H35
LAST COPY DESIGN DEPT
262

HIGHWAY RESEARCH REPORT

CHLORIDES AND BRIDGE DECK DETERIORATION

INTERIM REPORT

H35
69-09

STATE OF CALIFORNIA
BUSINESS AND TRANSPORTATION AGENCY
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT
NO. M & R 635116-4

Prepared in Cooperation with the U.S. Department of Transportation, Bureau of Public Roads November, 1969

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

STATE OF CALIFORNIA—TRANSPORTATION AGENCY

RONALD REAGAN, Governor

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

November, 1969

Research Project No. 635116-4
Interim Report

Mr. J. A. Legarra
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

Chlorides and Bridge Deck

Deterioration

Donald L. Spellman
Principal Investigator

Richard F. Stratfull
Co-Investigator

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

Reference: Spellman, Donald L., and Stratfull, R. F., "Chlorides and Bridge Deck Deterioration", State of California, Department of Public Works, Division of Highways, Materials and Research Department, August, 1969. Research Project No. 635116.

Abstract: As a result of a recent bridge deck study and other related work, a mathematical expression was derived which describes the distribution of chloride in concrete as related to depth below the surface in bridge deck concrete. The validity of the expression is supported by a similar distribution of salt found in piles submerged in bay water. Data are given which shows that the distribution of chloride in concrete is highly variable, and attention must be given to the number of samples when determining the average chloride content.

Steel was removed from one bridge deck and corrosion loss measured. While not structurally significant, the corrosion that had occurred was more than necessary to cause extensive cracking of the concrete.

It was concluded that deck deterioration due to corrosion of the steel could be effectively prevented in new structures by the use of a noncorrosive deicing agent, or the use of an effective sealing membrane to prevent salt intrusion. A membrane placed on a high chloride contaminated deck is likely to accelerate corrosion.

Half-cell potential measurements were made on sections of two bridge decks. They show that corrosion activity of the steel can be nondestructively detected by electrical measurements.

Key Words: Concrete, bridge decks, deterioration, repairs, corrosion, chlorides, statistical analysis, piles, steel, concrete coring, salt concentration, half-cell potential

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

ACKNOWLEDGMENT

This project was performed in cooperation with the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads, Agreement No. D-3-11.

The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those held by the Bureau of Public Roads.

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

TABLE OF CONTENTS

	Page
Introduction	
Summary and Conclusions	3
California Bridge Decks, General Construction	5
Chlorides in Concrete - Average Distribution	6
Chlorides in Concrete - Calculated Distribution	7
Corrosion Loss of Steel	10
Deterioration - Concrete	10
Sampling	12
Electrical Potentials	12
Discussion	15
References	18
Tables	
Figures	

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

CHLORIDES AND BRIDGE DECK DETERIORATION

By
D. L. Spellman[1], and R. F. Stratfull[2]

In cooperation with the Bureau of Public Roads, the California Division of Highways has been continuing its studies of the causes of corrosion of steel embedded in concrete[1-6]. This report is a phase of the current study to determine the level of chlorides in concrete that can cause corrosion of reinforcing steel.

As a result of an inspection made during 1960, it was considered that the most significant trouble observed at that time was that bridge substructures in contact with high chloride containing environments had corrosion of the reinforcing[4]. In a study of bridge decks in cooperation with the Bureau of Public Roads and the Portland Cement Association during the spring of 1962, only one out of a group of 21 California bridge decks selected for study was reported to have corrosion of the embedded steel[7].

Because of the lack of a history of significant number of bridge deck deterioration problems prior to about 1962, it has been assumed that a major contributor to the recently observed deck deterioration has been the accelerated statewide use of deicing salts starting in about 1960. This observation is supported by the fact that in 1955 the Division was just experimenting with salt, and by 1960, 3000 tons of salt were used in the sanding and snow removal operation. By 1968, the use of deicing salts had become so widespread that the estimated average tonnage being applied to California highways was about 10,000 tons per year.

During the summer of 1969, three construction contracts were advertised for the repair and resurfacing of 31 bridge decks. The contract bid price for the 31 bridges was about $777,000, or about $25,000 per bridge deck which indicates an average cost of $2.58 per square foot for the entire 300,673 square feet of bridge decks. However, this price does not

---

[1]Assistant Materials and Research Engineer - Concrete
[2]Senior Corrosion Engineer

ClibPDF - www.fastio.com

include the cost of concrete removal. It should be noted that most of these bridges are less than ten years old, and further amplifies the role of deicing salts as a primary cause of deterioration. Since corrosion of the deck steel has been relatively recently observed, it was decided to determine if deicing salts are in fact penetrating the concrete, and if so, determine the distribution and quantity of salts that are present. It is also interesting to note that four of the 21 cooperative study bridges[7] referred to previously as having no significant signs of corrosion are included in the recent repair contracts. Repair measures were apparently not required or considered necessary at the time of that study (1962). This illustrates that the rate of deterioration can be rapid.

ClibPDF - www.fastio.com

SUMMARY AND CONCLUSIONS

Sampling and Chloride Distribution

Sixteen bridge decks with various degrees of deterioration that have been subjected to deicing salts were cored and analyzed for chloride content. It was found that there was a basic mathematical relationship which would describe the distribution of chlorides with depth. In effect, the log of the chloride content is inversely related to the depth below the surface.

A basic mathematical expression was derived for the chloride analysis of the concrete obtained from piles that were continuously submerged in bay water. The mathematical expression for the distribution of chlorides in concrete was found to be the same for bridge decks or piling which indicated that for each additional inch of depth, the chloride content would be reduced by approximately one-half. Therefore, the mechanism for the absorption of salt may be similar and cracks in a concrete deck may only perform the role as a local accelerator to the incidence of corrosion.

The distribution of chloride in the concrete was found to be highly variable. On the average, the coefficient of variation of the chloride content was approximately 30%. Therefore, based upon a coefficient of variation of 30%, it would be advisable to obtain not less than six samples in order to estimate the average chloride content. Even with six samples, there is a probability that one out of twenty average values would have a sampling error of greater than about 24%.

Membranes and Corrosion

Previous experience[1] has shown that application of a membrane over chloride-contaminated concrete bridge decks can result in acceleration of the corrosion. Because of the similarity between the evidence of corrosion, the distribution and the concentration of chloride in piles and in decks, and the detection of similar electrical potential activity of deck steel, the application of a membrane to a deck could also result in acceleration of the corrosion.

ClibPDF - www.fastio.com

Metal Loss

The reinforcing steel from one distressed bridge deck was removed and it was found that the mean of the maximum corrosion loss within each foot of steel was 29 mils. While not structurally significant, this amount of corrosion loss is more than enough to cause concrete cracking and spalling. Laboratory testing showed that less than one mil of corrosion loss was sufficient to crack 7/8-inch thick concrete cover.

Corrosion Prevention

Based upon the mechanism of corrosion and design limitations, deterioration of a nominally chloride-free (less than 0.6-lb. per cubic yard) concrete deck due to corrosion can be prevented by using a noncorrosive deicing chemical, or a membrane barrier on the concrete surface. Other alternatives, such as the supply of artificial heat rather than salt to melt ice may also prevent corrosion. Of course, this method would have to be used where there was no salting of the adjacent pavement which could be "tracked" on the deck by traffic.

Half-Cell Potential

The half-cell potential of the reinforcing steel in sections of two bridge decks was measured and it is shown that deterioration is associated with corrosion of the steel as indicated by the electrical measurements. The measurements can be used to locate actively corroding reinforcing steel in bridge decks, and should show promise in evaluating repair techniques that are considered to be arresting the corrosion of the steel.

