	54	62	89	119	147	168
	63	54	93	107	151	177
	58	53	56	62	177	257
	62	441	110	100	128	226
	62	54	98	86	161	243
4	46	477	148	85	109	237
	50	477	120	95	307	179
	46	48	129	29	151	218
	46	54	61	109	158	270
	319	57	134	124	57	61
5	475	69	69	106	120	188
	349	43	104	90	125	106
	225	69	84	111	141	120
	80	69	86	78	132	183
	69	77	106	69	55	84
$\overline{X}$	148	135	95	92.6	142	169
σ	141	160	25.2	24.6	51.4	57.3
V	95	118	26.5	26.6	36.1	34.0

$\overline{X}$ - Mean σ - Standard Deviation V - Coef. of Variation

Note: 1. All measures are by weight of cement

2. Concrete is 6-sacks per cubic yard and cured under water for 28 days

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Table 9

Admixture-Inhibitor Study
Steam Plus Water Cure

Batch	Days to Active Potential					
	15 Lbs. Pozzolan	30 Lbs. Pozzolan	2% Lime	4% Lime	1% Sodium Benzoate	2% Sodium Benzoate
1	281	566	49	54	95	88
	211	515	48	47	88	60
	172	517	50	71	75	75
	176	268	60	64	88	104
	274	71	69	54	137	67
2	195	265	55	55	101	70
	181	36	66	37	62	73
	164	220	64	55	101	35
	159	468	59	48	55	70
	97	48	50	64	64	66
3	177	516	51	84	89	96
	138	376	62	160	98	124
	170	247	75	58	126	107
	56	448	33	62	51	98
	247	322	58	62	54	151
4	26	316	55	39	179	190
	165	431	85	61	181	139
	190	272	64	57	151	176
	90	517	61	50	151	124
	218	57	43	61	83	134
$\overline{X}$	169	324	58	62	101	102
σ	65.3	174	11.5	25.3	40.2	40.8
V	38.5	53.8	19.9	40.7	40.8	39.9

$\overline{X}$ - Mean σ - Standard Deviation V - Coef. of Variation

Note:
1. All measures are by weight of cement
2. All concrete contains 6 sacks of cement per cubic yard
3. Concrete first steam cured and then post cured by submersion in water for 28 days

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Table 10

Concrete Shrinkage Results

Cement Factor	Admixture, Type and Dosage	14-day Drying Shrinage 3x3x11-1/4" Bars. % Shrinkage	Avg. of 3 Bars % Control
6.00	None	.023	100
5.99	Pozzolan 15 lbs./sk.	.033	143
5.99	Pozzolan 30 lb./sk.	.047	205
6.00	Hydrated Lime 1.89 Lbs./sk. (2%)	.025	109
5.98	Hydrated Lime 3.76 lbs./sk. (4%)	.025	109
5.96	Na Benzoate 0.94 lb./sk. (1%)	.027	117
6.04	Na Benzoate 1.88 lbs./sk. (2%)	.021	92
5.02	None	.021	92
7.51	None	.025	109
9.01	None	.030	130

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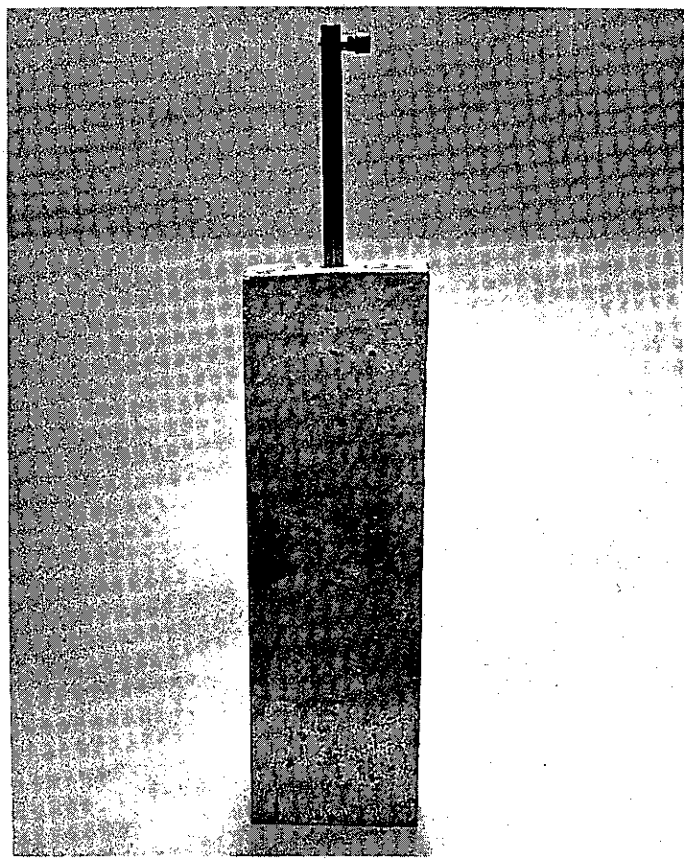

