SHRP-S-347

Chloride Removal Implementation Guide

ELTECH Research Corporation
Fairport Harbor, Ohio

Jack Bennett
Thomas J. Schue

Strategic Highway Research Program
National Research Council
Washington, D.C. 1993

SHRP-S-347
Contract C-102A
ISBN 0-309-05606-3
Product Code 2033

Program Manager: *Don Harriott*
Project Manager: *H.M. (Marty) Laylor*
Program Area Secretary: *Carina S. Hreib*

August 1993

key words:

alkali-silica reaction
bridges
chloride removal
concrete rehabilitation
corrosion prevention
electrochemical methods
impressed current anodes
rehabilitation

Strategic Highway Research Program
National Research Council
2101 Constitution Avenue N.W.
Washington, D.C. 20418

(202) 334-3774

1.5M/NAP/893

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

Contents

List of Figures

Abstract

Equipment and procedures for the electrochemical removal of chloride from reinforced concrete structures are described. This guide provides basic information needed to implement the chloride removal process on field structures. Pretreatment and posttreatment procedures are also discussed.

Executive Summary

Corrosion of reinforcing steel is recognized today as one of the major contributors to the deterioration of reinforced concrete structures. This corrosion is induced primarily by chlorides from deicing salts or seawater. One technique for dealing with this problem is chloride removal. The electrochemical removal of chloride from concrete structures is accomplished by applying an anode and electrolyte to the concrete surface and passing direct current (DC) between the anode and the reinforcing steel, which acts as a cathode. Since anions (negatively charged ions) migrate toward the anode, it is possible to cause chloride ions to migrate toward the anode and away from the steel.

Chloride removal is similar in principle to cathodic protection. The major difference is in the magnitude of the current, which is about 50 to 500 times that used for cathodic protection. The total amount of charge (current x time) applied for chloride removal is about the same as a cathodic protection system would deliver over a period of about 10 years. The other important difference is that chloride removal is a short-term treatment, whereas cathodic protection is normally intended to remain in operation for the life of the structure.

Chloride removal is particularly suited for structures in which active corrosion is occurring, but in which the concrete has little damage, no prestressed steel is present, and a 5- to 10-year extended service life is adequate.

Typical pretreatment surveys conducted prior to chloride removal include potential and delamination surveys. Chloride analysis is conducted to establish a pretreatment chloride contamination profile. Conducting a laboratory trial of the process on at least one core removed from the structure is also recommended in order to determine the level of current and length of treatment time expected. Reinforcing steel must be tested for electrical continuity. Petrographic analysis should be conducted to identify alkali-silica reactive aggregates in the concrete.

This chloride removal system uses an anode/blanket composite that is placed on the surface of the concrete. This composite is prefabricated and partially reusable. An electrolyte is provided that is circulated throughout the system. The electrolyte is a sodium borate (Na_3BO_3) or lithium borate (Li_3BO_3) buffered solution designed to maintain a basic pH for the duration of the process. This pH maintenance prevents etching of the concrete and the evolution of gaseous chlorine. Lithium borate electrolyte, which is more expensive, is used only when the structure contains potentially alkali-silica reactive aggregate.

The chloride removal process discussed in this guide uses about 260 gal (980 l) of 0.2 molar borate buffer solution per 1000 ft^2 (300 m^2) of treated surface. The electrolyte is prepared on site by mixing 0.2 lb (90 gm) of sodium hydroxide with 0.1 lb (45 gm) of boric acid per gallon of solution. The treatment process uses a current of 0.1 to 0.5 A/ft^2 (1.0 to 5.0 A/m^2) of concrete at a maximum of 50 volts. A treatment time of 10 to 50 days and a total charge of 60 to 150 A-hr/ft^2 (600 to 1500 A-hr/m^2) is considered normal. The process is monitored daily during this time.

This process will remove about 20 to 50 percent of the chloride present in the concrete. The amount of chloride removed depends on several factors, including the amount of chloride present, the distribution of chloride in the concrete, and the design of the reinforcement. After the treatment is complete, chlorides remaining in the structure are usually sufficient to reinitiate corrosion. These chlorides are usually distributed well away from the steel, and a long time is required for redistribution to take place. The return to corrosive conditions is further delayed by the buildup of alkalinity that takes place at the steel surface.

Alternate systems include a procedure that uses a ponded electrolyte on horizontal surfaces such as decks, and a proprietary system that uses a sprayed matrix of cellulose fiber to support the electrolyte. Each of these systems has its own attributes for particular types of structures and may be used effectively.

Posttreatment testing is normally conducted to determine the effectiveness of the process and its effect on the concrete in the structure. A potential survey can be used after completion of treatment to indicate the uniformity of current distribution. Concrete powder samples are taken for chloride analysis. Application of a sealer is recommended following treatment to prevent the ingress of additional chlorides and intrusion of moisture into the concrete.

At this time, it is difficult to judge how long this chloride removal process will be effective. Based on laboratory studies, it now appears that the procedure will prevent corrosion for at least 5 years, and possibly for 10 years or more, provided contamination with new chlorides is prevented. Additional field experience is needed for a better understanding of the chloride removal process, its effective life, and its effect on the structure.

1

Introduction

It is generally accepted that corrosion of reinforcing steel is a major cause of deterioration in reinforced concrete structures. This corrosion is induced primarily by chlorides from deicing salt or seawater. Two electrochemical solutions have been suggested for structures that are already salt contaminated and experiencing corrosion-induced deterioration: cathodic protection and chloride removal. Both of these techniques are possible since concrete is an ionic conductor and capable of supporting a small flow of electric current.