ClibPDF - www.fastio.com

CALIFORNIA BRIDGE DECKS
GENERAL CONSTRUCTION

In general, the thickness of concrete covering over the top mat of reinforcing has been specified to be a minimum of 1-1/2-inch in freeze-thaw areas. However, depending upon the economics of bridge design and the geographic location of the bridge, the specified cover over the reinforcing has ranged from 1 inch to 2 inches in thickness.

Starting in about 1960, the concrete cover over bridge deck steel has been specified as 2-inch in freeze-thaw areas, and 1-1/2-inch minimum in other areas.

As an indication of the good construction practice in California, for the 21 bridges that were investigated in the cooperative study[7], the average specified minimum cover was 1.28-inch and the actual measured minimum cover was 1.25-inch for 19 comparative measurements.

Normally, the bridge decks have been constructed of concrete having six sacks (94 lbs. each) of cement per cubic yard, and a water-cement ratio of about 5 to 6 gallons per sack of cement[7]. The range of the reported water-cement ratio was 4.6 to 6.2 gallons per sack of cement[7].

Beginning in about 1960, some concrete bridge decks in freeze-thaw areas had a specified minimum cement factor of 7 sacks per cubic yard.

ClibPDF - www.fastio.com

CHLORIDES IN CONCRETE
AVERAGE DISTRIBUTION

During the spring of 1969, 16 bridge decks were sampled by obtaining 4-inch diameter cores. The number of cores obtained from each deck varied from 6 to 22. The purpose of this range in number of cores was to determine the salt content and the minimum number of cores that were necessary for some specified degree of confidence in the test results.

Because the roadway as well as bridge decks are salted in the mountainous areas of California, an exact determination cannot be made of the precise amount of salt that comes in contact with the decks. However, on Table 1, bridges numbered 1 through 9 and 12 through 14 are on roadway sections of about 30 miles in length that receive an average of 50 tons of salt per year. The structures involved, received an estimated 0.2-pound of salt per year per sq.ft. of area. On Table 1, bridges 15 and 16 are in salt areas in which the roadway and bridge decks receive an average of 1000 tons of salt per year. Based on the square footage of application, it is estimated that bridges 15 and 16 have about 1 pound of salt applied per square foot of deck surface per year.

The average chloride content for each of the 16 bridges that were sampled is shown in Table 1, "Distribution of Chlorides in California Bridge Decks." The chloride values shown are for the lower face of each disk (i.e., top disk - 1").

For all 16 structures, the average chloride content in the concrete where the upper mat of steel is located was found to be about 2.6 pounds of chloride per cubic yard of concrete. The approximate average chloride content of the concrete in the deteriorated San Mateo-Hayward Bridge averaged about 1.9-pound of chloride per cubic yard of concrete[1]. Therefore, it is apparent that corrosion of steel in bridge decks, girders, and piles can corrode at what can be considered as relatively low levels of chloride content.

ClibPDF - www.fastio.com

CHLORIDES IN CONCRETE
CALCULATED DISTRIBUTION

In an effort to determine if there is a mathematical distribution of the chlorides in the concrete, the data for each bridge were plotted and a regression line was calculated by the method of least squares[8]. The basic equation for the correlation was:

$$\text{Log}_{10}C = (\text{Log}_{10}M)(S) + \text{Log}_{10}\, b \quad \ldots\ldots\ldots \quad (1)$$

Wherein:

C = chloride content of a 1-inch thick disk - pounds per cubic yard
M = slope of the regression line
S = maximum depth below surface for a 1-inch thick disk - inches
b = intercept of regression line on "Y" axis

When reducing this equation to eliminate the logarithms, the equation takes the following form:

$$C = b(M)^S \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The results of the regression analysis for all 16 bridges are shown on Table 2, "Calculated Distribution of Chlorides in Bridge Decks." Because the chloride content of the concrete is calculated in terms of the logarithm to the base 10, it will be observed that the standard error of the estimate[8] as shown on Table 2 is an anti-logarithm.

At the time of the calculations, only the data for bridges 1 through 14 were available; therefore, these data were combined to determine the overall average for the relationship between chloride content and depth. For the 14 bridges, the following correlation was derived by the method of least squares:

$$C = 9.60(0.441)^S \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

ClibPDF - www.fastio.com

Wherein:

C = chloride in a 1-inch thick disk, pounds per cubic yard
S = maximum depth below the surface for any 1-inch thick disk - inches, with a depth limit of 4 inches.

For the "n" of 56 values, the coefficient of correlation was 0.917, and the standard error of the estimate was the $\log_{10}$ of 1.50.

The calculated regression line and the average chloride content are shown on Figure 1, "Average Distribution of Chloride in Bridge Decks." It will be noted on Figure 1 that the calculated line is parallel to but consistently less than the line that shows the average. This is because there is a normal distribution of chloride in the concrete at any particular depth. As a result. the average is the arithmetic mean. However, in the regression analysis of chloride versus depth, the mathematical relationship for the chloride content is a logarithmic function. Therefore, the mean chloride content that is calculated by Equation (3) for each depth is not a simple arithmetic mean, but in effect, a geometric mean. The geometric mean should result in a value that is less than the simple arithmetic mean.

The simple arithmetic mean of the chloride content at each depth was calculated and the regression analysis resulted in the following equation:

$$C = 10.85(0.440)^S \quad \ldots\ldots\ldots\ldots \quad (4)$$

For the "n" of 56 values, the coefficient of correlation was 0.918, and the standard error of the estimate is the $\log_{10}$ of 1.49.

It will also be observed on Figure 1 that the average chloride content of the concrete at the 5 and 6-inch depths do not follow the same slope of the line as shown for chloride values for depths of 4 inches or less. This trend in the data was typical and none of the chloride values that were found for the concrete core disks that were obtained from 5 or 6 inches in depth were included in the regression analysis. The reason for the apparent disparity of chloride distribution at the 5 and 6-inch depth was not investigated.

ClibPDF - www.fastio.com

In order to determine if Equation (1) is a basic representation of the distribution of chlorides in concrete with depth, Tables 3 and 4 were prepared to show the results from new cores cut from six continuously submerged piles that were removed in 1968 from the abandoned 40-year old San Mateo-Hayward Bridge[1-6]. It should be noted that corrosion of the reinforcing was observed in all of those sections of the piles that were exposed to San Francisco Bay water. There was no observed evidence (cracking, rust stains, spalls, etc.) of corrosion in those sections of the piles that were continuously surrounded by the bay mud.

As shown on Tables 3 and 4, the 16-inch square piles were cored up to depths of 9 inches, or slightly more than one-half of the pile thickness. The data were plotted and analyzed by the method of least squares and the basic form of the equation was again found semi-logarithmic or the same as Equation (1).

For the sections of piling that have been continuously submerged for about 40 years, the derived relationship between the chloride content and depth was:

$$C = 40.6(0.682)^S \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Wherein:

C = chloride content of a 1-inch thick disk, pounds per cubic yard
S = maximum depth below the surface for any 1-inch thick disk, inches

For the "n" of 91 observations, the correlation coefficient was 0.932, and the standard error of the estimate was the $\log_{10}$ of 1.43.

For those sections of the piling which have been continuously submerged and in contact with bay mud for about 40 years, the derived relationship was:

$$C = 2.35(0.747)^S \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

For the "n" of 105 observations, the correlation coefficient was 0.641, and the standard error of the estimate was the $\log_{10}$ of 2.32.