Figure 1

Corrosion test specimen

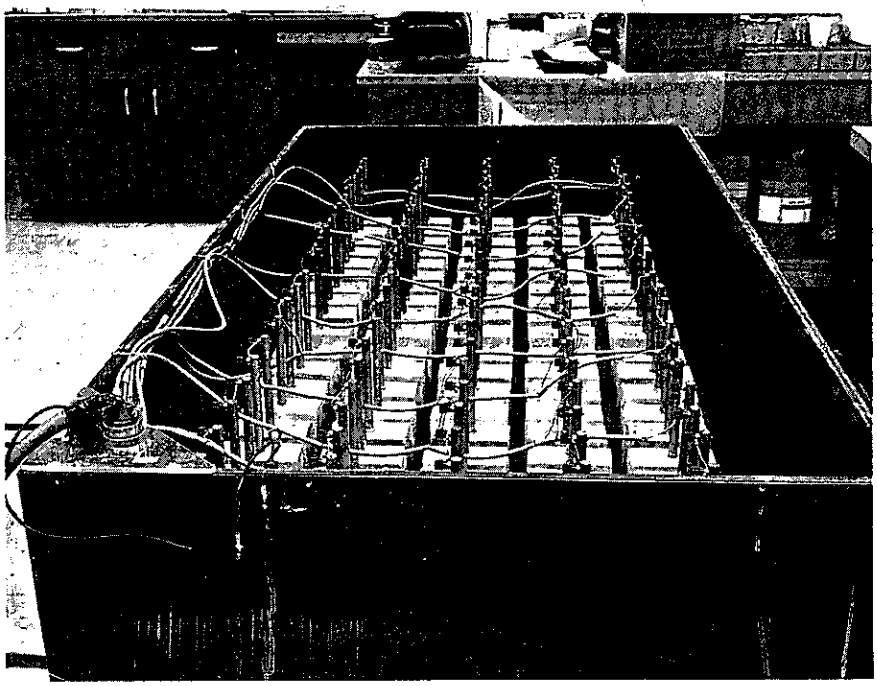

Figure 2

Partial immersion tests of steel in concrete

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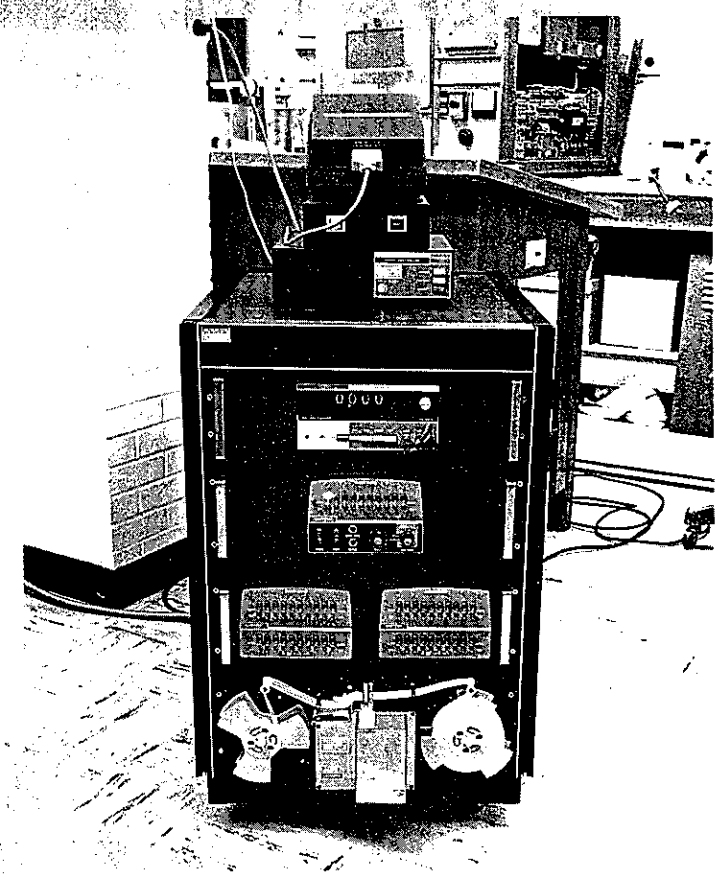