Cathodic protection was first applied by the California Department of Transportation on the Sly Park Road Bridge in June 1973.[1] Since those early days, many advances have been made in cathodic protection system components and test procedures, and today cathodic protection is an accepted technique.[2]

A 1988-89 survey conducted by Battelle Columbus Laboratories indicated that more than 275 bridge structures in the United States and Canada have been cathodically protected and that the total concrete surface under cathodic protection was about 9 million ft^2 (840,000 m^2).[3]

Chloride removal has not been studied or used as extensively as cathodic protection. Chloride removal was the subject of two major studies conducted under Federal Highway Administration (FHWA) contracts in the 1970s.[4,5] Both of these studies, as well as follow-up reports, concluded that chloride removed by electrochemical migration is a promising technique for use on salt-contaminated concrete.

Chloride removal is accomplished by applying an anode and electrolyte to the structure's surface and passing direct current between this anode and the reinforcing steel, which acts as a cathode. Conduction of direct current through concrete is accomplished by the movement of charged ions. Since anions (negatively charged ions) migrate toward the anode, it is possible to cause chloride ions to migrate away from the reinforcing steel and into the electrolyte. The speed at which this process is accomplished largely depends on the magnitude of the applied current. In general, the current used for chloride removal is 50 to 500 times higher than that used for cathodic protection.

The simple movement of ions through concrete does not appear to have any deleterious effects on the concrete. Changes that raise a number of concerns occur at the surface of both the anode and the reinforcing steel. These changes are the result of electrochemical reactions that take place wherever current enters or leaves the concrete.

Reduction reactions that result in an increase in alkalinity and the possible evolution of hydrogen gas take place at the steel according to the following reactions:

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$$

$$2H_2O + 2e^- \rightarrow H_2 + 2(OH)^-$$

The first of these reactions takes place very slowly since the availability of oxygen in concrete is very limited. Most of the current entering the steel will therefore result in the production of hydrogen on the steel surface. There was concern that this reaction could soften the cement paste around the reinforcing bar and reduce bond. The evolution of hydrogen could also cause hydrogen embrittlement and exert a tensile stress in the concrete, which could be harmful.

The reactions also show an important benefit. The production of hydroxyl creates more alkalinity at the surface of the steel, which tends to repassivate the steel and helps prevent the return of corrosion.

The electrochemical reactions that may take place at an inert anode are as follows:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

Either or both of these reactions may be important, depending on conditions. If the electrolyte is very acidic ($pH<4$), a significant amount of chlorine gas will evolve according to the reaction above, which would result in safety and environmental concerns. If the electrolyte is basic ($pH>7$), then the evolution of oxygen becomes the favored anodic reaction The small amount of chlorine that evolves under such conditions is rapidly hydrolyzed to hypochlorous acid and hypochlorite according to the following reactions:

$$Cl_2 + H_2O \rightarrow HClO + Cl^- + H^+$$

$$HClO \rightarrow ClO^- + H^+$$

Under these conditions, the evolution of both oxygen and chlorine produces acid (H^+). This outcome raises concern about etching of the concrete surface that is in contact with the electrolyte.

These concerns were addressed, and conditions were identified under which the chloride removal process can be conducted safely and effectively.[6] Current density was kept low enough to avoid damage to concrete and reduction in bond. The electrolyte pH was controlled to avoid etching of the concrete surface and generation of gaseous chlorine.

The chloride removal system described in this report uses an anode/blanket composite and a contained borate buffered electrolyte. The borate buffer maintains the electrolyte at a high pH despite acid generation at the anode. The anode used is an inert catalyzed titanium mesh, which resists corrosive anodic reactions.

The system is installed by fastening the anode/blanket composite to the concrete surface. For structures such as round substructure columns, installatio simply involves strapping the composite around the member. For other geometries, installation is more tedious. A sump tank is provided at the base of the structure to act as a reservoir for the electrolyte. The electrolyte is continuously pumped from the tank to the top of the structure and flows by gravity back into the tank.

The recommended current used for chloride removal is in the range of 100 to 500 mA/ft^2 (1000 to 5000 mA/m^2) of treated surface. Current levels below 500 mA/ft^2 (5000 mA/m^2) have proven harmless to the concrete structure. Current on field structures will usually be limited because of the 50 VDC maximum operating voltage. Article 110-17 of the National Electrical Code (NEC) requires exposed, live electrical parts operating at 50 V or more to be guarded, which is not possible with most chloride removal installations. The electrical resistance of the concrete in most structures is such that the process will usually operate at maximum voltage, and current will be well below 500 mA/ft^2 (5000 mA/ft^2).

The extent of the treatment process is usually expressed in terms of total charge (current x time). Effective chloride removal is usually accomplished by applying a total charge of 60 to 150 A-hr/ft^2 (600 to 1500 A-hr/ft^2). Too little treatment will not remove sufficient chloride or allow enough alkalinity to build up at the steel to effectively prevent corrosion. Too much treatment will involve unnecessary expense. The recommended amount of total charge is usually reached in 10 to 50 days. A higher charge and longer treatment time is recommended for structures in which the chloride content is high.

The treatment process described above will remove about 20 to 50 percent of the chloride present in the concrete. The amount of chloride removed depends on several factors, including the amount of chloride present, the distribution of chloride in the concrete, and the design of the reinforcement. After the treatment is complete, it is usually true that sufficient chlorides remain in the structure to reinitiate corrosion. The remaining chloride is usually distributed well away from the steel, however, and a long time is required for this redistribution to take place. The return to corrosive conditions is further delayed by the buildup of alkalinity that occurs at the steel surface.

This chloride removal process was demonstrated in field validation trials conducted on four structures: a bridge deck in Lucas County, Ohio, and substructures in Jacksonville, Florida; Albany, New York; and Latchford, Ontario, Canada. Each of these structures had unique characteristics and problems, but all four trials judged the process to be successful.[7] It has been recommended that these structures be monitored for a period of five years under an FHWA post-Strategic Highway Research Program (SHRP) monitoring effort, and that information published.