The derived relationships of chloride versus depth as well as the plot of the simple average of the actual chloride content versus depth are shown on Figure 2, "Chloride in Concrete Piling."

ClibPDF - www.fastio.com

CORROSION LOSS OF STEEL

A total of 47 lineal feet of corroded deck reinforcing steel from Bridge 15 (Table 1), was removed and corrosion loss was measured. The method used was to measure the maximum metal loss by means of a micrometer within each lineal foot of the lightly sandblasted steel and results are shown on Figure 3 as a distribution curve.

The distribution of metal loss shown on Figure 3 has a log-normal distribution. By graphic analysis, Figure 3 indicates that the mean of the maximum metal loss for each lineal foot of the No. 4 reinforcing steel was 0.029-inch, or 29 mils. For this particular bridge, it was apparent that 29 mils of maximum metal loss within each lineal foot of steel would not significantly affect the overall strength of the structure.

Although 29 mils of maximum metal loss due to corrosion does not appear significant, it was found that in about 16% of the laboratory specimens a maximum metal loss of less than one mil was sufficient to crack a 7/8-inch thickness of concrete cover[9].

Deterioration - Concrete

On Table 1, eleven of the listed bridges are currently under contract for repair and application of a membrane; three have been repaired under a previous contract, and two are considered for complete deck restoration in the near future.

Depending on whether or not there has been chain traffic, the concrete deterioration has been evidenced by surface scaling as a result of tire chain abrasion and freeze-thaw damage, while the primary contributing factor in the bridge deck deterioration repairs is the spalling or lifting of the surface concrete. Where spalls have been removed, various degrees of corrosion of the steel has been observed.

However, the area of reinforcing steel corrosion has not necessarily been related to the total area of concrete spalling. This is not considered unusual as concrete spalls

ClibPDF - www.fastio.com

have been previously observed in the bottom of beams which extended for the entire beam width at the plane of the reinforcing and not all of the steel was corroded[1].

ClibPDF - www.fastio.com

SAMPLING

The data shown on Table 1 were further mathematically reduced and resulted in an observation that on the average, there is a relatively constant coefficient of variation[10] of the chloride content at any bridge or for any depth. The mean coefficient of variation for the chloride data shown in Tables 1 and 4, is approximately 30%. With a coefficient of variation of about 30%, the precision in determining the chloride content in concrete will be highly contingent upon the number of samples. For example, according to the recommended practice for choice of sample size, ASTM Designation E 122-58[10], in order to not exceed a sampling error of 10% more than one in 20 times, about 35 samples would be necessary.

Because of the importance of the chloride content of concrete, and the apparent 30% coefficient of variation that is found in the distribution of chlorides in concrete, Figure 4, "Sample Size versus Sample Error", was constructed on the basis of the ASTM Recommended Practice for Sample Size[10]. On Figure 4, the relationship was calculated on the basis that sample error would exceed the calculated tolerable sampling error once in 20 times. These relationships should provide guidance for any future sampling program.

Electrical Potentials

Previous studies have shown that electrical potential measurements could be made on the surface of the concrete and the locations of reinforcing corrosion could be electrically detected[1,2]. In making the electrical potential measurements, one electrical connection is made to the reinforcing while the second electrical connection is made to a saturated copper-copper sulfate half-cell. The half-cell is placed on the surface of the concrete and the measurements are made by using a high input impedance electronic voltmeter.

In this study, the electrical potential, or half-cell potential of the steel, was measured over a 2-foot grid in the longitudinal and the transverse direction on

ClibPDF - www.fastio.com

sections of two bridge decks. Then contours were drawn through the points of equal potential.

The results of the potential survey for one bridge deck is shown on Figure 5, "Equipotential Survey of Bridge Deck 1723R." As will be noted on Figure 5, the equipotential contours only show values of -0.10 and -0.15 volt negative to the copper-copper sulfate half-cell. For this particular section of this bridge deck, there is no evidence of deterioration as determined by visual observation, and the "sounding" of the deck by means of dragging a chain over its surface to "hear" hollow areas. However, there is a relatively minor amount of deterioration visible in other locations on this bridge deck.

In previous laboratory and field studies[1,9], it was observed that the steel was passive or noncorroding in uncracked concrete when the half-cell potential was less than about 0.25-volt negative to the copper sulfate half-cell. In cracked concrete, actively corroding steel has a half-cell potential that has ranged from about -0.25 to about -0.50-volt to the copper sulfate half-cell[9].

The section of bridge deck shown on Figure 6, "Equipotential Contours of Bridge Deck 1723L", is a bridge of the same age and design as 1723R, and is on parallel alignment. The only difference is that the bridge deck shown on Figure 5 currently has extensive deterioration.

The potential measurements of the bridge deck steel shown on Figure 6 were made at the same time that the repairs were being made. Except for one area, the concrete was removed from the steel at the cross-hatched locations at the time the measurements were being made. Because the salt contaminated concrete was not completely removed from the periphery of the steel, the still partially embedded steel exhibited active potentials. It is surmised that the measured potential of the partially exposed steel is less than that which would be observed prior to concrete removal. For example, near the central area of Figure 6, a potential contour of -0.40-volt is shown in a location of repair. The maximum recorded half-cell potential at this location was -0.43-volt. At this location the measurements of the half-cell potential of the steel were made prior to the removal of the concrete.

As will be noted on Figure 6, there is relatively good agreement between the location of repair and the enclosed area that is delineated by the potential contour of about

ClibPDF - www.fastio.com

-0.20-volt. Also, where potential contours are less than -0.20-volt, there is a significant lack of repairs. In effect, it appears that the electrical potential contours not only establish the fact that electro-chemical corrosion of the steel exists[1], but they may also have significance for estimating the amount of as well as the locations for repair.

Because of the electro-chemical phenomenon of the corrosion of the steel in concrete, it may be feasible to use the half-cell potential measurements of the steel to evaluate not only the corrosion activity of the steel, but also to evaluate the effectiveness of repair methods for arresting the corrosion of the steel.

ClibPDF - www.fastio.com

DISCUSSION

Although the study only encompassed a few California bridge decks, other states have made reports of their investigations on bridge deck problems[11,12,13].

As indicated by this study, chloridates penetrate concrete in a manner that can be mathematically described. Therefore, it is apparent that concrete cracking of bridge decks is not a prerequisite for the penetration of chloride to the surface of the steel. That corrosion of reinforcing can occur independently of cracking was established by the field investigation of the San Mateo-Hayward Bridge and laboratory studies[5,9,14]. However, there is no question that chloride can penetrate more rapidly to the surface of steel that has a cracked concrete or poor quality concrete covering, but the lack of cracks per se in a bridge deck will not prevent the penetration of the chloride salt. Also, the presence of chloride and corrosion of the steel will be a cause of concrete cracking and spalling[1,9].

In a previous laboratory study[9], reinforcing with 7/8-inch of excellent quality concrete cover (8 sacks per cubic yard, 2 inches of slump, moist cured, and air entrained), was found to corrode when partially immersed in a salt solution in less than one year. Therefore, it is apparent that a "normal" or average concrete mix per se could not be expected to prevent the penetration of salts with the resulting corrosion of the steel. However, there is no question that high concrete quality standards and practices should be strictly adhered to not only as a corrosion deterrent, but also because of other structural and durability factors, such as shrinkage, freeze-thaw, abrasion, etc. In addition, with concrete of high shrinkage, the problems associated with the use of a membrane would be vastly increased because it would be necessary for the membrane to elongate and "roof over" concrete cracks.

