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16. Abstract

The protection against corrosion provided reinforcing bars by polymer-impregnated concrete was investigated. Partially-impregnated slabs and fully-impregnated piling specimens were used in the investigation. The slabs were sprayed with salt water for 20 months and the pilings were immersed in sea water for 12 and 28 months.

The bars from the control slabs had about 24 times more surface area corrosion than bars from the treated slabs. The chloride content in the treated slabs ranged from 4.6 percent to 38.2 percent of that in the control slabs.

The bars from the control piles had corrosion ranging from 10 percent to 39 percent over the surface area while the PIC specimens had corrosion over 0.5 percent or less of the bar area. The chloride content of the PIC piles ranged from 3.4 percent to 8.5 percent of the chloride in the controls.

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# CORROSION PROTECTION OF REINFORCING STEEL PROVIDED BY POLYMER-IMPREGNATED CONCRETE

by

David W. Fowler
Donald R. Paul
Piti Yimprasert

Research Report Number 114-2

Polymer-Impregnated Concrete for Highway Applications
Research Project 3-9-71-114

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

December 1974

# PREFACE

This report is the second in a series which summarizes the research findings related to applications of polymer-impregnated concrete. The research has emphasized the development of practical methods of application for highway bridge decks and the durability and service characteristics of the impregnated concrete.

This report summarizes research on the corrosion protection provided reinforcing steel in surface-impregnated slabs subjected to long-term salt water spray and fully-impregnated piles immersed in sea water for extended periods of time.

The authors wish to extend their appreciation to the personnel of the Texas Highway Department Materials and Tests Division (D-9) who performed chloride content determinations and microscopical examinations of the specimens. In particular, thanks are due to Donald O'Connor and Thomas Patty for their help.

Special mention is due Dr. J. T. Houston, formerly a Study Supervisor, for his construction of the specimens and initiation of the tests. The authors are indebted to Mr. Herman Schneeman, Jr. of District 16, who cooperated in placing and removing the pilings from the water. The suggestions and encouragement of John Nixon, Donald O'Connor, Maurice Ferrari, and Andy Seely of the Texas Highway Department were particularly helpful.

Future reports will summarize research related to

(1) repair of cracks and damaged beams;
(2) cycling loading tests of surface-impregnated reinforced concrete members; and
(3) methods of application for highway bridge decks.

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# ABSTRACT

The protection against corrosion provided reinforcing bars by polymer-impregnated concrete was investigated. Partially-impregnated slabs and fully-impregnated piling specimens were used in the investigation. The slabs were sprayed with salt water for 20 months and the pilings were immersed in sea water for 12 and 28 months.

The bars from the control slabs had about 24 times more surface area corrosion than bars from the treated slabs. The chloride content in the treated slabs ranged from 4.6 percent to 38.2 percent of that in the control slabs.

The bars from the control piles had corrosion ranging from 10 percent to 39 percent over the surface area while the PIC specimens had corrosion over 0.5 percent or less of the bar area. The chloride content of the PIC piles ranged from 3.4 percent to 8.5 percent of the chloride in the controls.

KEY WORDS: polymer-impregnated concrete, polymers, corrosion, reinforcing steel, chloride, slabs, bridge decks, piles.

# SUMMARY

Polymer-impregnated concrete (PIC) has been proposed for use in highway structures, to take advantage of the improved durability properties. Surface-impregnated bridge decks and fully-impregnated beams and pilings are possible applications that appear promising for the use of PIC.

Twelve pairs of slabs were cast and cured under field-simulated conditions. One of each slab pair was reinforced with seven No. 8 bars in the top surface. Ten of the slab pairs were dried, covered with sand, and soaked with a monomer solution that was polymerized to produce a polymer surface treatment. The ten treated slabs and two untreated control slabs that were reinforced were subjected to salt water spray, twice a day, for 20 months. The bars were then removed and examined for corrosion. The concrete was analyzed for chloride content. The polymer was found to significantly decrease the corrosion of the reinforcing steel. Bars from the control specimens exhibited 27 percent corrosion over the surface area, or about 24 times more corrosion than bars from treated slabs. The chloride content in the treated slabs ranged from 4.6 percent to 38.2 percent of that in the control slabs, which had an average chloride content of 23.3 lb/cu. yd.

Two series of small reinforced concrete piles were evaluated to determine the protection provided by full impregnation of monomer. The specimens were dried, evacuated, and soaked with monomer that was polymerized. The two series of specimens were placed in sea water for 28 months and 12 months, respectively. They were removed for evaluation of corrosion and chloride content. Bars from the two groups of control specimens had corrosion over 10 percent and 39 percent, respectively, of their surface areas while the bars from the PIC specimens averaged 0.2 percent and 0.5 percent. The maximum chloride contents in the two sets of control piling were 22.0 lb/cu. yd. and 20.3 lb/cu. yd. The PIC specimens had chloride contents ranging from 3.4 percent to 8.5 percent of the chloride in the controls.

# IMPLEMENTATION STATEMENT

The research results contained in this report indicate the improvements in protection of reinforcement against corrosion that result from polymer impregnation of concrete. Other results reported in Research Report 114-1 indicated excellent resistance to freeze-thaw, water penetration, and cyclic loading; excellent strength; and practical methods of application.

The advantages of partial polymer-impregnation of concrete bridge decks make the process an attractive alternative to existing methods of preventive maintenance and repair. It seems quite probable that polymer-impregnation will also be feasible for achieving more durability of piling, reinforced beams, and other reinforced concrete members.

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CHAPTER 2. PARTIALLY-IMPREGNATED SLABS

CHAPTER 3. FULLY-IMPREGNATED PILE SPECIMENS

# CHAPTER 1. INTRODUCTION

In recent years much attention has been given to the problem of deterioration of concrete highway bridge decks. Deterioration of concrete bridge decks can be caused or accelerated by many factors, including overloading, shrinkage and repeated loads. However, it is theorized that one of the, if not the major, causes of bridge deck deterioration is the ingress of water. Freezing and thawing of the water inside the concrete slab can result in severe damage to the concrete. Corrosion of the reinforcing bars, also a result of water penetration, is a serious problem because it is often progressive and may ultimately lead to cracking or spalling of the concrete. The use of salt as a deicing agent accelerates the corrosion of reinforcing steel.

The advantages of polymer-impregnated concrete have been well documented in the past several years. The compressive strength, tensile strength, stiffness, resistance to acid corrosion and water penetration, and freeze-thaw durability have been shown to be significantly improved (Refs 3 through 8).