This guide is intended to inform the user about chloride removal techniques. First, the procedures used to select candidate structures are described. Pretreatment surveys and preinstallation procedures are discussed. System design, equipment, and installation are described. Construction practices are presented. Finally, system removal and posttreatment procedures are detailed. Each of these aspects is discussed for a typical installation using an anode/blanket composite and a contained borate-buffered electrolyte. The final chapter deals with alternate systems that differ slightly from the anode/blanket approach. These systems include a ponded system for use on a horizontal top surface and a system that utilizes a cellulose fiber matrix to support the electrolyte without recirculation.

2

Criteria to Define Candidate Structures

The following checklist itemizes criteria which are "required" and "desired" for electrochemical chloride removal. Each of these items is discussed in detail in this chapter.

Required

- Chloride-induced corrosion
- No prestressed steel
- No alkali-reactive aggregate
- Reasonable steel continuity
- Reasonable concrete resistance

Desired

- Minimum concrete damage
- No coatings or overlays
- Minimum exposed steel
- Minimum disruption of traffic
- Available alternating current (AC) power
- Excellent continuity of steel
- Low concrete resistance
- Simple geometry

Chloride-Induced Corrosion

A candidate structure for chloride removal should be undergoing active corrosion caused by the presence of chloride ions at the level of the steel reinforcement. Although it is possible to conduct chloride removal before corrosion begins, the benefit of such treatment is questionable. Corrosion may also be caused by other factors, such as carbonation of the concrete cover. The chloride removal process presented in this report is not designed for such cases.

The presence of chloride-induced corrosion can be verified by a combination of survey techniques commonly used by corrosion and highway engineers.

A half-cell potential survey using portable reference electrodes can determine the probability of corrosion activity. Test procedures and guidelines for this survey are described in

American Society for Testing and Materials (ASTM) C 876-91, "Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete." Potentials more negative than -0.35 V versus a copper/copper sulfate reference electrode indicate greater than 90 percent probability that reinforcing steel corrosion is occurring in the area at the time of measurement.

Chemical analysis should be used to verify that corrosive levels of chloride are present at the level of the reinforcing steel. The American Concrete Institute (ACI) recommends a threshold limit for total chloride ion content in reinforced concrete to be 0.20 percent by weight of cement.[8] Many highway agencies and corrosion engineers use a total chloride ion content of 1.2 lb/yd^3 of concrete (0.7 kg/m^3) as the corrosion threshold limit.

Procedures and guidelines for chloride ion content testing are in American Association of State Highway and Transportation Officials (AASHTO) T 260-84, "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials." Research has demonstrated that sampling 12 random points in a zone will give a representative mean and standard deviation for chloride concentration in that zone.

The chloride content should be determined as a function of depth from the concrete surface. Chloride removal is best applied on structures in which most of the chloride contamination is near the concrete surface and lower near the reinforcing steel. This is where most of the current flows during treatment and where most ionic movement takes place. Chloride beneath the reinforcing steel will not be effectively removed.

Visual inspection, sounding for delamination, and corrosion rate measurements may also be used to verify the presence of active corrosion.

No Prestressed Steel

The chloride removal process will generate hydrogen at the reinforcing steel, which may cause hydrogen embrittlement in prestressed steel structures. Chloride removal is not recommended for such structures.

No Alkali-Reactive Aggregates

The chloride removal process may aggrevate the expansive reaction associated with alkali-reactive aggregates. It has been demonstrated in the laboratory and in one field trial that lithium ions in the electrolyte can control this reaction. Much is still unknown about the effectiveness of lithium ions, and the use of lithium is still considered experimental.

If the presence of alkali-reactive aggregates is unknown, a concrete core sample from the structure should be taken and submitted for petrographic analyses at a reputable laboratory.

Minimum Concrete Damage

Chloride removal works best on structures in which extensive concrete damage has not yet occurred. Loose and delaminated concrete should be removed, and these areas must be patched before treatment. This process requires a separate site visit by the contractor since patches should cure for 28 days to reach a stable resistivity. If the resistivity of the patch material does not closely match that of the parent concrete, current will not be uniformly distributed.

If cracks exist perpendicular to the concrete surface, use of a captive electrolyte will be difficult. Such cracks will channel liquid away from the treatment area, resulting in a loss of electrolyte. Cracks can be deeply sealed by epoxy injection, but this process involves additional expense. If chloride removal is to be conducted on an extensively cracked structure, a system using a sprayed cellulose fiber that does not use a recirculating confined electrolyte is recommended.

No Coatings or Nonconductive Overlays

The presence of any surface coating or nonconductive overlay will result in a high electrical resistance and prevent the flow of enough current at acceptable voltages. Such coatings must be removed before treatment, but this step will increase costs.

Minimum Steel Exposed at the Surface

Steel exposed at the surface of the concrete may cause a short circuit between the steel and anode. Even if a short does not occur, a high current may flow to the exposed steel, which will stop chloride removal from the adjacent concrete and will cause inefficiency.

Occasional steel present at the concrete surface may be insulated by using non-conductive epoxy, but this process will be costly if the exposed steel is extensive.

Minimum Conflict with Flow of Traffic

The chloride removal process can take 10 to 50 days, depending on the electrical resistance of the concrete and the extent of chloride contamination. Since the treatment time is relatively long, traffic control costs may be high. At this time this process is more applicable for substructures than for decks. Procedures have not been developed that allow traffic over a deck system during operation. Some substructures may require traffic control during system installation and removal.

Availability of AC Power

AC power for chloride removal may be difficult and expensive to obtain. The power requirement for maximum current flow, 0.5 A/ft^2 (5 A/m^2), is about 25 W/ft^2 (250 W/m^2). For large structures, 240 or 480 V, 3-ϕ AC power is usually required.