Figure 3 Data acquisition system for obtaining and recording potentials

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Figure 4

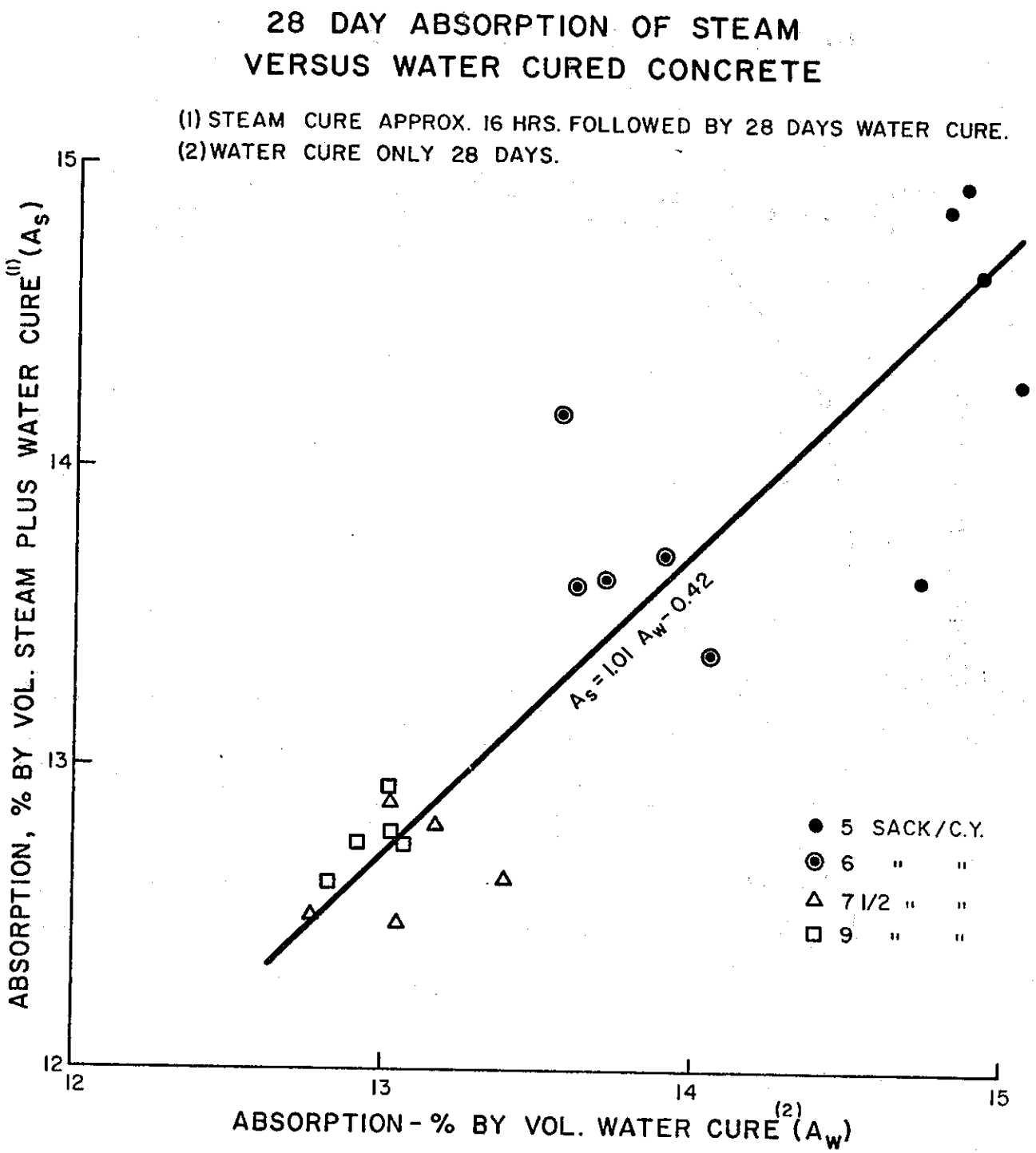

