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The report describes a portion of a broader corrosion study and examines in some detail the aspect of steel corrosion in portions of piling which were continuously submerged for a period of approximately 37 years in sea water.

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Under continuously submerged conditions, it was found that 8 out of 17, or approximately 47 percent of the pilings had heavy corrosion of the steel. The metal loss of the heavily corroded sections of the steel was in the character of irregular shaped, broad pits that ranged in depth between 0.017-inch and 0.260-inch. The average of the maximum pit depths was 0.114-inch for the pits having lengths up to approximately six inches.

The chloride content found in the continuously submerged concrete ranged between 13 and 34 pounds per cubic yard, and averaged 25 pounds per cubic yard.

On the basis of absorption measurements made of the concrete, it was calculated that there could be a 10% chloride solution in the concrete, while the bay water contained 1.7% chloride.

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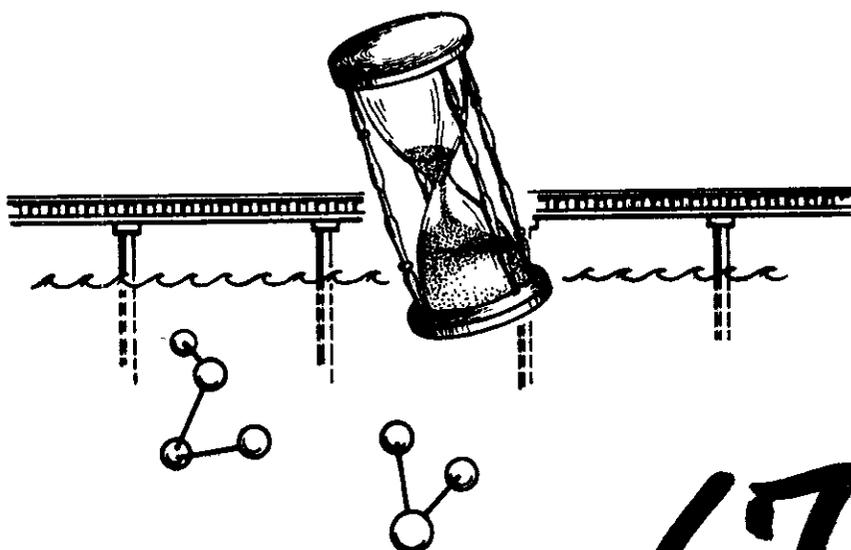
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CORROSION OF STEEL IN CONTINUOUSLY SUBMERGED REINFORCED CONCRETE PILING

By

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Donald L. Spellman and R. F. Stratfull



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MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

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INTRODUCTION

In cooperation with the Bureau of Public Roads, the California Division of Highways, Materials and Research Department, has been continuing its studies of the causes of corrosion of steel embedded in concrete^{1,2,3,4,5}. This portion of the over-all study is concerned with determining the level of chlorides in concrete that can cause the corrosion of the embedded steel and ascertaining the existence of corrosion of steel in continuously submerged portland cement concrete facilities.

Due to the difficulty of obtaining and inspection submerged sections of portland cement concrete structures, little data seems to be available in the literature that describe the long-time corrosion performance of such facilities. Recently, there has been an opportunity to inspect and sample the reinforced concrete piling which was being removed as part of the demolition of the then approximately 37-year old San Mateo-Hayward Bridge.

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A new bridge is being constructed to replace the old structure because of modern day traffic requirements plus the continuing excessive cost of maintenance¹, of the 7.04-mile long old bridge. The structure is located across the southerly arm of the San Francisco Bay.

This study is primarily a report on the findings at one bridge site. It is not considered that the data being presented is comprehensive or complete because it does not report on the incidence of corrosion nor the chloride content in concrete structures elsewhere. It merely adds knowledge in an area of corrosion that is now sparse.

SUMMARY AND CONCLUSIONS

The results of an inspection in the areas of continuously submerged portions of 17 reinforced concrete piles which were removed from the approximately 37-year old San Mateo-Hayward Bridge, showed that eight, or approximately 47 percent of the piles had significant corrosion of the reinforcing steel. The average maximum depth of corrosion pits of the steel was 0.114-inch.

The average chloride-ion content of approximately 2-inch thick fragments of concrete was found to be 25 pounds per cubic yard. Based on the 7-day absorption of the concrete, it is calculated that the chloride content of the water contained in the saturated concrete could average 10 percent by weight of the contained water. The San Francisco Bay water in the vicinity of the bridge has had a measured chloride-ion content of 1.7 percent.

The calculated difference in the chloride level of the concrete in areas of heavy corrosion and areas of light corrosion was quite small, on the order of 0.6-lb. per cubic yard. The difference does not seem to be significant. It appears that the corrosion phenomenon at these high levels of chloride concentration may be controlled by factors other than just the presence of salt.

This investigation did not determine the mechanism of corrosion of the steel in the continuously submerged sections of

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the piles. However, this phase of the over-all investigation demonstrated that with this particular salt contaminated concrete and approximately 2 inches of cover, corrosion occurs in continuously submerged sections of piling.

REINFORCED CONCRETE PILING HISTORY

There are many reports in the literature which acknowledge the corrosion performance of reinforced concrete piling. Lea and Watkins⁶, in their laboratory studies of partially immersed, simulated reinforced concrete piling, concluded that the primary cause of concrete deterioration was corrosion of the reinforcement. The results of their laboratory type studies are amplified by the full-scale studies reported by Tyler⁷. He reported that corrosion of the reinforcing steel in the piling somewhat obscured tests being made primarily to evaluate the performance of various cements.