As indicated by this study, additional cover should provide proportionate increase in the forestalling of corrosion. However, with the direct application of chloride deicing salts to a bridge deck, significantly increasing the amount of cover over the steel may not completely

ClibPDF - www.fastio.com

prevent early deterioration because of the presence of some degree of deck cracking. For example, in California, it has been reported that practically all 21 of the investigated bridge decks had some form of cracking[15]. In the states of Illinois, Minnesota, New Jersey, Ohio, and Texas, it was reported that about two-thirds of the spans and about four-fifths of the investigated bridges had some type of cracking[15].

Recent studies of 1962[3] and 1966[16] indicated that a primary cause of bridge deck cracking could be the result of drying shrinkage[3] of concrete age[16]. Although these observations[3,16] may be correct, it is also probable that these factors which have caused concrete cracking have normally been present to some overall degree throughout the history of reinforced concrete bridge deck construction.

Further evidence of the destructive role of deicing salts was the apparent lack of significant bridge deck deterioration that was observed during the statewide survey of California bridges in 1960[4]. Also, no significant evidence of bridge deck deterioration had been reported during the yearly inspection of all bridges by Engineers of the Bridge Department of the California Division of Highways prior to about 1960. Therefore, this study indicates that the primary cause of widespread accelerated bridge deck deterioration in California is the relatively recent and increased use of chloride deicing salts.

Because of the mathematical similarity in the distribution of salt with depth in concrete decks and piling, it is important that the primary mechanism for salt penetration be thoroughly investigated.

It is speculated that chloride is distributed in bridge decks as a result of a primary mechanism of absorption by capillary action, and loss of water by evaporation to the atmosphere. If such a mechanism applies to bridge piles, then an effective method for reducing the rate of chloride penetration would be to physically restrict the loss of water vapor to the atmosphere by use of a membrane. Coating of the entire pile, above <u>and</u> below the water line would be even more effective.

For bridge decks, it is obvious that either a protective membrane or sealant will be required to prevent the penetration of salt into the concrete, or noncorrosive deicing chemicals should be used to prevent deterioration due to corrosion of the embedded steel.

ClibPDF - www.fastio.com

Of course, if noncorrosive chemicals were used on bridge decks, they would also have to be used for some length on adjacent pavement because of the "tracking" of the corrosive salts by vehicles. California pavements are non-reinforced so that salt damage to pavements would be limited to scaling or other attack of non-air-entrained portions. All concrete in freeze-thaw areas is normally specified to be air-entrained.

ClibPDF - www.fastio.com

REFERENCES

1. Gewertz, M. W.; Tremper, Bailey; Beaton, John L.; and Stratfull, R. F., Corrosion of Reinforcing Steel and Repair of Concrete in a Marine Environment, HRB Bulletin 182, 1958, 41 pp.

2. Stratfull, R. F., The Corrosion of Steel in a Reinforced Concrete Bridge, Corrosion, Vol. 13, No. 3 June 1957

3. Stratfull, R. F., Progress Report on Inhibiting the Corrosion of Steel in a Reinforced Concrete Bridge, Corrosion, Vol. 15, No. 6, June 1959

4. Beaton, J. L., and Stratfull, R. F., Environmental Influence on Corrosion of Reinforcing Steel in Concrete Bridge Substructures, Highway Research Record 14, pp 60-78, 1963

5. Stratfull, R. F., Effect on Reinforced Concrete in Sodium Chloride and Sodium Sulfate Environments, Materials Protection, Vol. 3, No. 12, p. 75, Dec. 1964

6. Beaton, J.L.; Spellman, D.L.; and Stratfull, R.F.; Corrosion of Steel in Continuously Submerged Reinforced Concrete Piling, Highway Research Record 204, pp 11-21, 1967

7. Report 3, Durability of Concrete Bridge Decks, A Cooperative Study, California Division of Highways, U.S. Department of Transportation, Bureau of Public Roads, and Portland Cement Association, 1967

8. Brownlee, K. A., Industrial Experimentation, Chemical Publishing Co., Inc., Brooklyn, N. Y., 1949

9. Spellman, D. L. and Stratfull, R. F., Laboratory Corrosion Test of Steel in Concrete, State of California, Transportation Agency, Dept. of Public Works, Div. of Highways, Materials and Research Dept., Research Report No. M&R 635116-3, September 1968

ClibPDF - www.fastio.com

10. ASTM Committee E-11, ASTM Manual on Quality Control of Materials, Special Technical Publication 15-C, Jan. 1951

11. A Study of Deterioration in Concrete Bridge Decks, a Progress Report on Investigation 59-2A, HPR 1(4)-30 Division of Materials and Research, Missouri State Highway Department, Jefferson City, Missouri, Oct. 1965

12. Bukovatz, John E., Bridge Deck Deterioration Study, Part 7, Weathering Test of Reinforced Concrete Slab with Various Depths of Steel, State Highway Commission of Kansas, Planning and Research Department, 1968

13. Hughes, R. D., and Scott, J. W., Concrete Bridge Decks, Deterioration and Repair, Kentucky Department of Highways, Division of Research, June 1969

14. Ost, Borje, and Monfore, G. E., Penetration of Chloride into Concrete, Journal PCA, Vol. 8, No. 1, Jan. 1966, pp 46-52

15. Report 5, Durability of Concrete Bridge Decks, A Cooperative Study, published by the Portland Cement Association, 1969

16. Stewart, C. F., and Neal, B. F., Factors Affecting the Durability of Concrete Bridge Decks, Highway Research Record No. 226, pp 50-68, 1968

ClibPDF - www.fastio.com

TABLE 1

Distribution of Chlorides in California Bridge Decks

Bridge Number	No. of Cores	n		Calculated Pounds per Cubic Yard Depth below surface - inches					
				1	2	3	4	5	6
1-273	6	28	Mean	4.58	2.15	.91	.48	.44	
			Std. Dev.	1.89	1.05	.48	.18	.09	
2-266	6	29	Mean	3.85	2.31	.85	.49	.45	
			Std. Dev.	1.92	1.67	.65	.25	.03	
3-6119	6	25	Mean	4.42	2.72	.85	.40	.40	
			Std. Dev.	1.54	2.31	.40	.13	0.00	
4-6117	6	24	Mean	7.47	2.65	1.12	.63	.40	
			Std. Dev.	1.80	.76	.34	.24	0.00	
5-695	20	86	Mean	4.53	2.08	.75	.26	.26	.20
			Std. Dev.	1.56	1.45	.85	.16	.06	0.00
6-202	19	107	Mean	7.84	.85	.25	.23	.23	.28
			Std. Dev.	1.94	.31	.06	.06	.09	.11
7-289	6	31	Mean	5.25	3.61	1.21	.55	.46	.64
			Std. Dev.	2.93	2.60	.75	.18	.03	0.00
8-265	6	29	Mean	4.15	1.45	.64	.43	.45	
			Std. Dev.	1.61	.47	.25	.04	.02	
9-6116	22	104	Mean	5.73	2.47	.86	.33	.36	.18
			Std. Dev.	1.82	1.02	.38	.31	.32	.02
10-2515	7	31	Mean	1.79	1.87	1.06	.86	.81	
			Std. Dev.	1.30	1.88	.93	.58	.41	
11-513	11	46	Mean	8.32	3.47	1.82	.63	.42	.50
			Std. Dev.	2.60	2.68	1.92	.42	.02	.03