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Figure 5

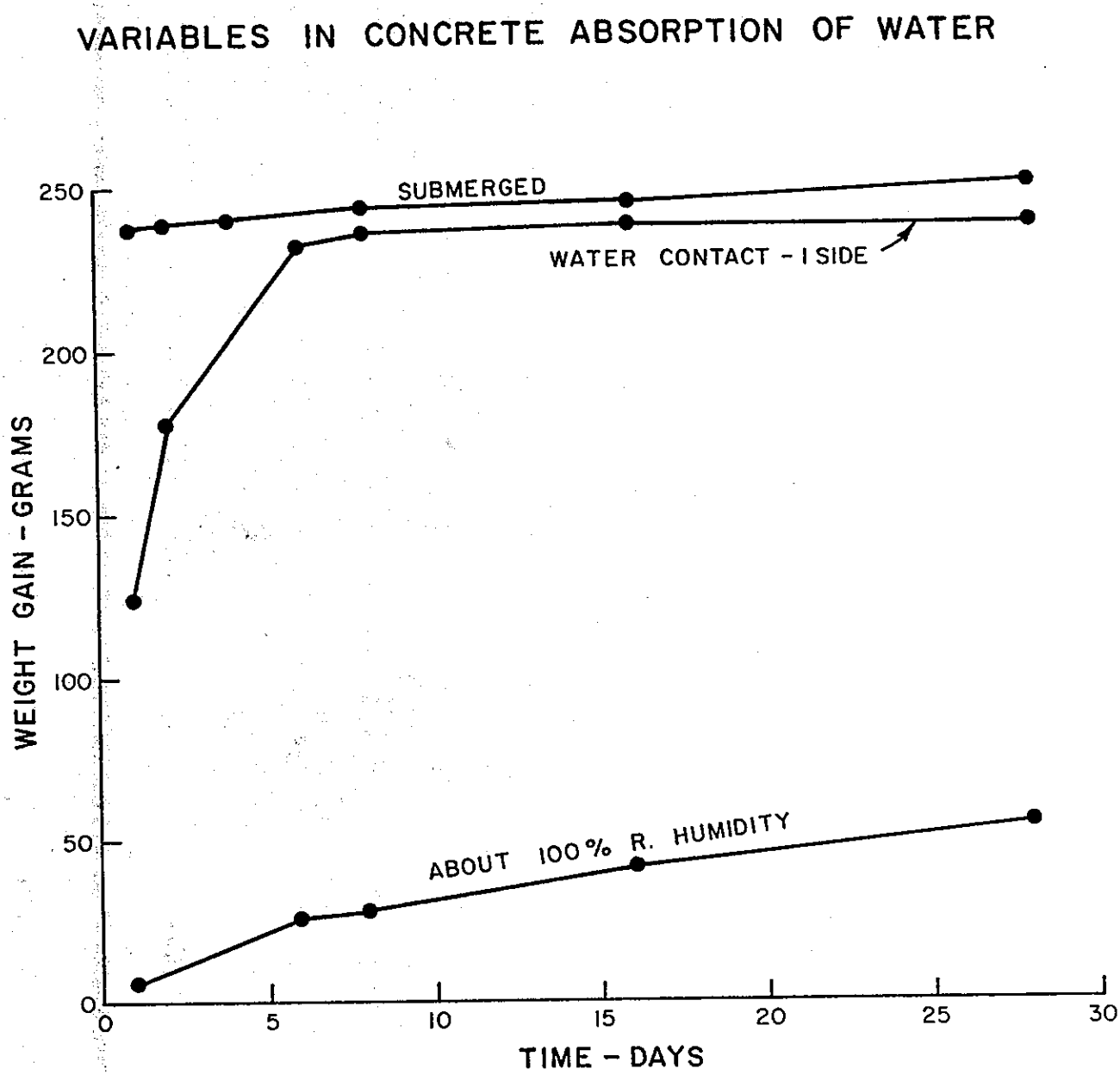

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Figure 6