As a result of these advantages, considerable research has been underway in the past several years to develop partial or surface impregnation techniques for concrete bridge decks (Refs 3 and 8). The resistance to freeze-thaw deterioration, water penetration, and equal or improved skid resistance afforded by the surface polymer-impregnation of concrete have been demonstrated to be significantly improved. Since freeze-thaw deterioration and corrosion of reinforcement are believed to be two of the primary causes of bridge deck deterioration, the surface impregnation procedure has considerable potential to prolong the life of bridge decks.

Studies were begun in 1972 to determine the degree of protection provided reinforcing steel by polymer-impregnated concrete in surface-impregnated slabs and fully-impregnated piling specimens. The materials, test methods, and preliminary results are described in a previous report (3). This report summarizes the evaluation of the specimens after long-term application of salt water. The corroded area of each bar and the chloride ion contents of the concretes were determined.

# CHAPTER 2. PARTIALLY-IMPREGNATED SLABS

## 2.1. Test Specimens

Twelve pairs of slabs, 5-1/2 x 40 x 43 in., were cast outdoors to simulate field curing and exposure conditions. Each pair consisted of one reinforced and one unreinforced slab. The arrangement of the seven No. 8 bars in each reinforced slab is shown in Fig 2.1. The nominal clear cover was 1-1/4 in. The concrete had a water-cement ratio of 6.5 gal/sk, a cement factor of 6.0 sk/cu. yd., a 3-in. slump, and a 28-day moist-cured compressive strength of 6400 psi.

## 2.2. Polymer Impregnation

The slabs were at least 90 days old before impregnation. Prior to impregnation, the slabs were dried with a heating blanket for a minimum of three days. Surface temperatures were in the range of 140 to $150^{\circ}$ F. After drying, the slabs were covered with a polyethylene membrane and permitted to cool.

A 1/4-in. depth of dry lightweight fine aggregate (expanded shale) was placed on each slab to hold the monomer. The slabs were sloped 1/4 in. per ft, to simulate the minimum slope of bridge decks. The slabs, which were treated in pairs, were then wetted thoroughly with the monomer solution. The aggregate was kept moist by periodic application of monomer as required. The monomers used were methyl methacrylate (MMA), isobutyl methacrylate (IBMA), and isodecyl methacrylate (IDMA). With each monomer, 1% (wt) benzoyl peroxide (BP) catalyst and 10% (wt) trimethylpropane trimethzcrylate (TMPTMA) cross-linking agent were used. The monomer systems and quantities are shown in Table 2.1. The soak times ranged from 10 to 24 hours.

After completion of the soaking period, the slabs were cured by ponded hot water ($200^{\circ}$ F) with a depth of 3 in. over a plastic membrane which covered the slabs or by heating blankets. Typical surface temperature curves for the two methods are shown in Fig 2.2. Due to the insulating effect of

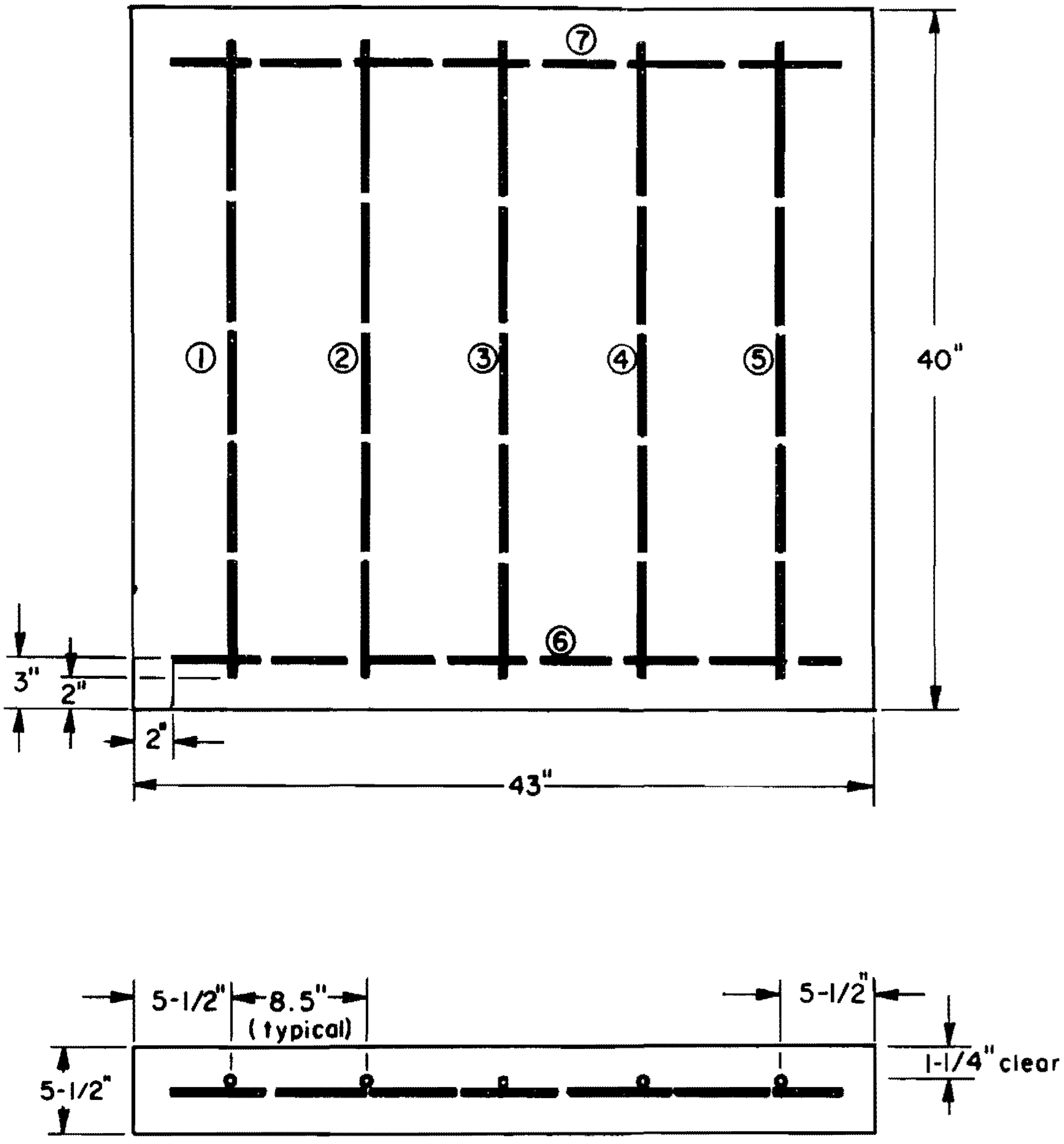

Fig 2.1. Arrangement of No. 8 reinforcing bars in test slabs.