Continued

ClibPDF - www.fastio.com

Table 1 (Continued)

Bridge Number	No. of Cores	n		Calculated Pounds per Cubic Yard Depth below surface - inches					
				1	2	3	4	5	6
12-6112	6	30	Mean	5.81	2.44	.74	.41	.42	.44
			Std. Dev.	1.39	.35	.21	.02	.02	0.00
13-244	21	94	Mean	3.58	1.50	.43	.32	.41	
			Std. Dev.	.96	.80	.24	.06	.05	
14-278	6	26	Mean	5.63	2.68	.87	.53	.46	
			Std. Dev.	1.61	.90	.22	.09	.03	
15	19	81	Mean	12.5	4.77	1.07	.464	.394	
			Std. Dev.	3.76	2.72	1.23	.248	.139	
16	20	84	Mean	10.4	4.58	1.68	.821	.504	
			Std. Dev.	4.25	2.27	1.45	.807	.619	

ClibPDF - www.fastio.com

TABLE 2

Calculated Distribution of Chlorides in Bridge Decks

Bridge Number	Year Built	Length Feet	Width Feet	Equation[1] Regression Analysis	Std. Error of Est. is Log_{10} of:	n	Coeff. of Correlation	Bridge Type
1-273	1960	159	84	$C=8.55(0.471)^S$	1.63	24	0.874	Conc.Grdr.,Cont.
2-266	1960	172	84	$C=6.54(0.501)^S$	1.93	24	0.776	Same
3-6119	1960	125	84	$C=10.0(0.438)^S$	1.65	22	0.878	Same
4-6117	1960	125	84	$C=15.2(0.432)^S$	1.35	22	0.956	Same
5-695	1960	136	84	$C=11.2(0.370)^S$	1.99	78	0.851	Same
6-202	1917	579	28	$C=14.2(0.309)^S$	1.88	86	0.903	R.C. Arch
7-289	1960	45	80	$C=10.5(0.471)^S$	1.87	24	0.813	Conc.Grdr.,Cont.
8-265	1960	134	84	$C=7.07(0.472)^S$	1.43	24	0.927	Same
9-6116	1960	250	84	$C=16.2(0.358)^S$	1.66	83	0.913	Conc.Grdr.,Box
10-2515	1936	120	24	$C=1.81(0.796)^S$	2.07	25	0.348	Conc. Girder
11-513	1963	352	32	$C=17.4(0.407)^S$	2.14	39	0.800	Conc. Grdr., Box
12-6112	1962	99	84	$C=13.7(0.404)^S$	1.28	24	0.975	Conc.Grdr.,Cont.
13-244	1959	126	28	$C=6.95(0.433)^S$	1.64	84	0.887	Same
14-278	1960	147	84	$C=12.0(0.443)^S$	1.34	24	0.956	Same
15	1959	92	39	$C=36.7(.306)^S$	1.99	74	0.888	Same
16	1960	---	48	$C=17.7(.456)^S$	2.20	75	0.747	Same

(1) C = chlorides, lbs./cubic yard; S = depth below concrete surface, inches

ClibPDF - www.fastio.com

TABLE 3

Chloride in Submerged Piles Exposed to Bay Water

Avg. Depth Below PCC Surf.(Ins.)	Pile Core		Lbs. Chloride per Cubic Yard of Concrete - 1" Disk										
	1-3	1-4	2-1	2-2	3-5	3-6	4-3	4-4	4-5	5-3	5-4	6-3	6-4
1	24.00	26.00	30.00	28.00	22.00	22.00	26.00	20.00	22.00	38.00	20.00	22.00	18.00
2	17.60	22.00	18.00	16.00	18.00	18.00	16.00	14.00	18.00	22.00	19.20	15.20	18.00
3	14.00	15.20	12.00	12.00	12.00	12.00	13.20	12.00	-----	12.00	14.40	12.00	13.20
4	9.60	12.00	12.00	7.20	10.00	9.60	9.60	10.00	-----	7.20	12.00	10.00	8.80
5	7.20	7.60	6.40	5.20	-----	6.40	5.60	8.00	-----	5.20	8.40	5.60	8.00
6	7.20	5.60	3.60	2.00	3.60	3.00	3.60	3.80	-----	2.40	4.00	3.20	5.60
7	3.60	2.80	2.00	0.80	1.40	1.80	-----	2.40	-----	-----	1.80	1.28	4.00
8	3.20	1.60	1.40	-----	-----	1.00	-----	-----	-----	-----	1.20	-----	3.80
9	3.00	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----