There have been many reports which have described the corrosion of reinforcing steel in atmospherically exposed sections of piling^{1,4,8,9,11}. It has also been reported that there has been satisfactory performance over a period of 20-30 years even when piling have been badly cracked as a result of driving¹⁰.

There has been general agreement in the literature that the passivity of steel in concrete is destroyed by chlorides, and corrosion is usually the result of a galvanic type of corrosion cell^{11,5,12,13,14,15,16, 17}. One could assume that there would be a uniform moisture and chloride content of a submerged pile. However, Copenhagen¹⁴ found differentials in the salt content of a pile submerged in sea water for at least a year.

The corrosion of steel in concrete has been reported when there are differentials in the salt content within the concrete^{1,12,14}. However, corrosion of the steel is not known to normally occur in relatively salt-free concrete in California bridges. Figure 1, Deterioration of a Structure versus Chloride Content, shows that at chloride contents in excess of approximately 0.1-pound per sack of cement in a 5.4-sack concrete, the degree of deterioration of the concrete as a result of corrosion of the steel is not directly related to the chloride content¹. These data were obtained from atmospherically exposed beams of a bridge. The chloride contents shown in Figure 1 are averages for 1-inch thick disks cut from 2-inch diameter cores.

For this same bridge, Figure 2, Deterioration Versus Resistivity, the data indicate that once the chloride content of the atmospherically exposed concrete is sufficiently great, the resistivity of the concrete in the anodic areas is a controlling factor in the deterioration¹. Within certain limits, the resistivity of a concrete is inversely related to its moisture content¹. Therefore, it would seem that if a concrete contained a high level of chloride-ion and was submerged so that its resistivity was low, corrosion of the steel could occur. It is assumed that the rate or even the incidence of visible results of corrosion would probably be controlled by polarization effects, the relative surface areas of the anode and cathode, and also, time.

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Characteristics of the Concrete San Mateo-Hayward Bridge

Previous studies¹ were initiated to determine the degree to which the particular concrete used in this structure may have promoted corrosion of the reinforcing steel. Available construction records show that the average cement content of the concrete in the piles was 6.9 sacks per cubic yard.

The slump of the concrete used in casting the piles was reported as varying from 3 to 6-1/2 inches, but was generally indicated as within the range of 3-inch to 5-inch. Gravel used as coarse aggregate, nominally of 1-1/2-inch to No. 4 size, had a high percentage passing 1 inch. Construction records pertaining to grading of the sand are meager, but analysis of hardened concrete samples from the bridge show it to be well graded with a fineness modulus of the order of 2.8.

Based on the grading of the aggregate and the slump of the concrete, it was estimated that the water content was about 40 gallons per cubic yard. From the cement factors as reported, water-cement ratio for the piles was computed to be about 5.7 gallons per sack of cement.

The water of San Francisco Bay at the bridge site contains approximately 17,000 ppm of chloride-ion, or about 86 percent of the concentration of average sea water¹. Recommendations of the American Concrete Institute for exposures comparable to that at the bridge site, are water-cement ratios not in excess of 4.5

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gallons per sack in piles¹⁸. The water-cement ratios used in the bridge are, therefore, about 1 gallon per sack higher than would be recommended for this exposure today.

Compressive strengths (28-day) of 170 test cylinders made during construction of the piles were reported to be in the range of 4000 to 5000 psi.

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SAMPLING METHOD

In general, the method for removal of the piling was first to excavate approximately five feet of mud below the base of the pile, then repeatedly bend it until it broke. Figure 3 shows the piling in place while excavation of the bay mud from the base of the piles was in progress. In many cases, concrete was stripped from the pile in such a way as to twist the steel reinforcement. Only the steel in those piles exhibiting the least amount of removal damage at the mud line were sampled.

After a pile was removed and placed on the deck of the barge, it was photographed. Then by means of a jackhammer, the concrete was removed to expose the steel. Fragments of the removed concrete were identified and retained for further laboratory analysis. All sampling was performed within minutes after the pile was removed.

Figure 4 shows the typical line of demarcation between the mud and free water exposure of the piles.

Figure 5 shows the appearance of a pile just prior to the removal of the concrete for sampling. In some cases, the corrosion products (rust) from the steel had penetrated to the surface of the concrete.

Figure 6 shows a pile after the reinforcing steel had been removed. A torch was used to cut the steel. All samples

of the steel were approximately six feet long, extending approximately three feet in each direction from the mud line.

Results - Corrosion of the Steel

The steel was stripped from one corner of each of 17 piles and any evidence of corrosion was immediately noted by visual evaluation and later measured by a micrometer.

Figure 7 shows the appearance of a removed oval-shaped and approximately 4-foot long reinforcing bar. The locations of the mud or water, which was in contact with the concrete, are noted on the photograph.

Figure 8 is a close view of the corrosion of the same steel bar which is shown in Figure 7, and shows a fragment of the concrete which was in contact with the steel. The dark area on the surface of the concrete fragment is a rust stain. On Figure 8, the area of relatively non-corroded steel is the lightly colored area. The "spotty" or localized corrosion of the steel was typical.