TYPICAL HALF CELL POTENTIAL OF STEEL IN CONCRETE

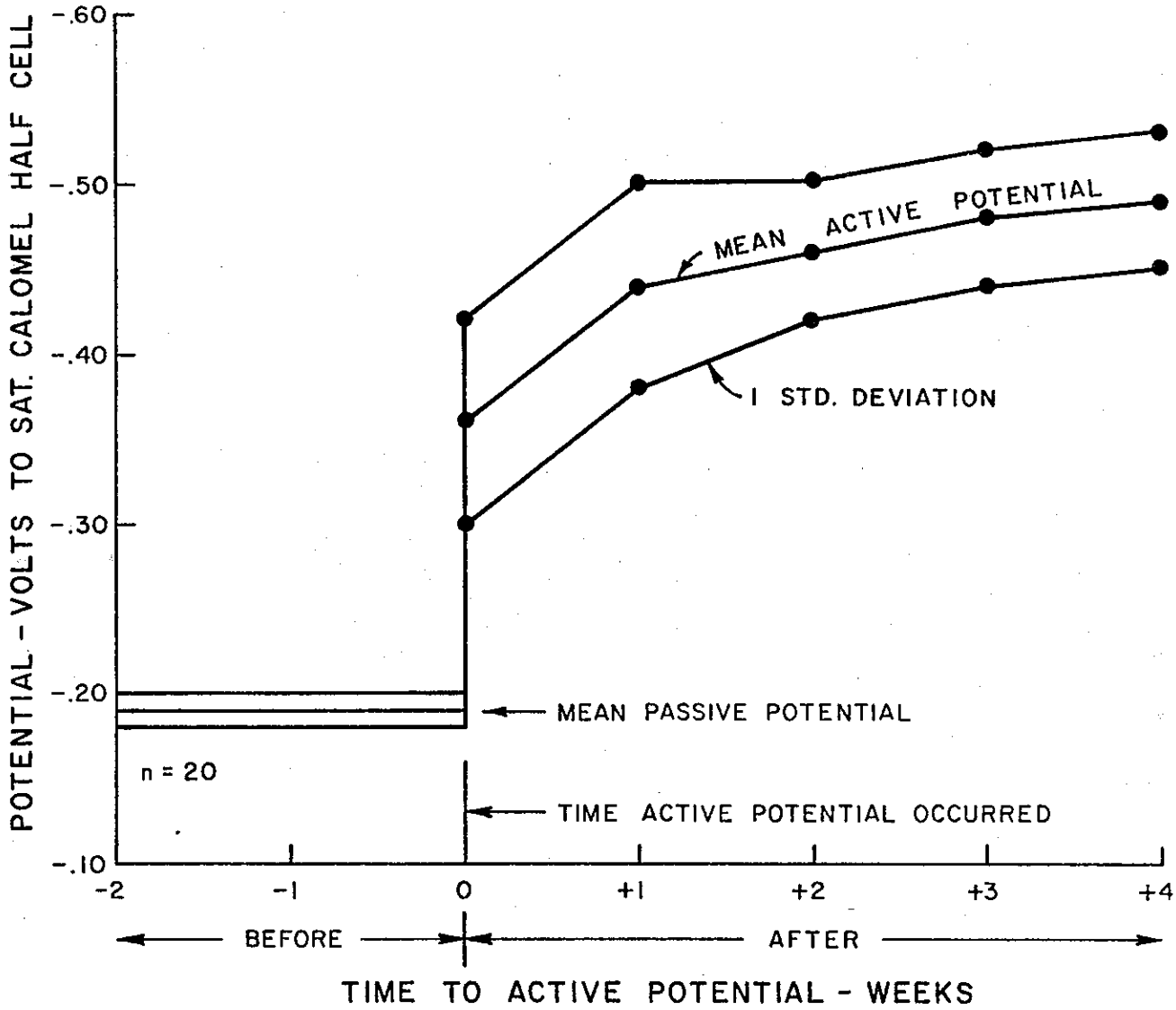

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Figure 7