ClibPDF - www.fastio.com

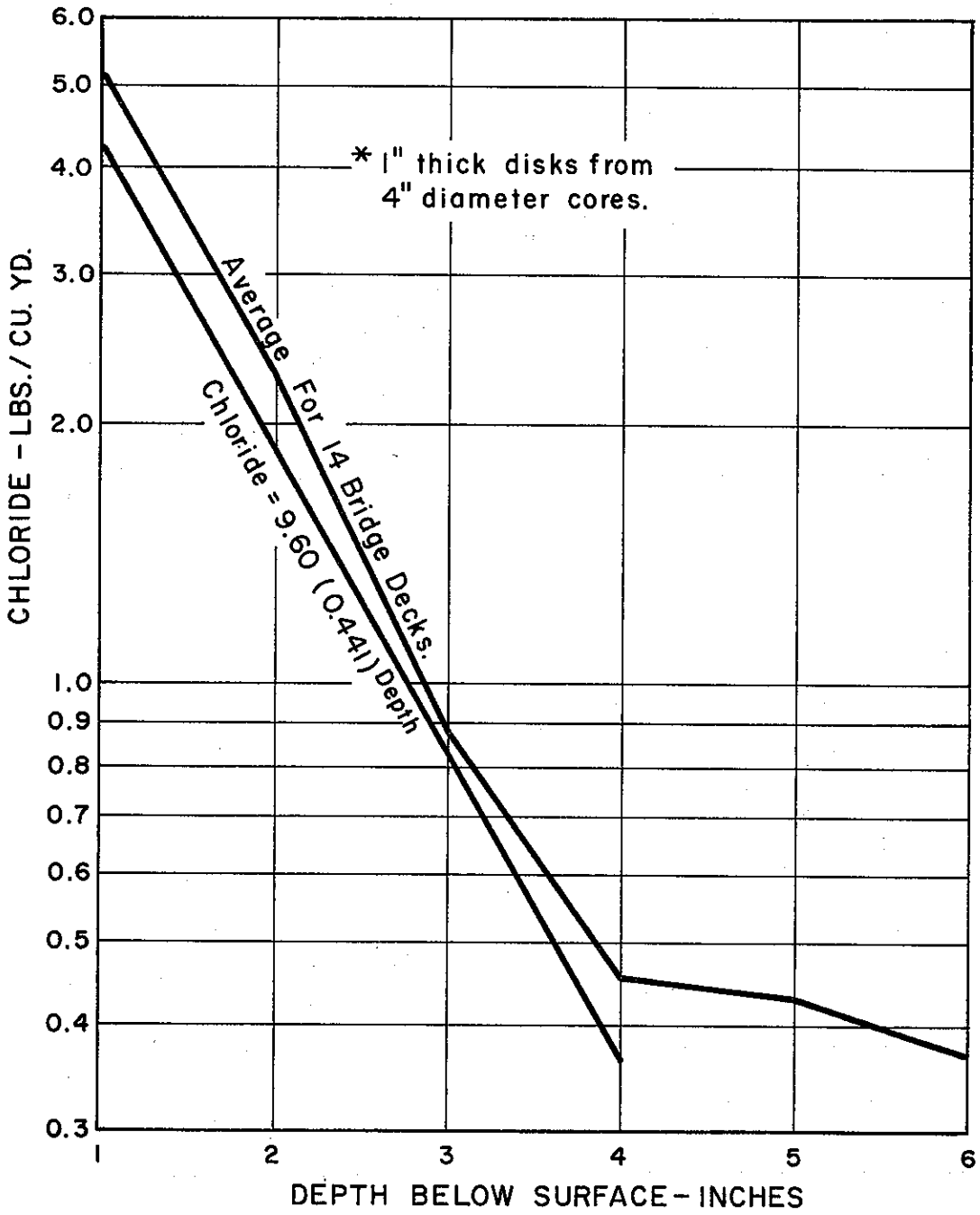
TABLE 4

Chloride in Submerged Piles Exposed to Bay Mud

Avg. Depth Below PCC Surf. (Ins.)	Lbs. Chloride per Cubic Yard of Concrete - 1" Disc Pile Core													
	1-1	1-2	2-3	2-4	3-1	3-2	3-3	3-4	4-1	4-2	5-1	5-2	6-1	6-2
1	2.00	2.60	1.40	1.20	1.60	1.12	1.28	1.08	15.20	8.00	1.20	1.20	6.00	3.40
2	1.12	1.40	0.72	0.52	0.80	0.60	0.88	0.80	12.00	7.20	0.72	0.60	3.40	1.80
3	1.00	0.88	0.40	0.48	0.48	0.52	0.56	0.48	8.00	4.40	0.72	0.36	1.80	1.00
4	0.64	0.68	0.40	0.28	0.36	0.36	----	0.32	6.00	3.40	0.48	0.32	1.20	0.72
5	0.48	0.44	0.20	0.20	0.32	0.28	----	0.28	4.00	2.00	0.20	0.24	0.80	0.52
6	0.36	0.44	0.20	0.12	0.20	----	----	0.28	3.00	1.40	0.16	0.20	0.48	0.32
7	0.24	0.48	0.16	0.12	0.24	----	----	0.36	-----	1.00	0.16	0.16	0.32	0.28
8	0.20	0.48	----	0.16	0.32	----	----	0.28	-----	0.80	0.56	0.24	0.20	0.28
9	----	----	----	0.16	----	----	----	0.40	-----	----	----	0.16	0.28	----

ClibPDF - www.fastio.com

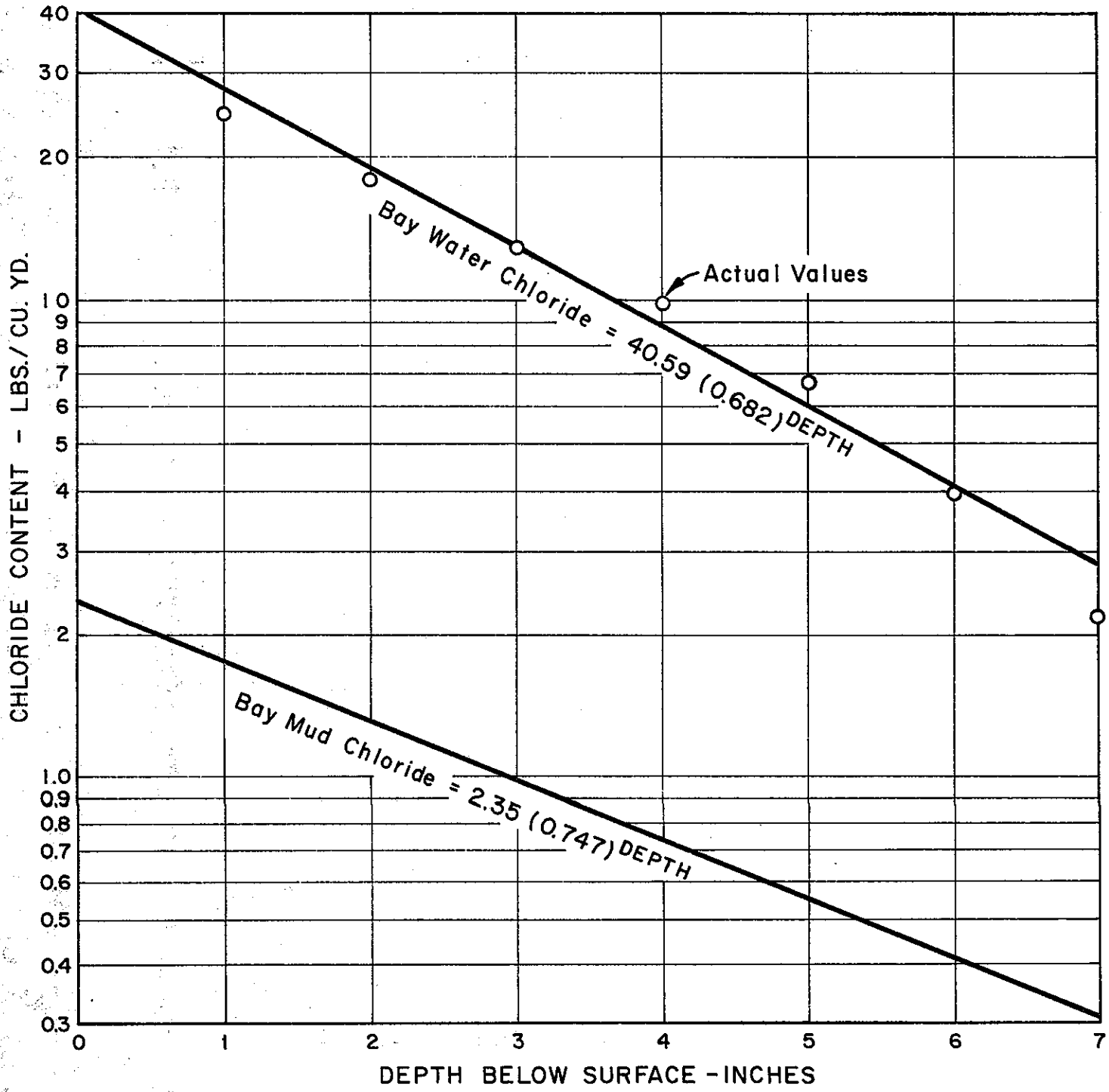
AVERAGE DISTRIBUTION OF CHLORIDE IN BRIDGE DECKS*