## TABLE 2.1. SUMMARY OF SLAB TREATMENTS AND FREEZE-THAW TESTS

| Slab No. | Monomer System | Quantity of Monomer, ml/m$^2$ | Soak Time, hours, and Temperature Range, ° F | | Cure Method | Average Polymer Depth, in. | Maximum Freeze-Thaw Cycles |
|---|---|---|---|---|---|---|---|
| 1 | Control | --- | | | --- | --- | 30 |
| 2 | MMA[a] | 4280 | 10 | 73°-94° | HW[c] | 0.25-0.75 faint, uniform | 120[e] |
| 3 | IBMA[a] | 3600 | 10 | 77°-93° | HW | 0.75 faint, uniform | 91 |
| 4 | IBMA[a] | 4500 | 24 | 75°-90° | HW | 0.5-1.5 faint, uniform | 117 |
| 5 | IDMA[a] | 2700 | 10 | 77°-93° | HW | 0.25-0.5 very faint, uniform | 120[e] |
| 6 | Control | --- | --- | | --- | --- | 40 |
| 7 | IDMA[a] | 3600 | 24 | 75°-90° | HW | 0.25-0.5 dark to faint | 117 |
| 8 | MMA[a] and | 6750 | 24 | 75°-93° | | 0.5-0.75 faint, uniform | 120[e] |
| | MMA[b] | 900 | 0.25 | 93° | HW | | |
| 9 | MMA[a] and | 4500 | 18 | 59°-80° | | | |
| | MMA[b] | 1350 | 1 | 80° | HB[d] | 0.25-0.5 faint, non-uniform | 120[e] |
| 10 | MMA | 6750 | 24 | 75°-90° | HW | 0.5-0.75 faint, uniform | 120[e] |
| 11 | MMA | 9900 | 18 | 59°-80° | HB | 0.25-0.50 faint, uniform | 120[e] |
| 12 | MMA | 9900 | 24 | 58°-82° | HB | 0.5 very faint, uniform | 120[e] |

[a] Monomer system included monomer, 1% BP, 10% TMPTMA

[b] Second monomer application included monomer, 4% lauroyl peroxide, 4% DMPT

[c] HW = hot water

[d] HB = heating blanket

[e] Testing terminated after 120 cycles

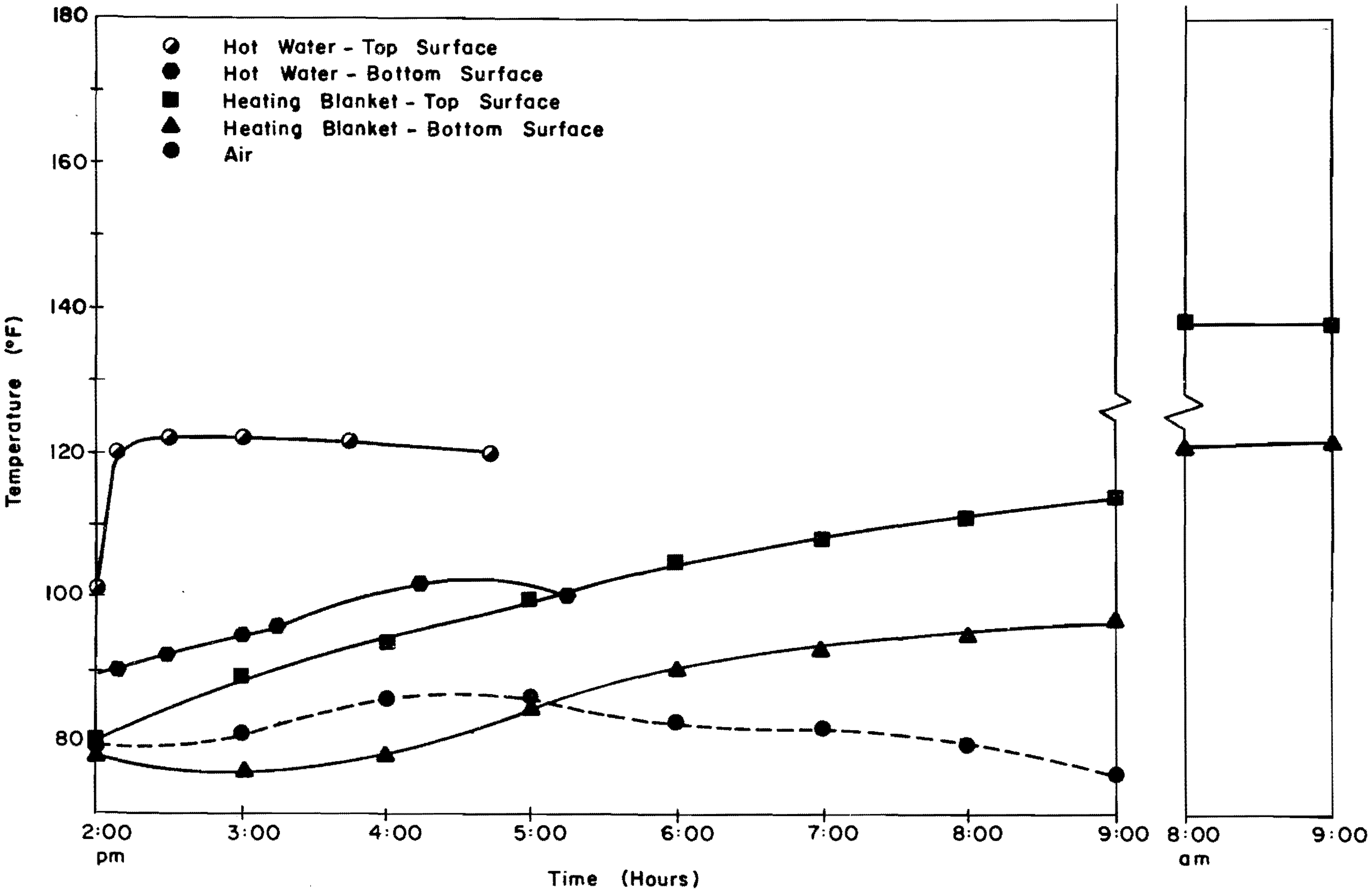

Fig 2.2. Time-temperature curves for field-treated slabs.

the lightweight fine aggregate, the surface temperatures of the slabs did not attain the temperature of the water during curing or the surface temperatures of the heating blankets during drying. During the entire treatment procedure, the slabs remained outdoors in an unprotected environment.