Figure 9 shows a close view of the corrosion attack at a different location than that shown in Figure 8, but is on the same piece of steel which is shown in Figure 7. This location is where the concrete was apparently in continuous contact with the bay mud. In all cases, the bay mud line on the piles was at least ten feet below the low tide water level at the time of inspection.

Of the 17 piles that were inspected, eight, or about 47 percent, were found to have significant corrosion of the reinforcing steel. The steel in the other nine piles had what appeared to be a minor surface spotting of rust.

The maximum corrosion penetration of the steel in those piles having significant corrosion varied from 0.017-inch to 0.260-inch in depth and averaged 0.114-inch.

The maximum amount of measured metal loss for each pile is shown in Table 1 along with other data on the concrete cover.

On Table 1, it will be noted that the maximum amount of metal loss was generally observed in the vicinity of the mud line on the surface of the piling. The reason that the maximum amount of metal loss was found near the mud line is not clear. However, as will be observed on Figures 7 and 8, significant amounts of corrosion loss of the steel was also found in the water contact zone of the piles.

Chloride-ion in the Concrete

Concrete fragments obtained at the locations of corrosion were chemically analyzed for chloride content by means of an acid titration. The results of the chloride analysis (Table 1), are indicative of the average chloride content of the concrete for the total depth of cover over the steel. Insufficient time was available to permit the taking of concrete cores which could have permitted chloride determination at greater depths.

As indicated by Table 1, the calculated amount of chloride-ion found in the continuously submerged concrete ranged between 13 and 34 pounds and averaged 25 pounds per cubic yard.

As a comparison, Figure 10 shows the chloride-ion concentration which was previously found in atmospherically exposed sections of piling in this same bridge after approximately 28 years of exposure¹. The chloride contents shown in Figure 10 are averages for 1-inch thick disks cut from 2-inch diameter cores. It was calculated that for a 2-inch depth of cover and 28 years of exposure to salt spray, the average chloride content in this concrete was approximately five pounds per cubic yard. However, an average of 25 pounds of chloride-ion was found in the submerged (but different) piling in this structure after approximately 37 years of service.

As shown in Table 1, the average 7-day absorption of the samples obtained from the piling in this study is equivalent to 255 pounds of water per cubic yard of concrete, while the average chloride-ion content was 25 pounds per cubic yard. These results indicate that a calculated chloride content of approximately 10 percent by weight of the absorbed free water could be in this concrete. The chloride content of the bay water was found to be approximately 1.7 percent.

We have no construction records that indicate bay water was used as mixing water, or that calcium chloride was added, nor has any previous testing indicated that there were additions of

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chloride to the concrete mix.

Concrete Absorption

In this investigation, the method used to measure concrete absorption was as follows:

1. The concrete was first oven dried at approximately 230°F for 28 days.
2. Immediately after oven drying, the concrete was immersed in tap water at $72 \pm$ °F for a total of 28 days.
3. The weight gain of the concrete at 7 days was chosen to represent the absorption of the concrete.
4. The volume of the concrete under test was determined at the 28th day of soaking by the weight in air-weight in water method.

The results of the absorption tests are shown in Table 1, and are shown as pounds of water per cubic yard of concrete.

We have outlined the method that we are presently using for measuring concrete absorption because thus far, for our purpose, it seems to show promise for obtaining reasonably reproducible results. Our investigation of a method for measuring concrete absorption is not complete, therefore we cannot comment at this time upon its absolute accuracy nor its relative value for distinguishing between concretes of various mix designs. However, the trend of some of the absorption data indicate that after 28

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days of soaking, the weight gain of some of the concrete samples has been within the range of 15 to 25 grams of the free water which this same concrete had contained even after two years of underwater curing. The 7-day absorption value for some of the concrete samples has been within 8 to 12 grams of the amount of water absorbed after 28 days of soaking. These weight values are for concrete cylinders that have a free water content that ranges between 350 and 400 grams at the conclusion of the various submerged curing times. Therefore, since our studies of concrete absorption are not complete, we have chosen at this time, the 7-day absorption value primarily because it is a common time element in concrete technology.

DISCUSSION

Basically, this phase of the over-all investigation was primarily concerned with two questions which were: (1) What chloride content of the concrete will result in corrosion of imbedded steel? and (2), Does steel corrode in continuously submerged piling?

With regard to the first question, it would not seem unusual to find corrosion of steel when the chloride content in the continuously submerged concrete is in the range of 25 pounds per cubic yard. What is surprising is that such a high quantity of chloride was found.

Recently Ost and Monfore¹⁹ have reported that the migration of chlorides into concrete is greatly dependent upon the water-cement ratio of the original concrete mixture. Depending upon the test parameters, they found chloride contents in the concrete at an indicated range from 0 to about 30 pounds or more per cubic yard after one year of testing.

Other studies have shown that concrete samples have absorbed up to approximately 45 pounds of chloride-ion per cubic yard after 88 days of testing⁵.

The mechanism of the corrosion of the steel in these piles was not investigated and is, therefore, subject to speculation. Previous work on the atmospherically exposed portions

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of piling from this bridge showed the presence of cathodic potential gradients in these areas. The potential measurements indicated that the anode was in the tidal water and splash zone of the piling. No potential measurements were made on the continuously submerged areas of the pilings. Also, no potential measurements were made during this later study.