EFFECT OF CEMENT FACTOR ON TIME TO ACTIVE POTENTIAL

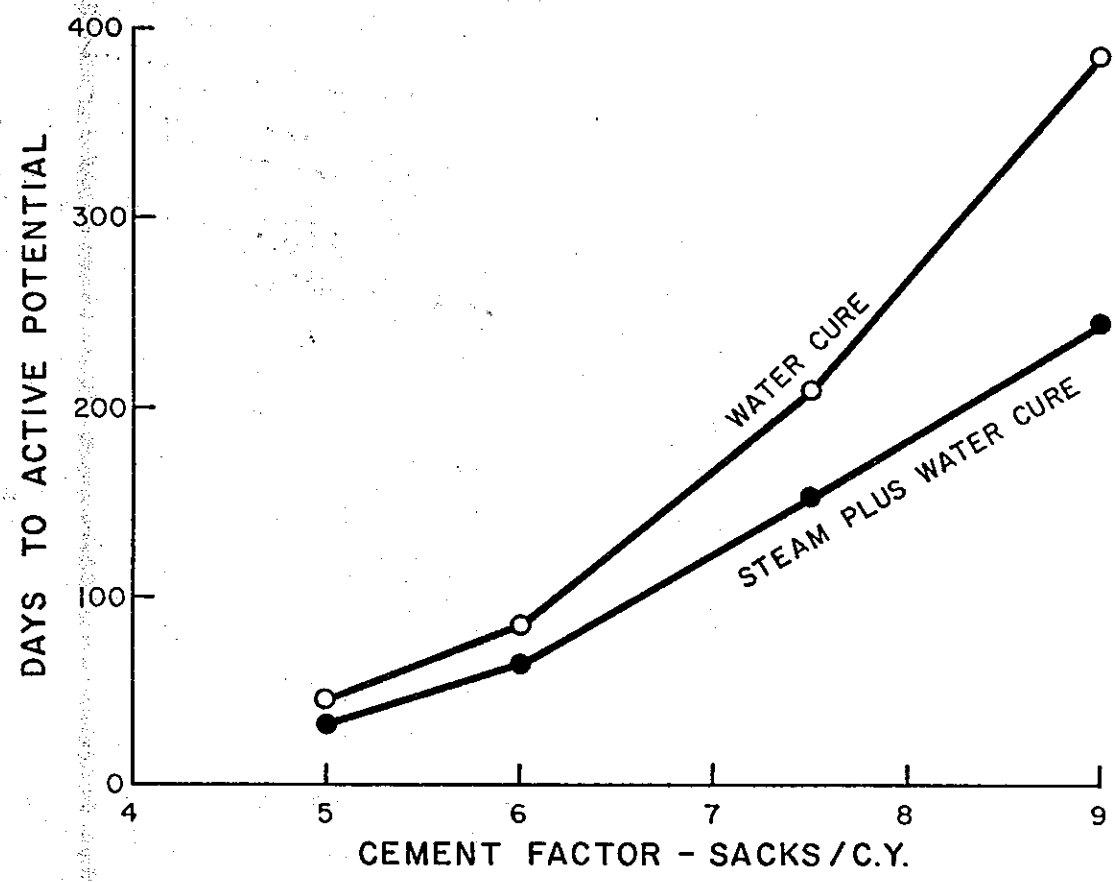

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Figure 8