## 2.3. Test Procedure

After 10 pairs of slabs were treated, each reinforced slab was placed on four concrete blocks to elevate it. The unreinforced slabs were cut into 12 x 12-in. specimens and taken to the laboratory for water penetration, abrasion, and freeze-thaw tests, which have been previously described (3). The number of freeze-thaw cycles each specimen underwent is given in Table 2.1. The control specimens, 1 and 6, failed after 30 and 40 cycles, respectively. All of the specimens treated with MMA completed 120 cycles, which was the arbitrary limit.

Each reinforced slab was sprayed twice daily, five days each week (except when it was raining), with a solution of 7.5 pounds of salt in 30 gallons of water. The salt water spray application began July 20, 1972, and continued until March 29, 1974, a period of 618 days.

## 2.4. Evaluation of Specimens

At the conclusion of the water spray application, the control slabs had developed cracks above the reinforcing bars (Fig 2.3), with some corrosion stain in evidence on the surface. The treated specimens were generally in very good condition (Fig 2.4) although some stain was observed along the sides where the form tie wire protruded.

The slabs were broken with an air hammer. The reinforcing bars and representative pieces of the concrete were removed for further evaluation.

2.4.1. Quality of polymer impregnation--The depth and quality of the polymer impregnation in each of the treated slabs are given in Table 2.1. The polymer impregnation was relatively poor in contrast to the results achieved using current procedures. The color of the polymer was generally faint, and the depth of the impregnation ranged from 1/4 to 3/4 in. Microscopical examinations did not reveal polymer within the few entrapped air voids found near the surface or within microcracks extending from the top surface (9). The primary reason for the low quality treatments was most

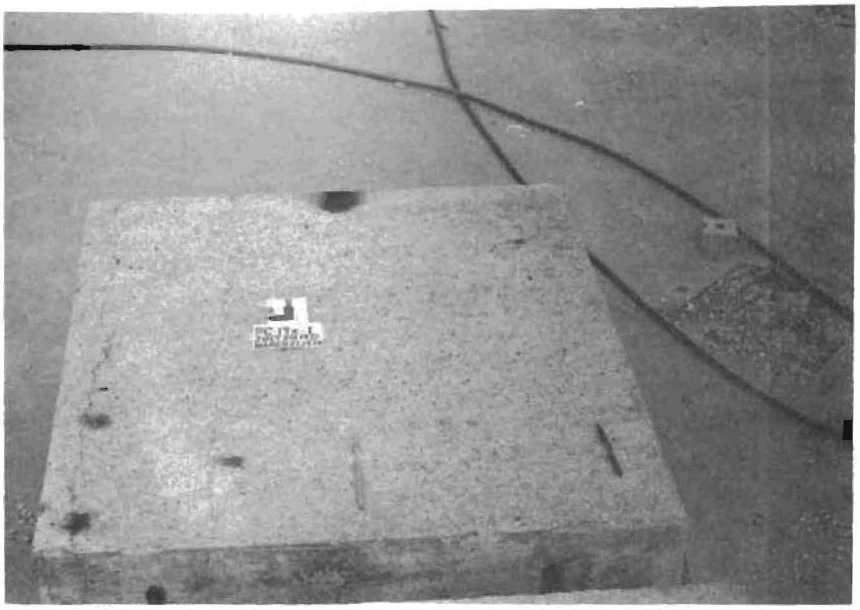

Fig 2.3. Unimpregnated control slab (No. 1) after salt water spray exposure.

Fig 2.4. Impregnated slab (No. 7) after salt water spray exposure.

likely the low drying temperatures (140° to 150° F) which were being used at the time of these treatments. Additionally, the higher quality concrete probably resulted in a lower porosity, which allows less monomer to be absorbed as compared to lower strength concrete.

The lower quality impregnation provided an indication of the minimum protection that would be expected to be provided by PIC. The significantly better treatments which are now routinely obtained should provide better protection.

2.4.2. Corrosion of reinforcing bars--To determine the corrosion of the reinforcing bars, each bar was examined on the basis of the upper half surface and the lower half surface. Each bar was further subdivided into 1/2-in. increments. The amount of surface area covered with corrosion was estimated for the upper and lower surface for each 1/2-in. increment. This procedure was based on the evaluation reported in Ref 10.

A photograph of bars from a typical control slab and a typical treated slab are shown in Figs 2.5 and 2.6, respectively. A summary of the corrosion measurements is given in Table 2.2. Corrosion values are given (1) for all of the bars; (2) for the interior bars only (Refs 2, 3, and 4); and (3) for exterior bars only (Refs 1, 5, 6, and 7). It was apparent that some water came in through the sides of the slabs, where there was no polymer to provide protection. The interior bars, neglecting the outer three inches at each end, provide a more realistic representation of the corrosion protection. It can be seen from Table 2.2 that all of the interior bars from the treated slabs had lower corrosion values than the average from all of the bars, except No. 3, which had the same values. The interior bars from the controls, 1 and 6, indicated more corrosion than the average of all the bars. Based on the interior bars, the control specimens had an average corrosion of 27.0 percent versus only 1.1 percent for the average of all the treated slabs, which indicates 24 times more corrosion for the control specimens. The effectiveness of the polymer impregnation becomes even more significant when the relatively poor quality of the polymer impregnation is considered.