Thus far, it has not been determined whether the corrosion in the submerged section of the piles on this bridge is sustained by a submerged cathode or by a cathode which is in the atmospherically exposed section of the pile.

Because of the high level of chloride found in the submerged sections of the piling, it would seem worthwhile to investigate the mechanism of chloride build-up in concrete. Previous work has indicated that chlorides may accumulate in concrete by assuming that chloride containing water entered the concrete by absorption and left salt behind as a result of evaporation⁴.

It appears that the mechanism of salt accumulation in concrete may not be simple. For example, in the laboratory, the placing of initially salt-free and air-dry reinforced concrete specimens in a saturated salt solution has resulted in visible evidence of corrosion of the steel in the range of 12 to 25 days⁵. Current, but unreported and unfinished testing by us of reinforced concrete in saturated salt solutions, has shown that if the concrete is first saturated with "clean" water before being immersed

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in salt water, then it will take at least eight months for corrosion of the steel to occur instead of 12 to 25 days⁵. Therefore, it seems that the salt content and the time to corrosion for reinforced concrete may be significantly controlled by the amount and nature of the moisture in the concrete immediately prior to its being placed in an aggressive environment. For concrete that is saturated with "clean" water, it is speculated that chloride would penetrate by means of diffusion or by capillary action which could be the result of the evaporation of the originally contained water. It also appears that if the diffusion process was the controlling mechanism for chloride entry, then it would be expected that the calculated chloride content in the approximately 37-year old concrete at this bridge would be no greater than that which is found in the bay water, since higher concentrations would tend to diffuse outward.

The results of this phase of the investigation indicates that emphasis should be placed upon understanding the mechanism of chloride accumulation in concrete, so as to devise ways to prevent build-up to levels that result in corrosion of the steel.

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The work involved in this study was performed as part of a corrosion study in cooperation with the Bureau of Public Roads; however, the opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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Table 1
Corrosion Test Results

Bent No.	Pile No.	Calculated Lbs. of Chloride per Cubic Yard	7-day Water Absorption, Lbs./Cu.Yd.	Concrete Cover in Inches	Depth of Maximum Metal Loss in Inches	Location of Maximum Metal Loss
231	2	24.7	248	1-3/4	0.210	Mud line
232	1	26.8	298	2-1/2	Minor rust	Mud line
	2	23.6	258	2-3/8	" "	" "
	3	25.3	258	1-3/4	0.095	" "
	4	13.4	266	2	0.260	" "
233	1	25.9	283	2-1/4	Minor rust	Mud line
	2	26.2	273	2-1/4	" "	" "
	3	27.3	256	2	" "	" "
234	1	28.4	265	2	Minor rust	Mud line
	2	25.2	249	2	0.119	" "
	3	13.9	243	2-1/4	Minor rust	" "
	4	29.5	288	2-1/2	" "	" "
245	3	27.0	244	2-1/4	0.017	1-1/2' above mud line
	4	27.2	239	2-1/4	0.039	2' below mud line
246	1	33.6	241	1-1/4	0.097	Mud line
258	1	19.2	231	2-1/4	0.073	1-1/2' below Mud line
	2	24.0	227	2-1/4	Minor rust	Mud line
Average		24.9	255		0.114	