If sufficient AC power is not available, a generator can be used, but this will be expensive in terms of equipment, fuel, and labor costs.

Good Electrical Continuity of Steel

The chloride removal process requires good electrical continuity of the steel to distribute current evenly throughout the structure. Current will not flow to steel that is discontinuous, and the treatment will not be effective in the discontinuous areas.

Experience indicates that the electrical continuity of most structures is adequate, but continuity problems may exist in some structures, especially very old ones. If any doubt exists, the electrical continuity of the steel should be verified. Extensive continuity bonding can be expensive.

The test for electrical continuity is conducted using a high-impedance voltmeter (10 megohm minimum) with a resolution of 0.1 mV. The millivolt scale on the voltmeter is selected, and the leads from the voltmeter are connected to the two pieces of steel being tested. Electrical continuity exists when the voltage difference between the two pieces of steel is no greater than 1.0 mV.

Acceptable Concrete Resistance

If the electrical resistance of the concrete is too high, chloride removal current will be low and treatment times will be long. Concrete resistance may be high for very dense, good-quality concrete or for latex-modified concrete. High concrete cover over the reinforcing steel may also contribute to high resistance.

Concrete resistivity can be determined in the field using an AC resistance meter and the "Wenner Four Pin" method described in ASTM G 57. Concrete resistivity usually ranges from 10,000 to 50,000 ohm-cm. Concrete with resistivity in the high end of this range will require a longer time to pass a given amount of charge, and costs will be higher.

The best way to determine the expected voltage, current, and treatment time is to conduct a laboratory chloride removal test on a core from the structure. The core should contain a steel bar if possible. To conduct the test, electrolyte is placed in a pond on top of the core, and current is passed between an anode in the pond and the steel bar. A few days of operation will establish the initial parameters for the structure in question.

Simple Geometry

Some structural elements are easier to process than others. The system using an anode/blanket composite is especially suited for round columns and is more difficult to use on large, flat surfaces. The system using sprayed cellulose fiber is more easily adapted to flat surfaces, but even this system has difficulty adhering to large soffit areas. Large, flat, horizontal decks are easily handled by constructing an electrolyte pond.

Other Factors

Chloride removal, although highly effective for controlling corrosion, has a limited lifetime. Although experience is limited, the effective lifetime appears to be about 5 to 10 years. Until more experience is gained, another technique should be used if a longer life is needed.

An important advantage of chloride removal is the relatively short treatment time. After treatment, there is no need for monitoring and maintenance. Chloride removal may be advantageous for remote structures or where monitoring and maintenance would be difficult.

Equipment is normally left unattended during treatment and hence is subject to theft or vandalism, which may be a concern at some sites.

3

System Design

Design Types

Many different designs are possible for chloride removal systems. Designs that have been used on field structures include those with a ponded electrolyte, sprayed electrolyte fiber matrix, and anode/blanket composite. This chapter describes the procedure for chloride removal using an anode/blanket composite that is fixed to the concrete surface. This composite is wetted with electrolyte to complete the circuit for current flow.

The ponded system is the best system for large horizontal bridge decks. The anode/blanket composite system works best on structures with simple geometry, especially those with round columns. The sprayed fiber system is better suited for large flat surfaces and complex geometries.

Anode/Blanket Composite

An anode/blanket composite design (figure 3-1) was developed for the chloride removal process described in this report. This composite is prefabricated and reusable, consisting of two blanket materials and an anode. It is placed on an inner, nonreusable pad adjacent to the concrete.

The anode in the composite is made of inert catalyzed titanium mesh capable of lasting several treatments. The anode is typically a flexible, highly expanded mesh that will conform easily to a variety of surfaces. The lifetime of the anode is controlled by proper selection and thickness of the catalyst applied to the titanium surface. Catalyzed titanium anodes are proprietary and are available from at least three suppliers.

The anode used for the field trials was obtained from ELGARD Corp., and is called ELGARD-300. It is supplied in rolls 4 ft wide x 200 ft long (1.2 m wide x 60 m long), and has a diamond dimension of 2 in. x 0.92 in. (51 cm x 2.3 cm). The electrical resistance of the mesh is 0.008 Ω/ft (0.026 Ω/m).

A 5-ft (1.5-m) long, catalyzed coated titanium current distributor strip, 0.5 in. wide, 0.035 in. thick (12.7 mm wide, 0.9 mm thick) is spot resistance welded to the 4-ft (1.2-m) wide edge of the anode mesh in 3 to 4 spots per linear foot. A 1/4-in. (6.4-mm) diameter hole near the end of the strip, approximately 1 ft (0.3 m) from the mesh, is prepared for the system's positive connection with a 1/4-20 bolt.

The inner blanket serves as the main path for current flow between the anode and the reinforcing steel. Its ability to retain electrolyte for long periods of time and to conform to irregular concrete surfaces is of utmost importance. The material selected for the inner blanket was Sorb_X S-92, manufactured by Matarah Industries, Inc. This material is composed of 33 percent polypropylene fiber and 67 percent cellulose fiber. The inclusion of cellulose fiber is important for moisture retention properties. If electrolyte flow to the system is interrupted, the Sorb_X fiber will retain enough electrolyte to allow the treatment to continue for several hours. This material is friable and is not reusable.

The composite consists of two geotextile materials and the anode. GTF 350 EX, manufactured by Exxon Inc., is located between the Sorb_X inner blanket and the anode mesh. Polyfelt TS-1000, manufactured by Gundle Lining Systems, is located outside the anode mesh. The geotextiles and the anode can be sewn together to provide a reusable unit. These materials were selected for their strength and ability to provide good electrolyte contact. The Polyfelt material is particularly strong and will support straps to secure the system.