2.4.3. Chloride ion content--The chloride ion content was determined by the Texas Highway Department Materials and Tests Division from specimens taken from the top surface of slabs 1, 2, 4, 7, 8, and 12 (Ref 7). The specimens were approximately four inches square and varied in depth from 1-1/4 in. to 3-3/4 in. Samples for analysis were obtained by drilling holes with a 5/8-in. diameter concrete drill to a depth of 1-1/4 in., which was the approximate

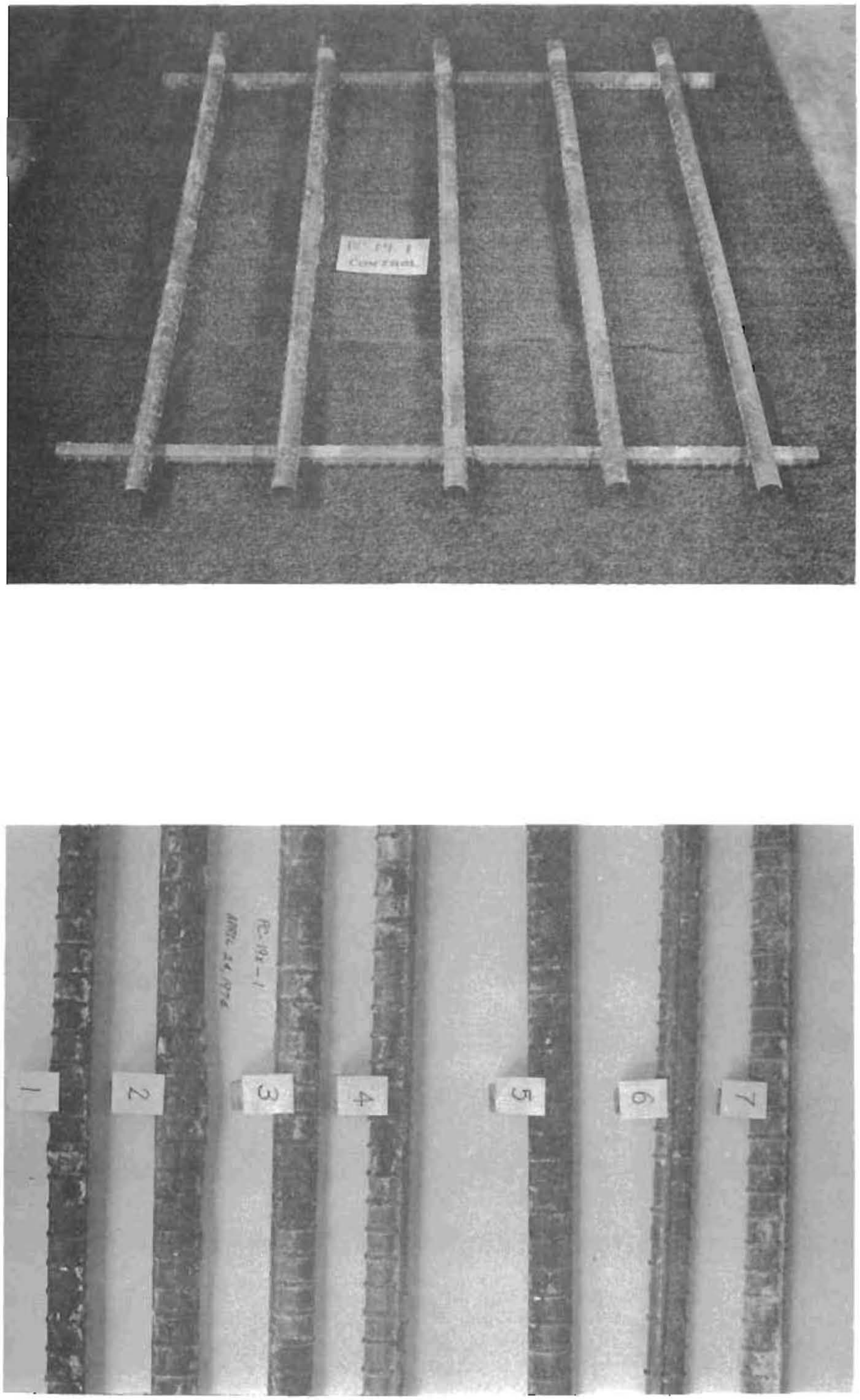

Fig 2.5. Bars from unimpregnated control slab (No. 1).

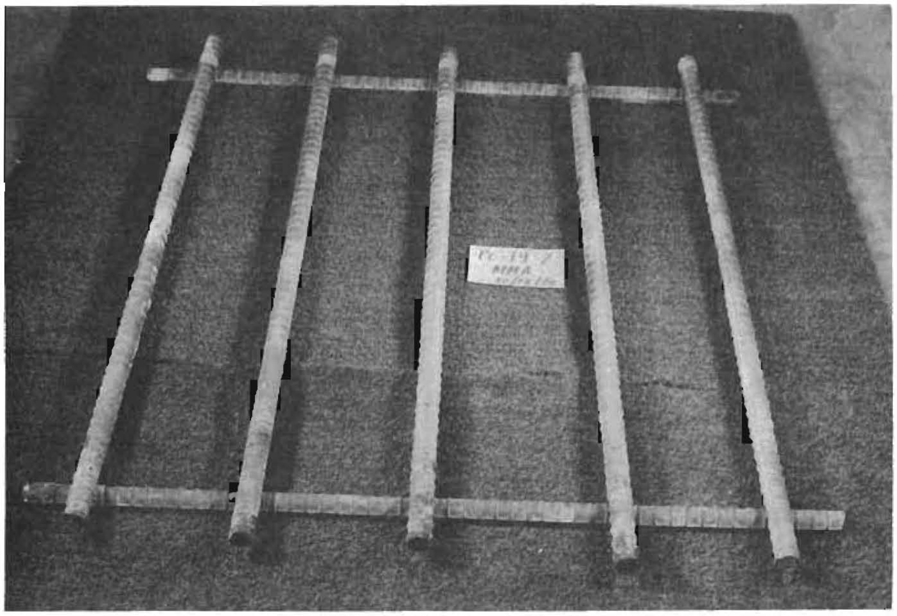

Fig 2.6. Bars from an impregnated slab (No. 7) after salt water spray exposure.

TABLE 2.2. SUMMARY OF CORROSION OF SLAB REINFORCING[a]

| Slab | Monomer | Total for All Bars, % | Outside Bars (1, 5, 6, 7), % | Interior Bars[b] (2, 3, 4), % |
|---|---|---|---|---|
| 1 | --- | 25.0 | 19.0 | 30.0 |
| 2 | MMA | 7.5 | 10.0 | 0.7 |
| 3 | IBMA | 2.5 | 2.2 | 2.5 |
| 4 | IBMA | 2.4 | 3.7 | 0.2 |
| 5 | IDMA | 4.4 | 7.0 | 1.0 |
| 6 | --- | 21.6 | 19.0 | 24.0 |
| 7 | IDMA | 2.0 | 2.7 | 0.7 |
| 8 | MMA | 2.0 | 2.2 | 0.7 |
| 9 | MMA | 1.5 | 1.7 | 1.2 |
| 10 | MMA | 3.7 | 4.5 | 1.3 |
| 11 | MMA | 3.3 | 4.9 | 1.2 |
| 12 | MMA | 2.4 | 3.5 | 1.3 |

[a] Based on percentage of surface area of bar.