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DETERIORATION OF A STRUCTURE VERSUS CHLORIDE CONTENT

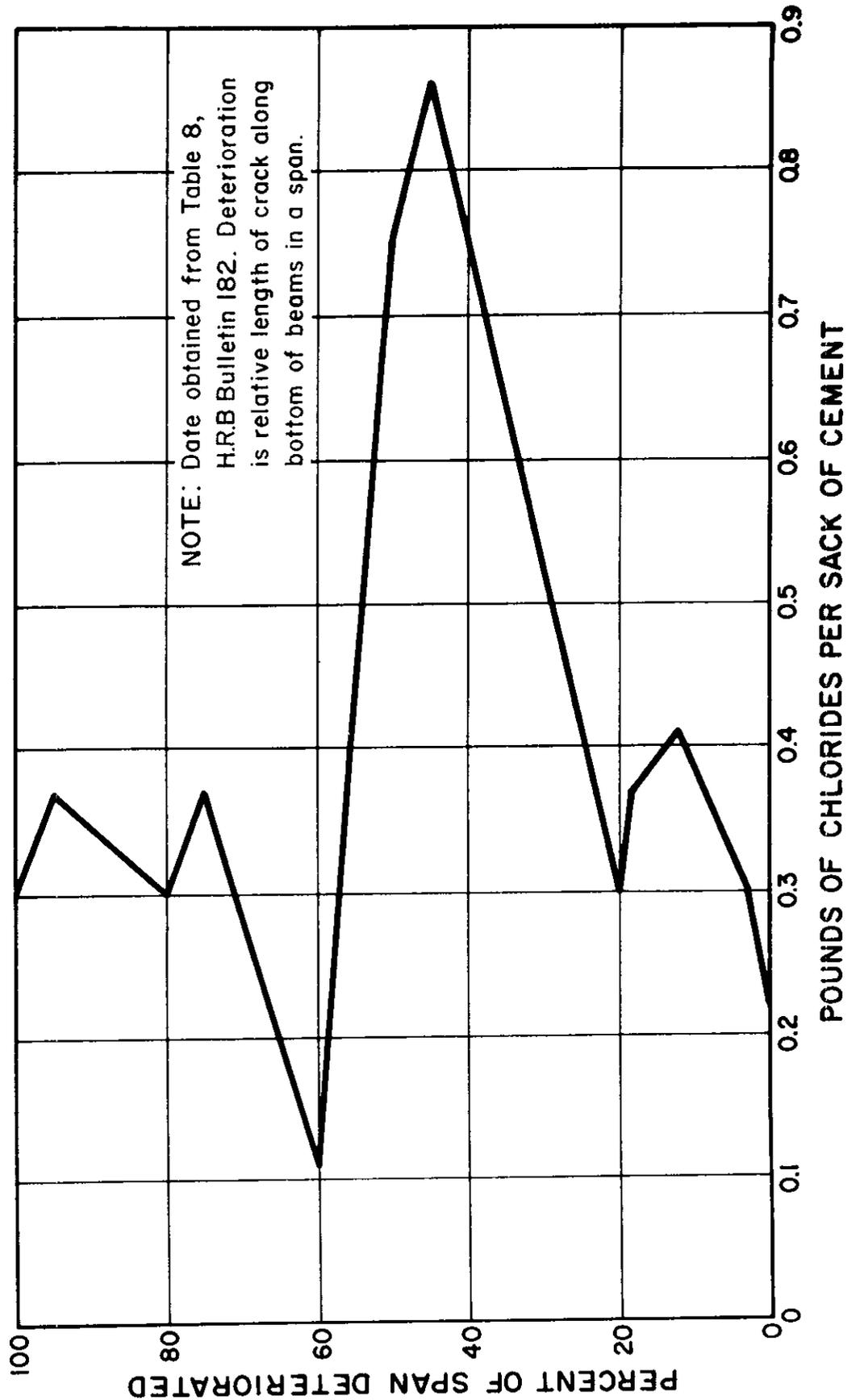


Fig. 1

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DETERIORATION VERSUS RESISTIVITY

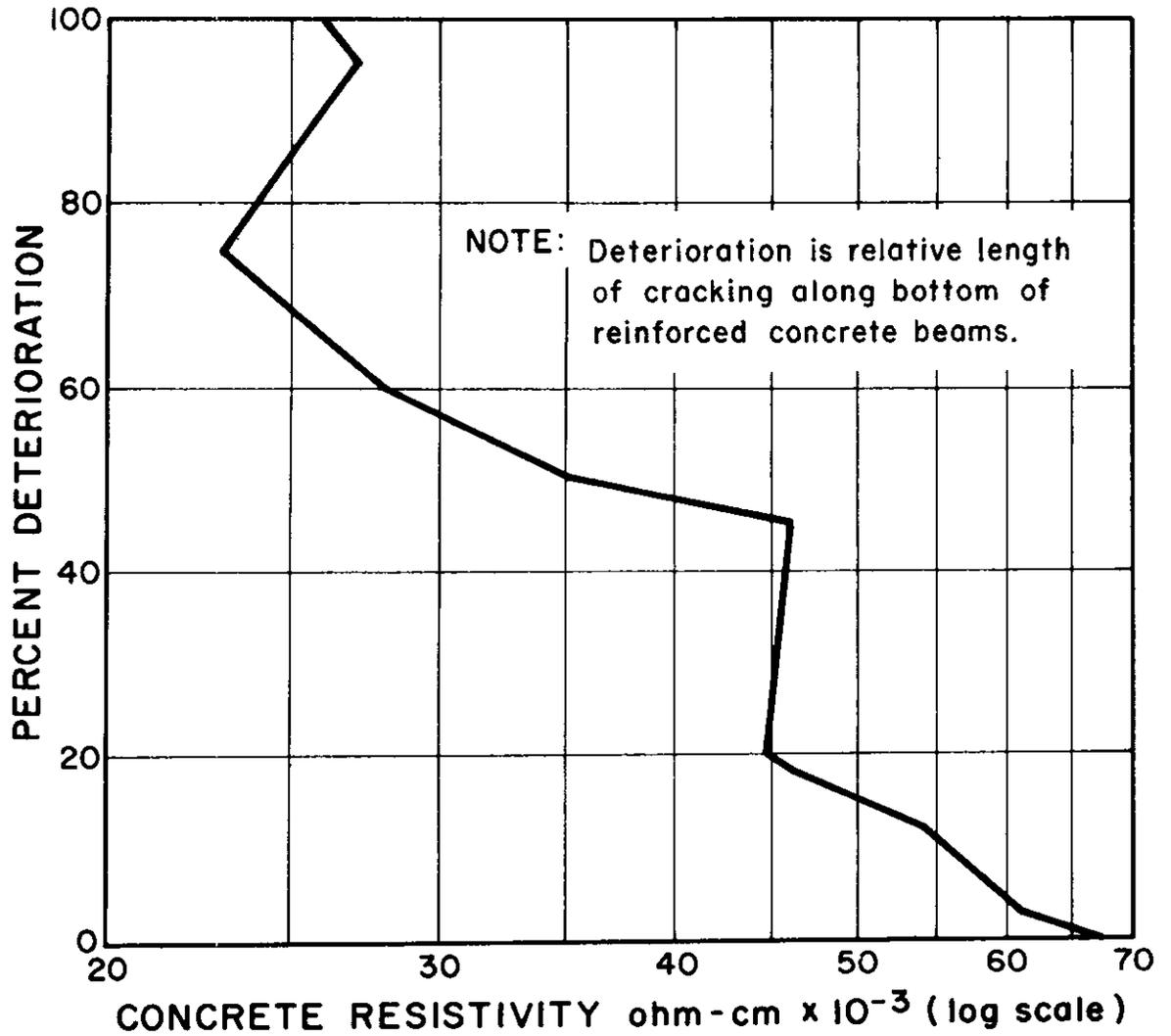


Fig. 2

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Figure 3. Excavating mud from base of piers. Superstructure removed.