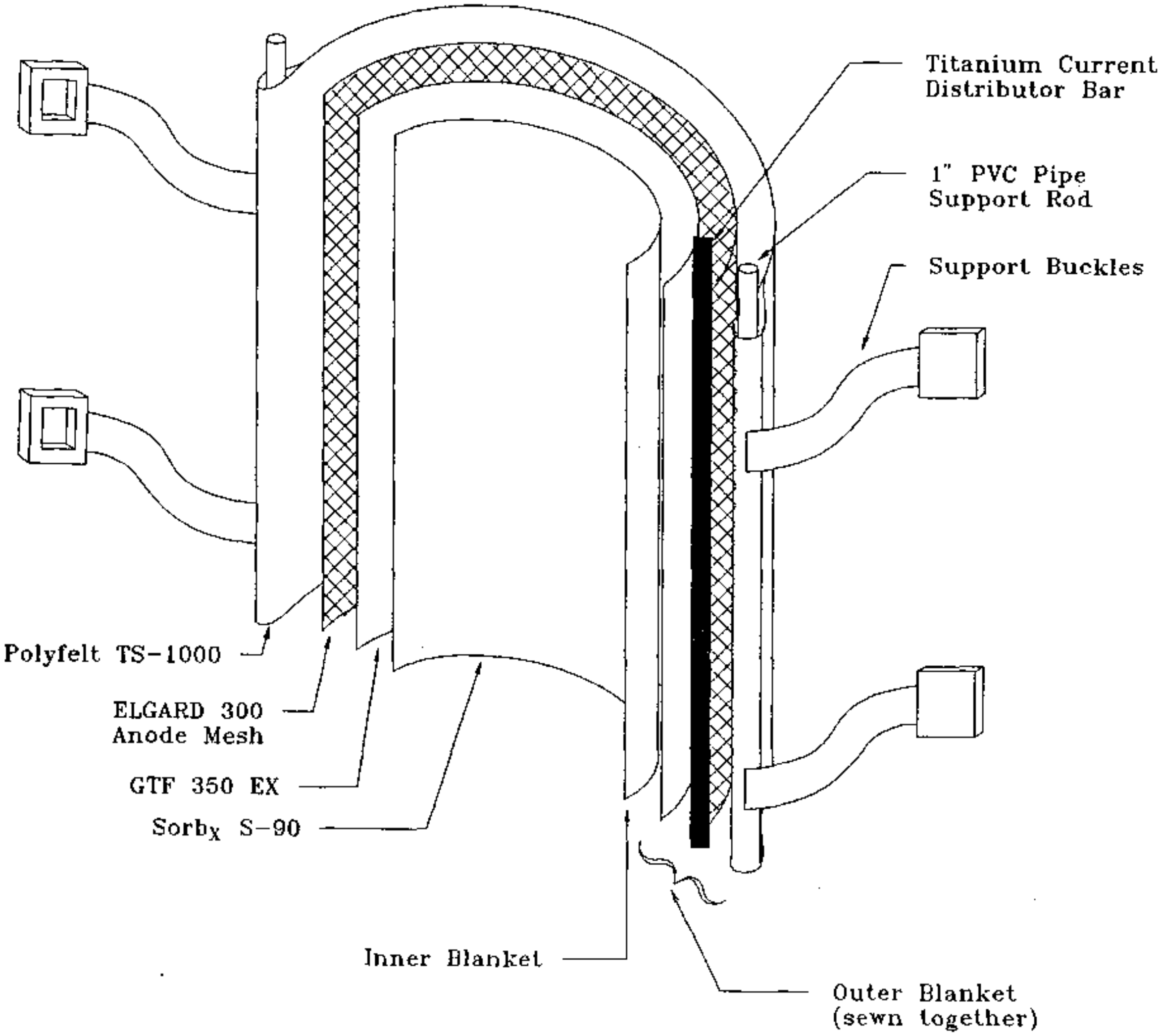

Figure 3-1. Anode/Blanket Composite

A plastic film wrapped around the outside of the anode/blanket composite can also be used to minimize evaporative losses or dilution of electrolyte caused by rainwater entry. Depending on the geometry of the member being treated, additional bands or other means of securing the system may be needed. Close and uniform contact between the inner blanket and the concrete is essential.

Electrolyte Circulation

The anode/blanket composite design also uses a captive electrolyte and continuous circulation of electrolyte throughout the treatment period. The captive electrolyte is very useful for monitoring and can be analyzed for chloride content to determine the amount of chloride removed from the concrete. Monitoring for pH can help avoid etching of the concrete surface caused by acid buildup. A confined electrolyte also prevents unwanted runoff to the environment. Continuous circulation of electrolyte makes for uniform electrolyte distribution and therefore better current distribution.

Circulation is accomplished by pumping electrolyte from a sump to the top of the treatment area, where it is distributed from a manifold. The flow rate is about 2 to 10 gal/min (7 to 40 l/min) for each 1000 ft^2 (100 m^2) of treated area. It flows by gravity down through the system and is collected at the bottom and returned to the sump tank. The circulation system is shown schematically in figure 3-2.