ClibPDF - www.fastio.com

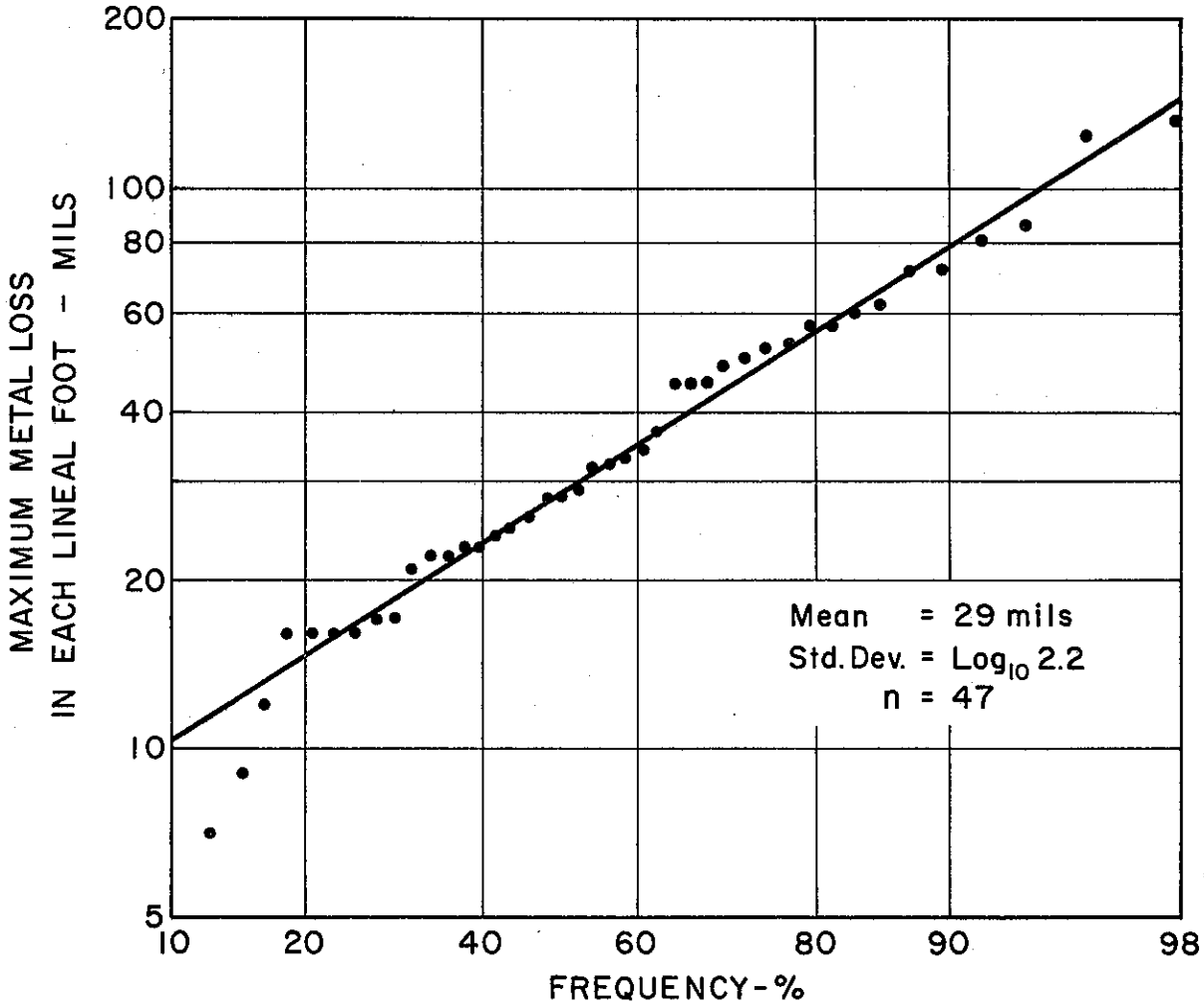
Figure 2

CHLORIDE IN CONCRETE PILING



ClibPDF - www.fastio.com

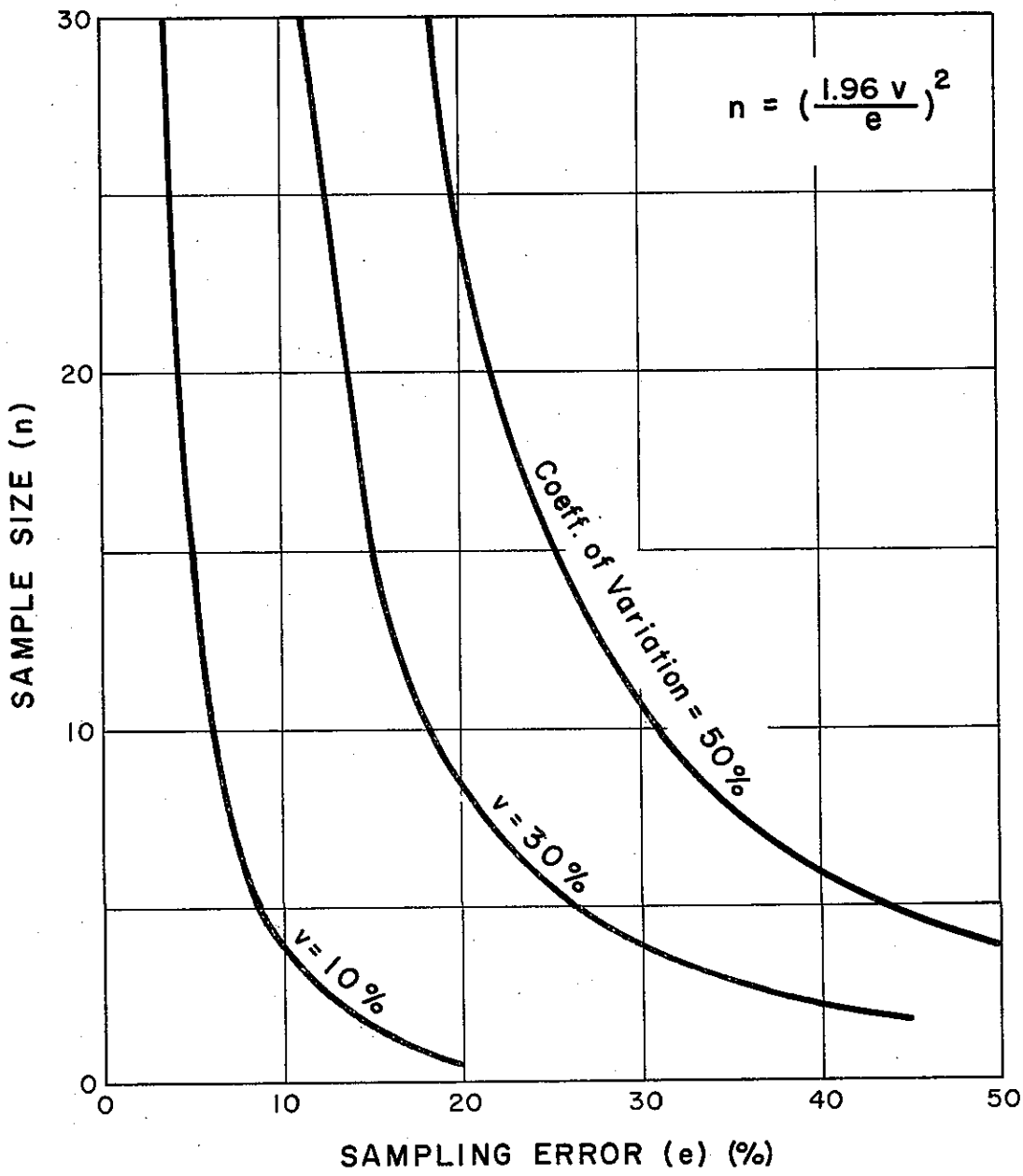
CORROSION OF REINFORCING
IN BRIDGE 15



ClibPDF - www.fastio.com

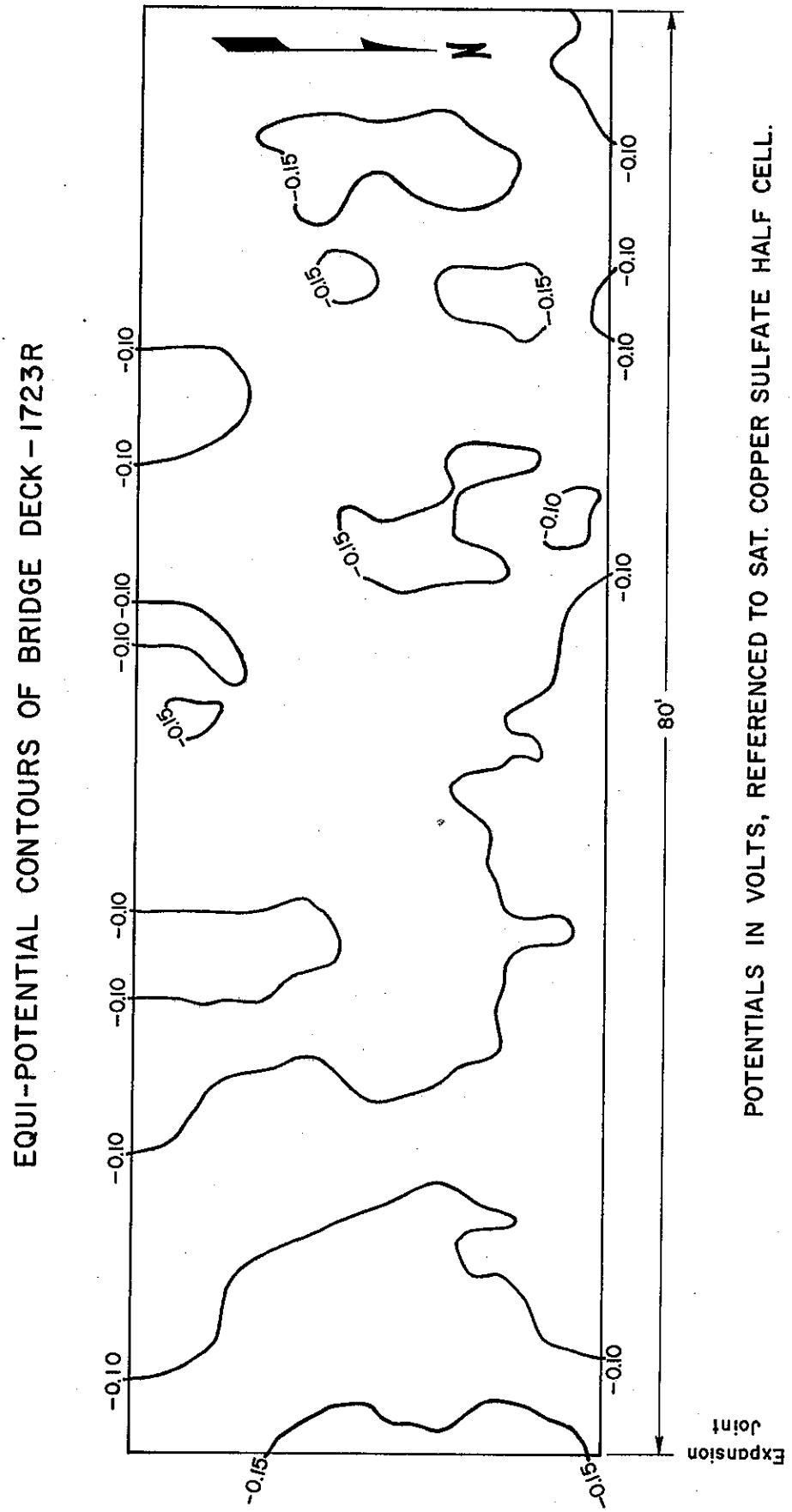
Figure 4

SAMPLE SIZE VERSUS SAMPLE ERROR



ClibPDF - www.fastio.com

Figure 5