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Figure 4. Appearance after removed pile. Note line of demarcation between exposure to free water and mud immersion.

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Figure 5. Removing concrete with jackhammer. Note the rust stain (dark area) immediately adjacent to bit of the jackhammer.

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Figure 6. Corner of pile after removal of reinforcing steel.

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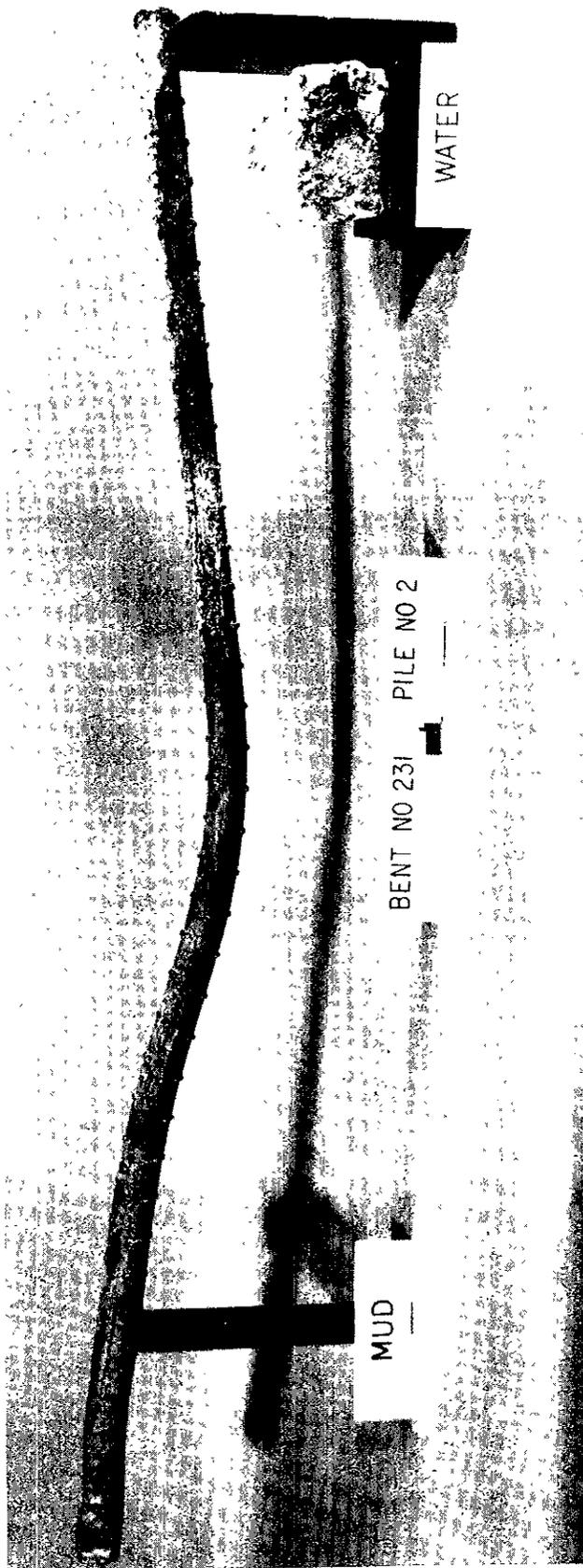


Figure 7. Condition of 1.10" x 1.37" oval reinforcing steel. Notations of "Mud" and "Water" are where the pile was in contact with those environments.