[b] Neglecting 3 in. at each end.

clear cover for most of the slabs.

In most cases the chloride content was determined by a Texas Highway Department procedure which consists of leaching the pulverized concrete with hot distilled water and then titrating with a standard silver nitrate solution. The end point was determined using a pH meter and specific ion electrode. This procedure determines only water soluble chloride.

For comparison, some of the slabs, 1 and 12, were analyzed using the Federal Highway Administration (FHWA) procedure (11). The sample is treated with nitric acid and the result represents the total chloride content. Normally the values obtained using the FHWA procedure are higher than those obtained by the THD method.

The results are presented in Table 2.3 in terms of percent by weight and parts per million of chloride based on the weight of pulverized concrete dried at $71^{\circ}$ C. In addition the chloride contents are given in terms of pounds of chloride per cubic yard of concrete based on an assumed density of 4000 lb/cu. yd. The values presented in Table 2.3 represent the average of two tests per slab for the THD method and one test per slab for the FHWA method. It should be noted that the constiuents of the concretes used in these studies produce chloride contents of 0.2 to 0.3 lb/cu. yd., which are included in the measured values of the test specimens.

The results show that the polymer impregnation was quite helpful in reducing the penetration of chloride into the concrete. Slab 4, treated with IBMA, indicated a chloride content nearly 30 percent as high as that in the control slab. Slab 8 had the highest chloride content of the treated slabs analyzed, but slab 12, which had a very low chloride content (1.1 lb/cu. yd.), apparently had the best MMA treatment of the series based on freeze-thaw durability and would be expected to more closely represent the treatments that are presently being obtained.

TABLE 2.3. CHLORIDE CONTENT OF SURFACE-IMPREGNATED SLABS

| Specimen | THD Method | | | FHWA Method | | | Ratio of PIC to Control[a] |
|---|---|---|---|---|---|---|---|
| | Percent | PPM | lb/cu. yd. | Percent | PPM | lb/cu. yd. | |
| PC-19-1 | 0.58 | 5830 | 23.3 | 0.62 | 6200 | 24.8 | --- |
| PC-19-2 | 0.09 | 858 | 3.4 | | | | 0.147 |
| PC-19-4 | 0.17 | 1740 | 7.0 | | | | 0.298 |
| PC-19-7 | 0.05 | 528 | 2.1 | | | | 0.091 |
| PC-19-8 | 0.22 | 2228 | 8.9 | | | | 0.382 |
| PC-19-12 | 0.03 | 268 | 1.1 | 0.04 | 409 | 1.6 | 0.046 |

[a] Based upon THD method

# CHAPTER 3. FULLY-IMPREGNATED PILE SPECIMENS

## 3.1. Test Specimens

Two series of specimens were placed in sea water to evaluate the protection provided by PIC. The specimens were 3 x 3 x 46 in. and contained a No. 6 bar 41-in. long in the center. A galvanized steel hook was cast into one end to provide a means of attaching the specimens. The clear cover on the bars was approximately 1-1/8 in. The first series (PC-16) was made of non-air-entrained concrete with a water-cement ratio of 6.5 gals/sk, a cement factor of 6.0 sk/cu. yd., a slump of 6 in., and a 28-day moist-cured compressive strength of 5190 psi.

The second series (PC-37) was made of non-air-entrained concrete with a water-cement ratio of 8.5 gals/sk, a cement factor of 4.5 sks/cu. yd., a slump of 5 in., and a 28-day compressive strength of 3940 psi.

## 3.2. Polymer Impregnation

The specimens were fully dried, cooled, and placed in a vacuum of ~ 26 in. Hg. for 15 hours. The monomer solution was injected into the evacuation chamber before the vacuum was released. The monomers used were methyl methacrylate (MMA), styrene (S), isobutyl methacrylate (IBMA), and butyl acrylate (BA). The catalyst was benzoyl peroxide (BP). The monomer system for each specimen is given in Table 3.1.

All specimens were soaked for 5 hours, after which they were wrapped in polyethylene and cured in hot water. Water temperatures were ~ 175° F except for PC-37-10, 11, and 12, in which case the temperature was 140° F. The polymer loadings were nearly constant and ranged from 4.24 percent to 4.78 percent.

## 3.3. Test Procedure

The piles were placed in sea water at the ferry crossing at Port Aransas, Texas, to a depth of 34 in. The tests of PC-16 began January 13, 1972.

TABLE 3.1. SUMMARY OF CORROSION OF PILE REINFORCING

| Specimen | Benzoyl Peroxide % (wt) | Monomer | Polymer Loading, %[d] | Corrosion,[a] % | Average Corrosion for Group, % |
|---|---|---|---|---|---|
| PC-16-1 | --- | --- | --- | 11.30 | 9.90 |
| PC-16-2 | --- | --- | --- | b | |
| PC-16-3 | --- | --- | --- | 8.50 | |
| PC-16-4 | 1.0 | MMA | 4.45 | 0.40 | 0.32 |
| PC-16-5 | 1.0 | MMA | 4.56 | b | |
| PC-16-6 | 1.0 | MMA | 4.44 | 0.25 | |
| PC-16-7 | 1.0 | S | 4.72 | 0.35 | 0.25 |
| PC-16-8 | 1.0 | S | 4.73 | b | |
| PC-16-9 | 1.0 | S | 4.77 | 0.15 | |
| PC-16-10 | 0.5 | MMA | 4.74 | 0.06 | 0.03 |
| PC-16-11 | 0.5 | MMA | 4.70 | b | |
| PC-16-12 | 0.5 | MMA | 4.66 | 0 | |
| PC-37-1 | --- | --- | --- | 45.00 | 39.25 |
| PC-37-2 | --- | --- | --- | 51.50 | |
| PC-37-3 | --- | --- | --- | 22.00[c] | |
| PC-37-4 | 1.0 | MMA | 4.24 | 0.60 | 0.33 |
| PC-37-5 | 1.0 | MMA | 4.40 | 0 | |
| PC-37-6 | 1.0 | MMA | 4.64 | 0.40 | |
| PC-37-7 | 1.0 | IBMA | 4.78 | 0.16 | 0.74 |
| PC-37-8 | 1.0 | IBMA | 4.76 | 0 | |
| PC-37-9 | 1.0 | IBMA | 4.57 | 2.05 | |
| PC-37-10 | 1.0 | BA | 4.61 | 0.60 | 0.42 |
| PC-37-11 | 1.0 | BA | 4.34 | 0.10 | |
| PC-37-12 | 1.0 | BA | 4.53 | 0.55 | |