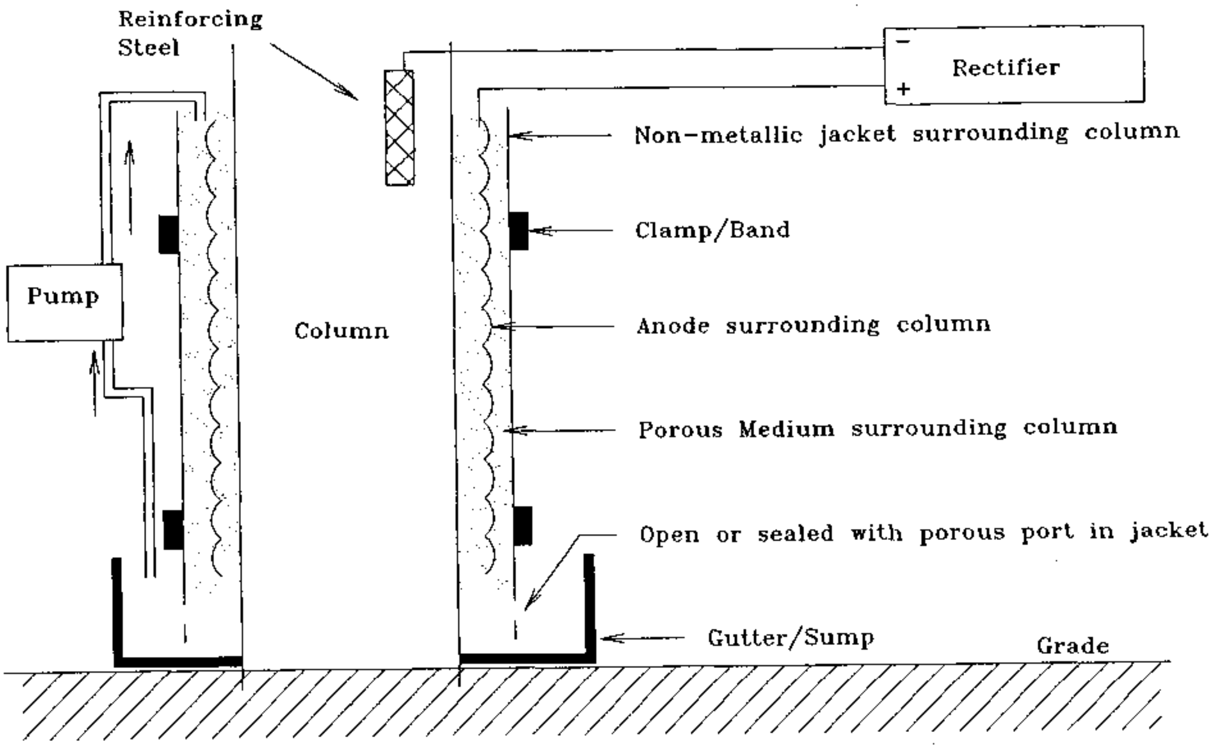

Figure 3-2. Circulation System

Polyvinyl chloride (PVC), polyethylene, and polypropylene piping or hose are all recommended materials for the circulation system. Plastic centrifugal pumps with magnetic drives have been proven especially effective. A plastic rain gutter was used in one case to collect electrolyte at the bottom of the treated area.

Confining the electrolyte at the bottom of the system is sometimes difficult. In most cases, a heavy application of caulking material between the concrete surface and the collection element will be sufficient. Columns have been sealed with a 1-ft (30-cm) wide rubber band that was vulcanized together after it was wrapped around the column. The bottom of the rubber band was sealed with urethane caulking material and further secured with plastic banding (figure 3-3).