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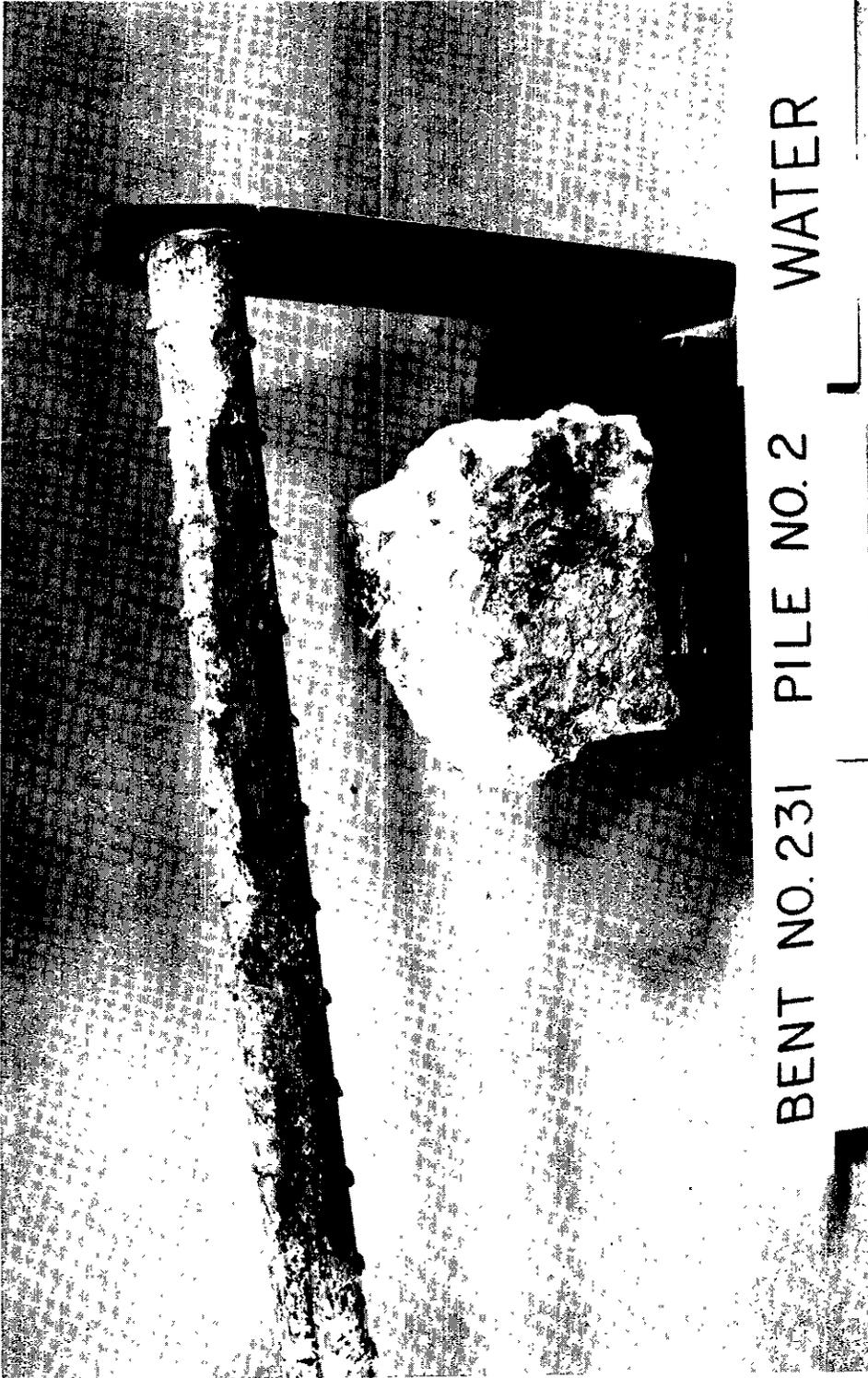


Figure 8. Close view of section of steel that is shown in Figure 7. Area where concrete was in continuous contact with bay water. Maximum metal loss in this area was 0.117". Dark area on concrete fragments is rust stain from the steel.

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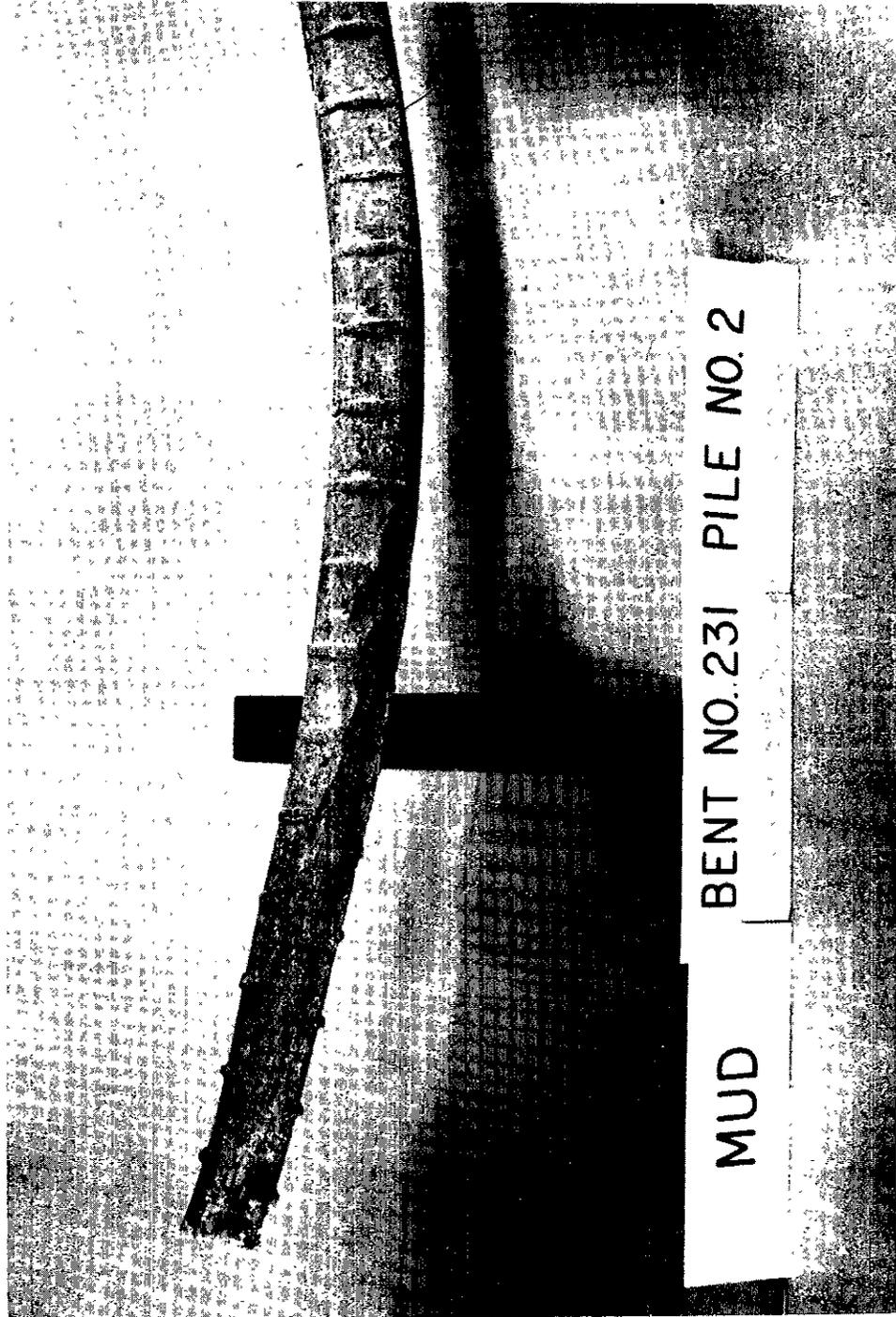