[a] Based on surface area of bar

[b] Removed after 197 days; not included in evaluation

[c] Based upon a net length of 28 in.; remainder of bar destroyed in evaluation

[d] $\frac{\text{Impregnated weight - oven dry weight}}{\text{oven dry weight}}$

Specimens 2, 5, 8 and 11 were removed on July 28, 1974. The remainder of the specimens were removed May 28, 1974. Series PC-37 specimens were placed in sea water May 9, 1973, and removed May 28, 1974.

### 3.4. Evaluation of Specimens

The specimens were covered with barnacles after the exposure to the sea water. The specimens were dried before proceeding with the evaluation.

3.4.1. Corrosion of reinforcing bars--The bars from two specimens from PC-16 that were removed after 197 days exposure are shown in Fig 3.1. The arrow points toward corrosion on the bar from specimen 2 which was unimpregnated. No corrosion was visible on any of the bars from impregnated specimens, and polymer can be observed along the bars of one of these specimens.

After 866 days, bars from the PC-16 treated specimens had developed very small, localized areas of corrosion. The method of measuring the area of corrosion was the same as for slab bars. The results are shown in Table 3.1. The bars from the control specimens had corrosion over 9.9 percent of their surface area. The bars from the PIC specimens had corrosion over an average of only 0.20 percent of their surface (Fig 3.2).

The PC-37 specimens, after 384 days of exposure, indicated substantial corrosion on the bars from the control specimens, 39 percent over the bar surface. However, the bars from the impregnated specimens had corrosion over only 0.5 of their surface. The significantly larger corrosion of the controls for PC-37 as compared to PC-16 was probably due to the lower quality concrete, although the PC-37 specimens were in the water less than half as long as were the PC-16 specimens. In a previous study it was found that increasing the water-cement ratio from 6.25 to 7 gals/sk. in slabs with a one-in. cover resulted in an increase of nearly 70 percent in the corrosion (10).

3.4.2. Chloride ion content--Samples for analyses were obtained 10 in. from the top and 10 in. from the bottom of representative specimens, using a 5/8-in. masonry drill. Samples were obtained from the surface to a depth of 1/2 in. and from a depth of 1/2 in. to 1 in., which was the approximate clear cover of the reinforcing steel. The methods of analyses were the same as for slabs (section 2.4.3).

The results are summarized in Table 3.2. Each value of chloride ion content is the average of two tests. The coefficient of variation was very

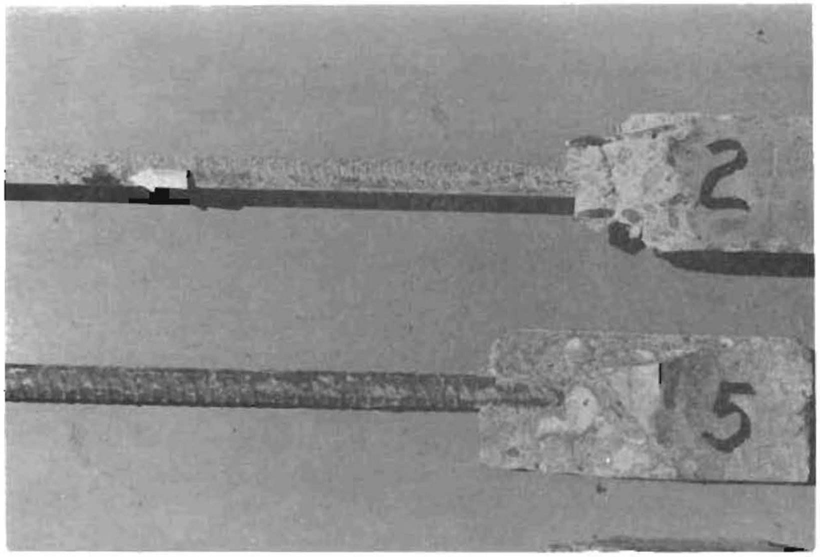

Fig 3.1. Comparison of control and impregnated PC-16 piles after 197 days exposure.

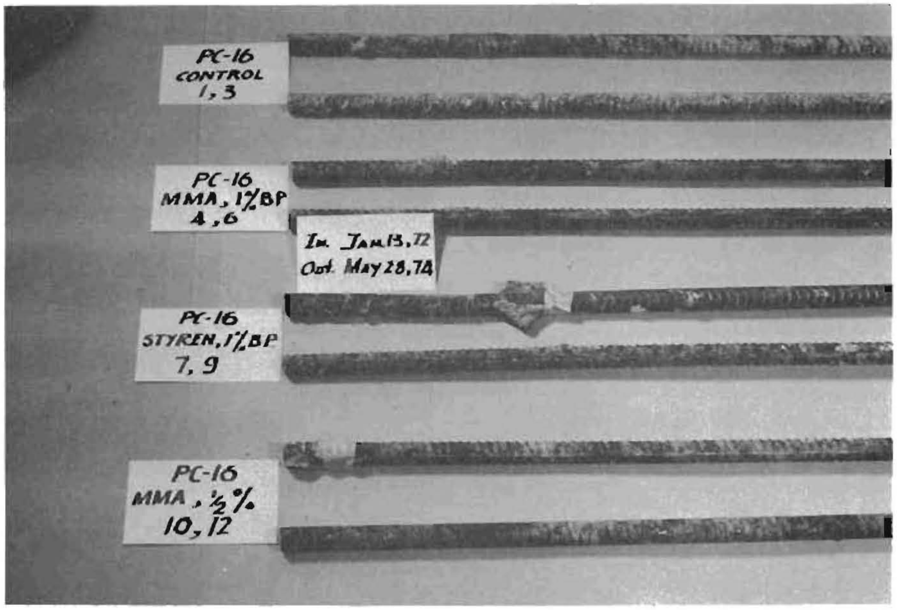

Fig 3.2. Bars from PC-16 piles after 866 days exposure.