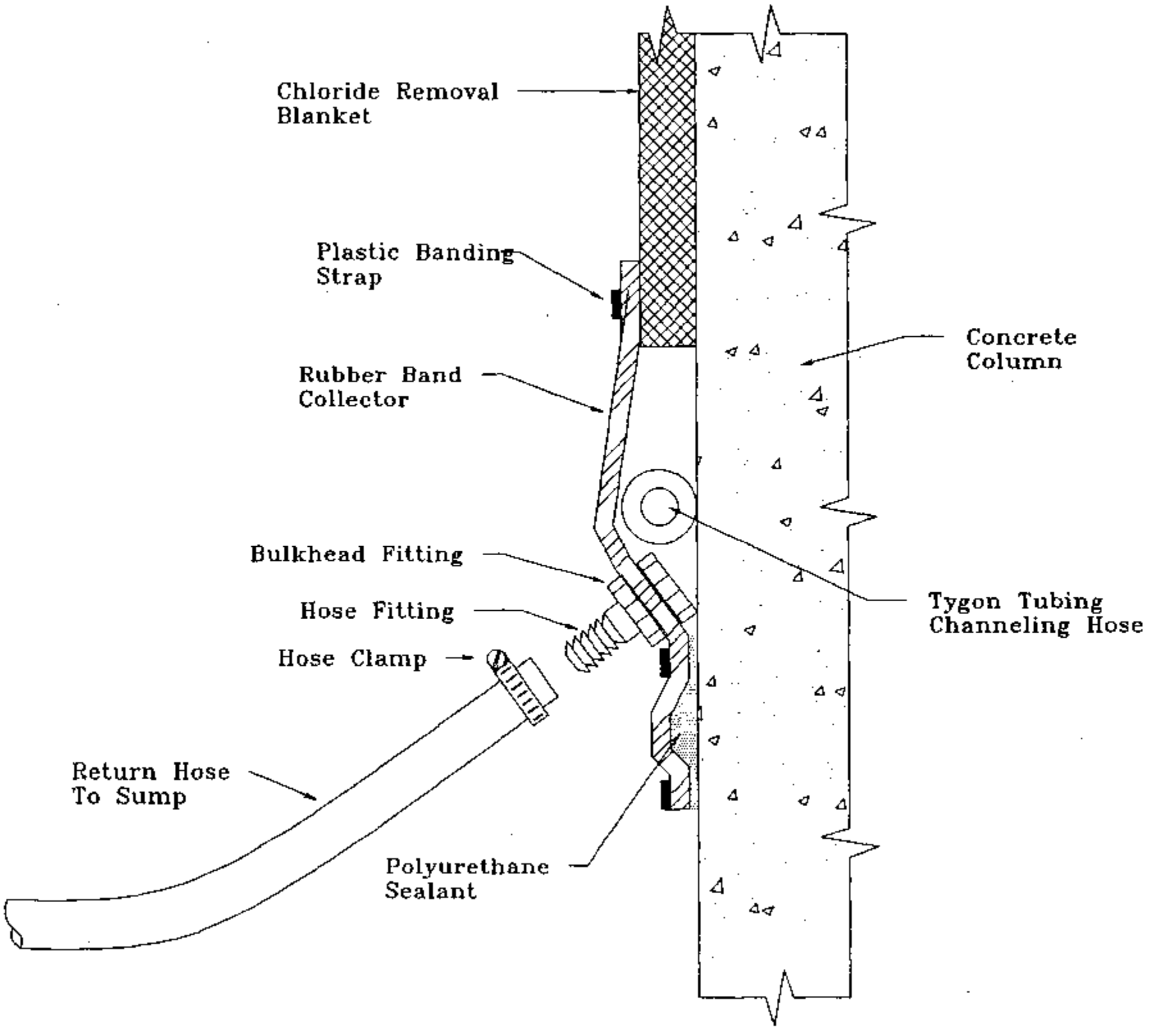

Figure 3-3. Electrolyte Collection System

If there are vertical cracks in the concrete, these sealing techniques may not be sufficient. Electrolyte will enter the crack above the collection element and exit the crack below the collection element. If electrolyte losses are significant, it may be necessary to seal the cracks by epoxy injection.

Another problem is dilution of the electrolyte by rainwater. Such dilution makes accurate analysis difficult and may cause electrolyte overflow. To avoid this problem, it may be necessary to prevent rainwater runoff from entering the system.

In summary, the circulation and maintenance of a confined electrolyte has advantages. Analysis of the electrolyte permits the amount of chloride removed to be calculated and allows for pH maintenance.

Electrolyte Composition and Preparation

A pH-buffered electrolyte should be used to prevent the electrolyte from becoming too acidic. An acidic electrolyte results in etching of the concrete surface and the production of chlorine gas. A sodium borate (Na_3BO_3) electrolyte is recommended for its buffering capacity, cost, safety, and environmental impact. In theory, the acid generated by 100 A-hr would be neutralized by 1.24 moles of sodium borate. In practice, sodium borate is much more effective—about 0.2 moles will maintain neutrality during 100 A-hr. This is probably because large amounts of hydroxide ions are being driven out of the concrete and into the electrolyte during the process.

The upper limit of solubility for sodium borate is about 0.3 moles/liter, and 0.2 moles/liter is recommended. At this concentration, an estimate of the needed volume of electrolyte is given by the following:

Volume (in gallons) = (0.0026) x (amp-hours) x (square feet)

where (square feet) is the area of concrete treated
(amp-hours) is the total planned charge

The pH should be monitored, particularly toward the end of the treatment process, and should not be allowed to drop below 6.0.

An electrolyte containing 0.2 moles/liter sodium borate will contain 25.56 gm/l of the salt. The electrolyte can be made on site by adding 24.0 gm sodium hydroxide and 12.4 gm boric acid per liter. This is equivalent to about 0.2 lb sodium hydroxide and 0.1 lb boric acid per gallon.

The following example illustrates the preparation of electrolyte needed for a structure with 1000 ft^2 (100 m^2) of treated area to receive a total charge of 100 A-hr/ft^2:

Volume (in gal) = (0.0026) x (100 A-hr) x (1000 ft^2)
= 260 gal

sodium hydroxide = (0.2 lb/gal) x (260 gal)
= 52 lb

boric acid = (0.1 lb/gal) x (260 gal)
= 26 lb

When the structure is known to contain alkali-silica reactive aggregates, lithium borate electrolyte is recommended. A 0.2 molar (15.93 gm/l) lithium borate (Li_3BO_3) solution is prepared by adding 14.4 gm lithium hydroxide and 12.4 gm boric acid per liter. This is equivalent to about 0.12 lb lithium hydroxide and 0.1 lb boric acid per gallon.

The following example illustrates the preparation of lithium borate electrolyte using the parameters from the previous example:

Volume (in gal) = (0.0026) x (100 A-hr) x (1000 ft^2)
= 260 gal

lithium hydroxide = (0.12 lb/gal) x (260 gal)
= 31.2 lb

boric acid = (0.1 lb/gal) x (260 gal)
= 26 lb

Such solutions are prepared by slowly adding the boric acid to the water while stirring, then adding the sodium or lithium hydroxide while stirring.

Safety equipment and procedures are given on the Material Safety Data Sheet (MSDS) and should be heeded.

Treatment Current and Time

It is necessary to determine the amount of total charge needed for the chloride removal process. Total charge is usually expressed as current (amps) x time (hours). Typically, a total charge of 60 to 150 A-hr/ft^2 (600 to 1500 A-hr/m^2) is sufficient, although there may be cases in which more or less charge is used. A light treatment might be used when chloride contamination is not high and is still located near the surface of the concrete. A heavy treatment would be used when high concentrations of chloride have penetrated deeply into the concrete and corrosion of the steel is well underway. In some cases, it may be desirable to conduct a laboratory chloride removal test on cores to determine the proper amount of charge to be used.

The maximum current used for the chloride removal process is 0.5 A/ft^2 (5.0 A/m^2) of concrete. This level assumes a steel-to-concrete surface area ratio of about 1:1. If there is significant deviation from this ratio, such as for lightly reinforced structure elements, a proportionally smaller current should be used. Greater currents may result in some reduction of steel-concrete bond and possible damage to the structure.

The maximum current of 0.5 A/ft^2 (5.0 A/m^2) can be reached while remaining under 50 V when the concrete is very conductive. In this case, it is advisable to conduct a chloride removal laboratory test on a core removed from the structure prior to treatment to determine current and voltage requirements.