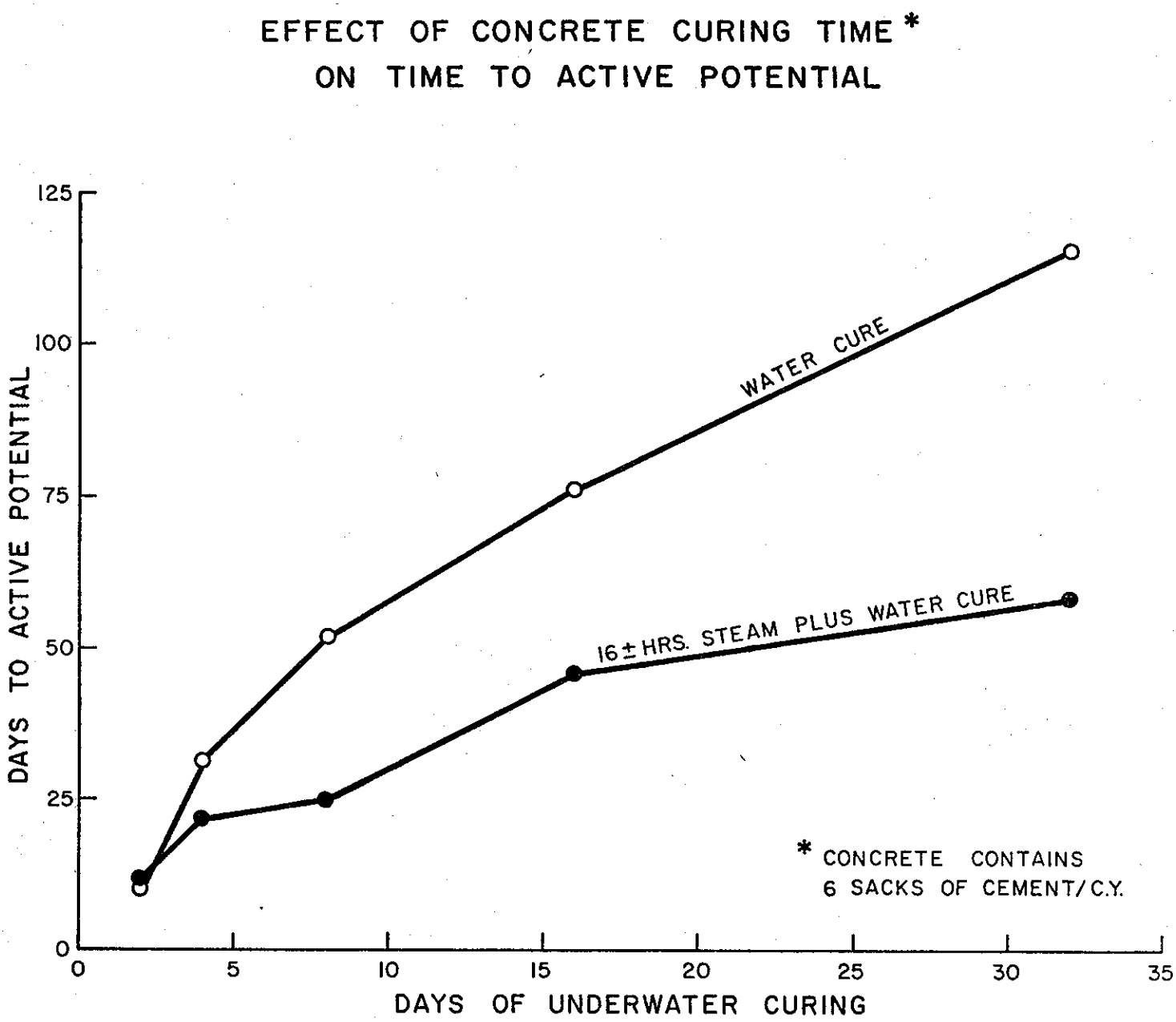

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Figure 9

WATER VERSUS STEAM CURED CONCRETE *

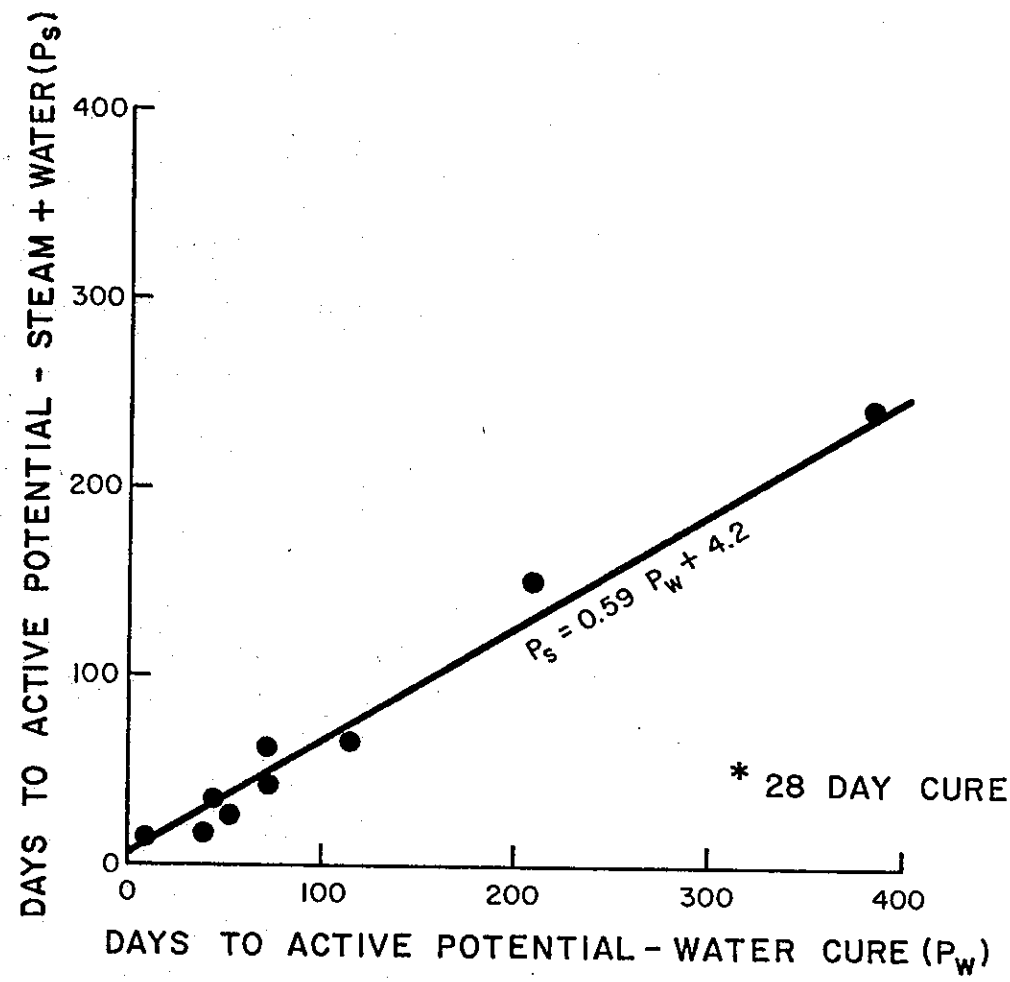