TABLE 3.2. CHLORIDE ION CONTENT OF PIC PILES

| Specimen | Location in Pile | Depth from Surface, in. | THD Method | | | FHWA Method | | | Ratio of PIC to Control[a] |
|---|---|---|---|---|---|---|---|---|---|
| | | | Percent | PPM | lb/cu. yd. | Percent | PPM | lb/cu. yd. | |
| PC-16-1 | Top | 0 - 0.5 | 0.38 | 3801 | 15.2 | 0.44 | 4446 | 17.9 | |
| | | 0.5 - 1.0 | 0.34 | 3481 | 13.7 | | | | |
| | Bottom | 0 - 0.5 | 0.55 | 5490 | 22.0 | 0.62 | 6230 | 24.9 | |
| | | 0.5 - 1.0 | 0.39 | 3876 | 15.5 | | | | |
| PC-16-4 | Top | 0 - 0.5 | 0.17 | 1698 | 6.8 | 0.20 | 1952 | 7.8 | |
| | | 0.5 - 1.0 | 0.02 | 200 | 0.8 | | | | 0.058 |
| | Bottom | 0 - 0.5 | 0.21 | 2128 | 8.5 | | | | |
| | | 0.5 - 1.0 | 0.01 | 140 | 0.6 | 0.03 | 286 | 1.1 | 0.034 |
| PC-16-7 | Top | 0 - 0.5 | 0.12 | 1149 | 4.6 | | | | |
| | | 0.5 - 1.0 | 0.01 | 118 | 0.5 | | | | 0.034 |
| | Bottom | 0 - 0.5 | 0.13 | 1282 | 5.1 | | | | |
| | | 0.5 - 1.0 | 0.02 | 215 | 0.9 | | | | 0.056 |
| PC-37-2 | Top | 0 - 0.5 | 0.51 | 5086 | 20.3 | 0.54 | 5414 | 21.6 | |
| | | 0.5 - 1.0 | 0.34 | 3440 | 13.8 | | | | |
| | Bottom | 0 - 0.5 | 0.47 | 4702 | 18.8 | | | | |
| | | 0.5 - 1.0 | 0.26 | 2622 | 10.5 | | | | |
| PC-37-6 | Top | 0 - 0.5 | 0.14 | 1401 | 5.6 | | | | |
| | | 0.5 - 1.0 | 0.03 | 267 | 1.1 | | | | 0.078 |
| | Bottom | 0 - 0.5 | 0.18 | 1816 | 7.3 | 0.19 | 1916 | 7.7 | |
| | | 0.5 - 1.0 | 0.02 | 222 | 0.9 | | | | 0.085 |
| PC-37-9 | Top | 0 - 0.5 | 0.07 | 748 | 3.0 | 0.07 | 686 | 2.7 | |
| | | 0.5 - 1.0 | 0.02 | 156 | 0.6 | | | | 0.045 |
| | Bottom | 0 - 0.5 | 0.08 | 749 | 3.0 | | | | |
| | | 0.5 - 1.0 | 0.02 | 163 | 0.6 | | | | |
| PC-37-12 | Top | 0 - 0.5 | 0.06 | 630 | 2.5 | 0.06 | 566 | 2.3 | |
| | | 0.5 - 1.0 | 0.02 | 174 | 0.7 | | | | 0.051 |
| | Bottom | 0 - 0.5 | 0.09 | 890 | 3.6 | | | | |
| | | 0.5 - 1.0 | 0.01 | 138 | 0.6 | | | | 0.053 |

[a] Based upon THD method.

low (< 1%) for all but the very low chloride contents. The ratios of the chloride content for the PIC specimens to the chloride content for the control are shown in the right-hand column for the depth of 0.5 to 1.0 in. from the surface. They vary from 0.034 to 0.058 for the better quality concrete (PC-16) and from 0.045 to 0.085 for the lower quality (PC-37), which indicates very effective protection provided by the PIC.

Table 3.3 summarizes the ratio of chloride contents of the outer half inch to the inner half inch. As would be expected, the chloride content is always greater near the surface. However, it is interesting to note that for the controls (PC-16-1 and PC-37-2) the chloride content ranges from only 9 to 80 percent greater for the outside half inch as compared to the inner half inch. For the PIC specimens, in addition to having much lower absolute chloride contents, the gradient is much greater, indicating perhaps a much more efficient filtering system.

## TABLE 3.3. SUMMARY OF RELATIVE CHLORIDE ION CONTENT AS A FUNCTION OF DEPTH FROM SURFACE

| Specimen | $\frac{\text{Chloride Ion Content of Outer 1/2 Inch}}{\text{Chloride Ion Content of Inner 1/2 Inch}}$ | |
|---|---|---|
| | Location in Pile | |
| | Top | Bottom |
| PC-16-1 | 1.09 | 1.42 |
| PC-16-4 | 8.49 | 15.20 |
| PC-16-7 | 9.73 | 5.96 |
| PC-37-2 | 1.48 | 1.80 |
| PC-37-6 | 5.25 | 8.19 |
| PC-37-9 | 4.80 | 4.60 |
| PC-37-12 | 3.62 | 6.45 |

# CHAPTER 4. CONCLUSIONS

Surface-impregnated slabs and fully-impregnated piles have been subjected to long-term salt water exposure tests to determine the corrosion protection provided by the polymer. Evaluation of these specimens leads to the following conclusions:

(1) The corrosion of bars in unimpregnated control slabs was about 24 times greater than for bars in partially-impregnated slabs, even though the impregnation was relatively shallow (1/4 to 3/4 in.) and faint.

(2) The average chloride ion content measured from the slab surface to the bar ranged from 1.1 to 8.9 lb/cu. yd. in the impregnated slabs or 4.6 to 38.2 percent of the chloride content of the control slabs (23.3 lb/cu. yd.).

(3) The corrosion of the bars in the fully-impregnated piles ranged from 0.25 percent to 1.00 percent of the surface area as compared to 9.9 percent for bars in the higher quality control concrete and 39.25 percent in the lower quality concrete.

(4) The maximum measured chloride contents of the higher and lower quality concrete piles were 22.0 lb/cu. yd. and 20.3 lb/cu. yd., respectively. The PIC specimens had chloride contents ranging from 3.4 percent to 8.5 percent of the controls.

(5) In all but two samples tested, the FHWA method gave higher chloride ion contents than the THD method.

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