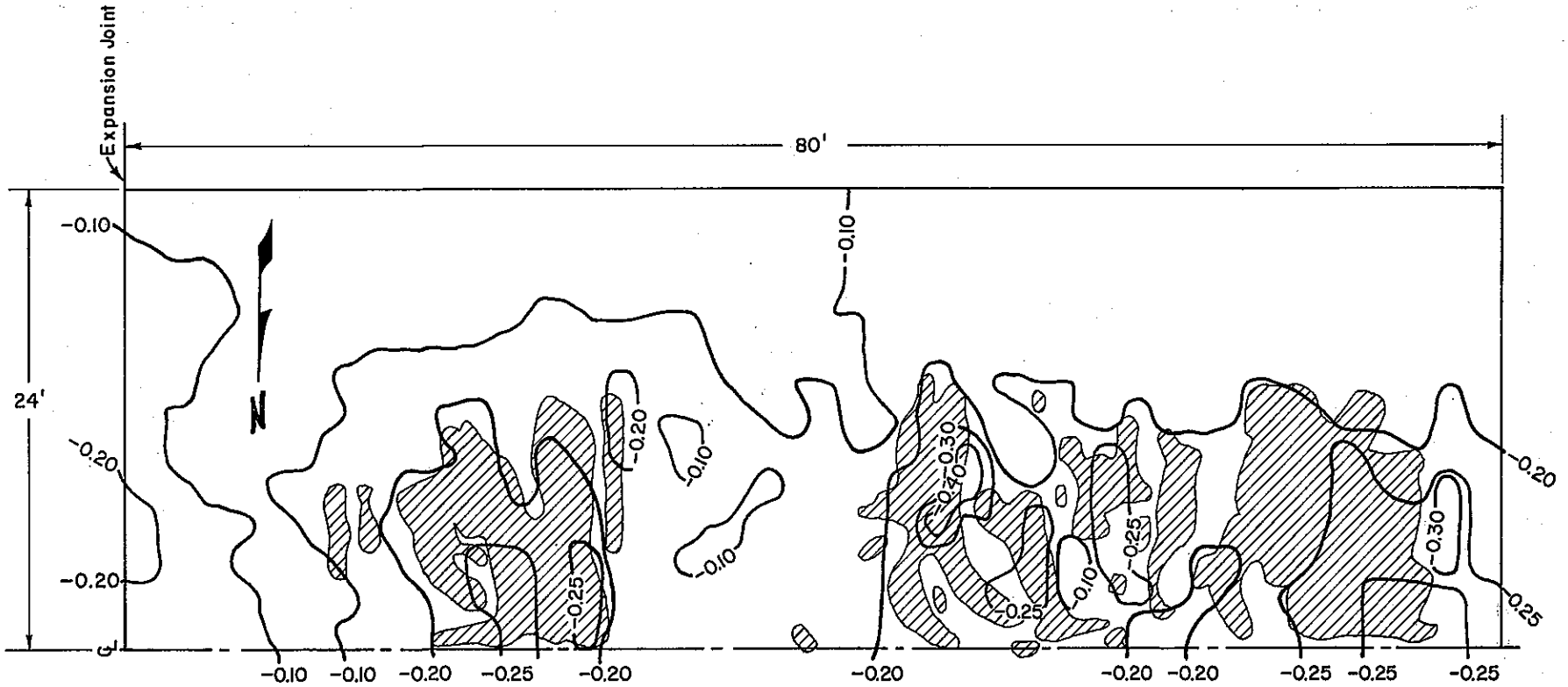


POTENTIALS IN VOLTS, REFERENCED TO SAT. COPPER SULFATE HALF CELL.

ClibPDF - www.fastio.com

Figure 6

EQUI-POTENTIAL CONTOURS OF BRIDGE DECK - 1723L



AREAS OF CORRODING STEEL

POTENTIALS IN VOLTS, REFERENCED TO SAT. COPPER SULFATE HALF CELL.

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com

ClibPDF - www.fastio.com