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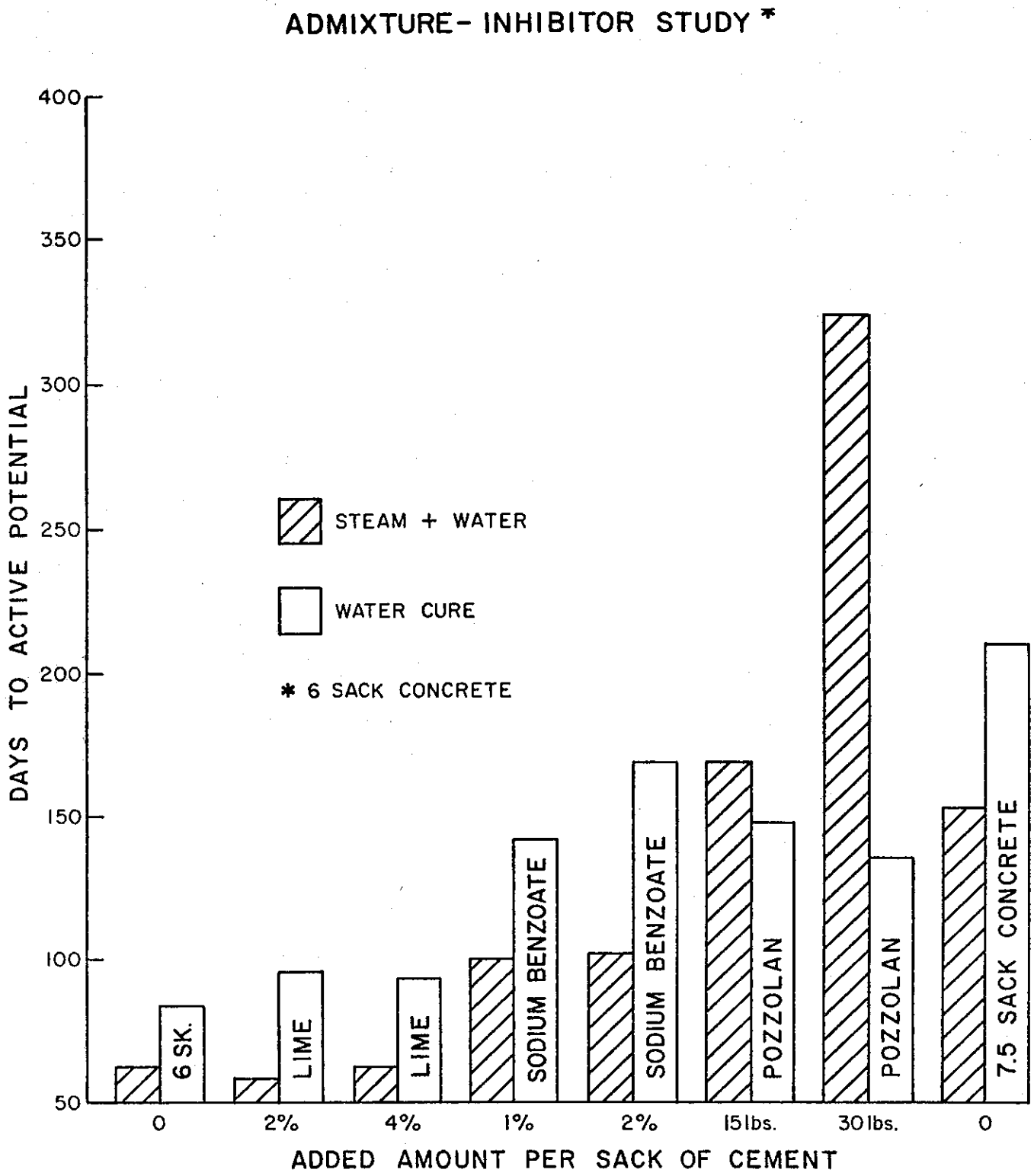
Figure 10



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