Figure 9. Close view of section of steel that is shown in Figure 7. Area where concrete was in continuous contact with bay mud. Maximum metal loss in this area was 0.210".

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CHLORIDE - ION IN ATMOSPHERICALLY EXPOSED PILING SAN MATEO-HAYWARD BRIDGE

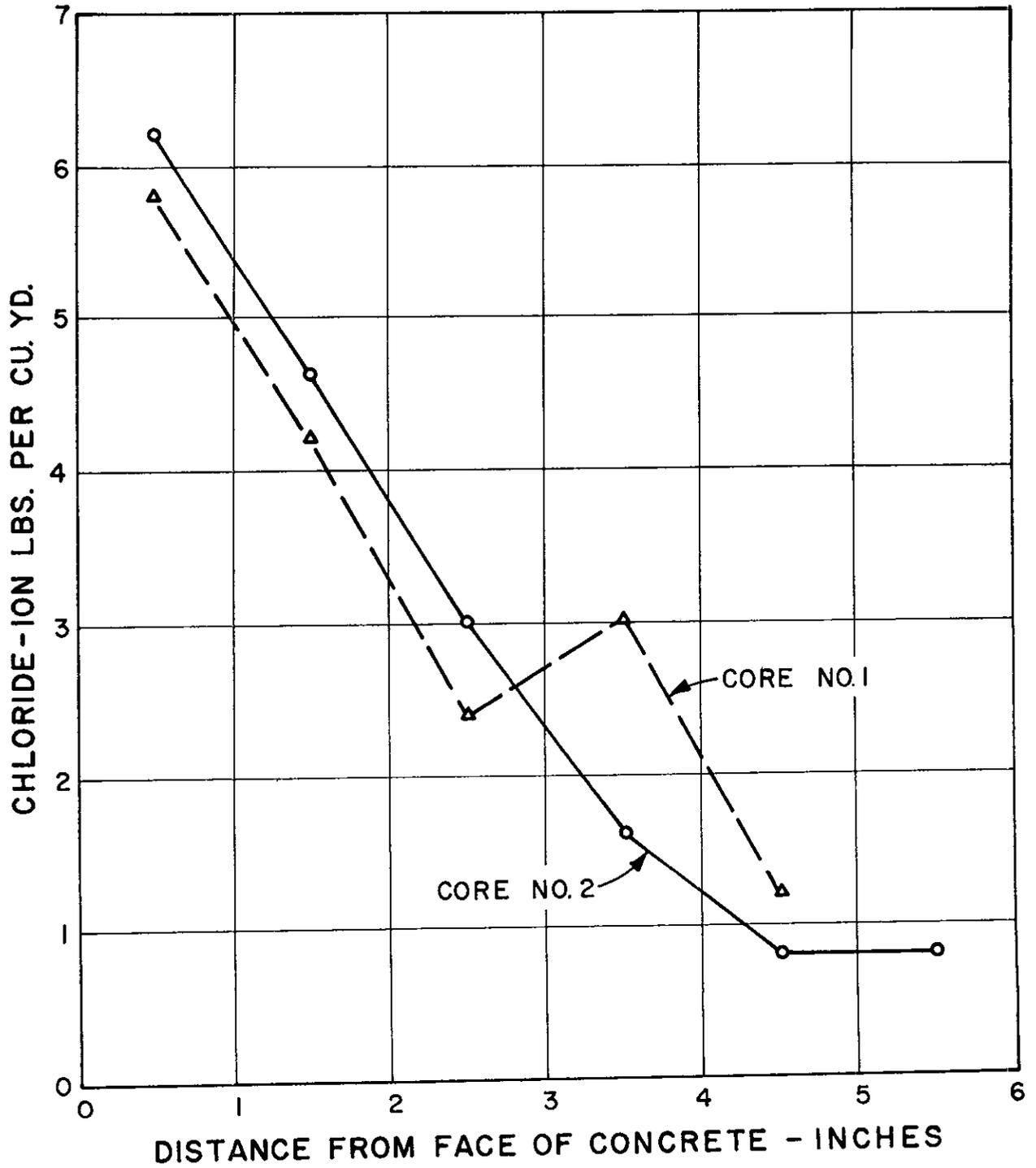


Fig. 10