Once the charge and expected current have been determined, it is possible to predict the treatment time. Time is calculated according to the following formula:

$$\text{time (hours)} = (\text{A-hr/ft}^2) \div (\text{A/ft}^2)$$

For example, if the total charge is 100 A-hr/ft^2 (1000 A-hr/m^2) and the expected current is 0.2 A/ft^2 (2 A/m^2), then the expected time is

$$\begin{aligned} \text{time} &= (100 \text{ A-hr/ft}^2) \div (0.2 \text{ A/ft}^2) \\ &= 500 \text{ hr} \\ &= 21 \text{ days} \end{aligned}$$

A treatment time of 10 to 50 days is considered normal.

4

Equipment

Electrical System

DC Power Supply

The power supply provides direct current for operating a chloride removal system. The operating parameters of the power supply are site dependent, and should be sized to accommodate a wide range of site conditions. The power supply should have forced-air cooling and be contained in a lockable, outdoor enclosure.

The DC output should be sized according to the largest anticipated area to be treated. With a maximum operating current density of 0.5 A/ft^2 (5.0 A/m^2) and a maximum zone size of 1000 ft^2 (100 m^2), the DC output current requirement would be 500 A.

The control panel should be equipped with DC voltage and current controls, DC voltmeter, DC ammeter, amp-hour meter, and on/off switches.

Current Distribution Box

A current distribution box is a device that distributes the current to the anode. It essentially splits the treated area into several subzones, which operate electrically in parallel. The current distribution box, though not necessary, is strongly recommended. It provides a means of monitoring the operation and a way to remove a subzone anode if repairs are needed.

A schematic of a typical current distribution box is shown in figure 4-1. A 0.01-ohm, 50-watt resistor in each anode lead is used to monitor the current to that anode. The current, in amps, to the anode is determined by multiplying the voltage drop, in volts, across the resistor by 100.

Selector switches, banana jacks, and a digital voltmeter can be added for monitoring.

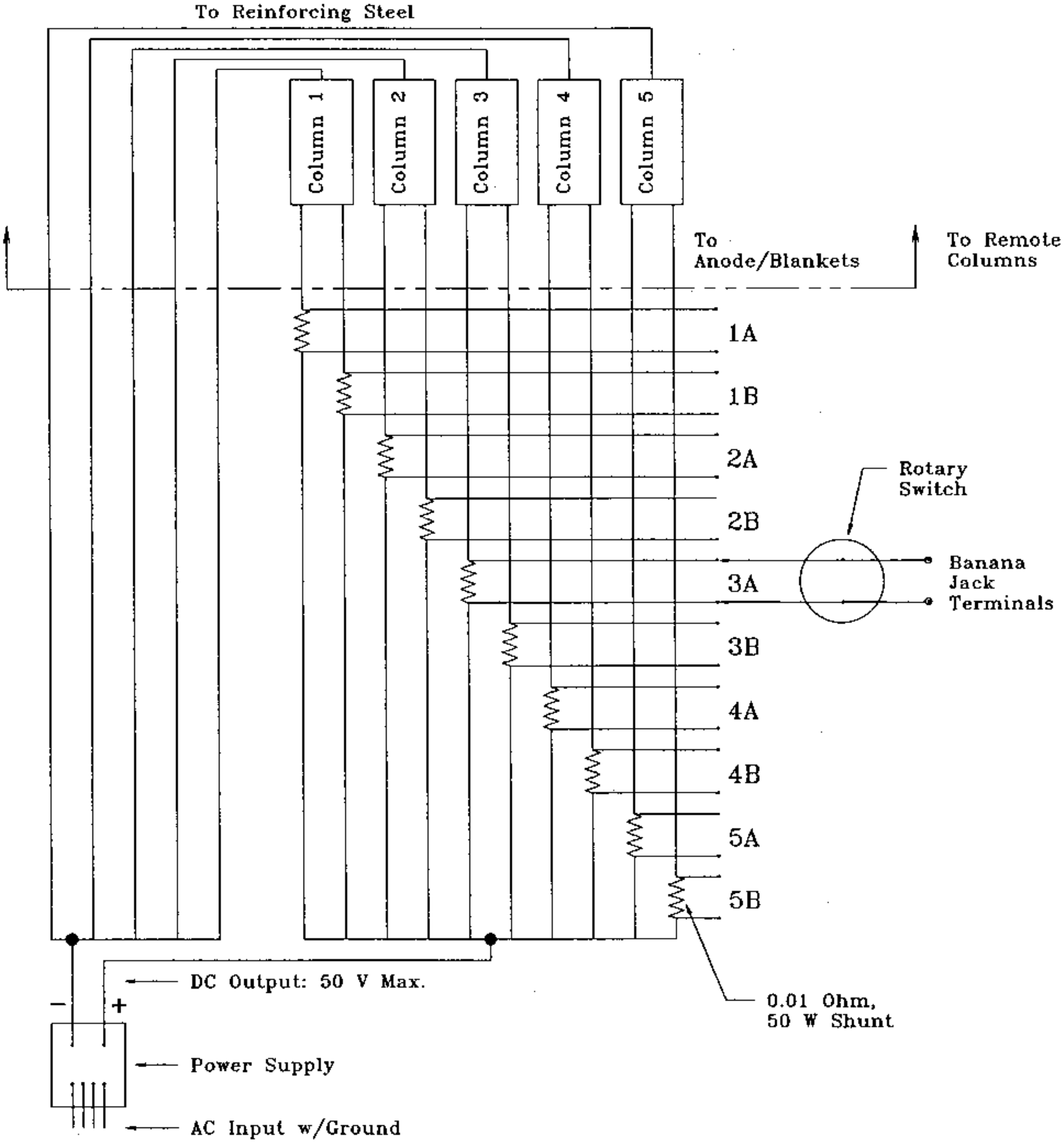

Figure 4-1. Typical Current Distribution Box Wiring Diagram

Wiring

The AC power line should be sized according to NEC for the power supply. Proper grounding should be provided. The size of the DC wires from the power supply to the distribution box should be based on the power supply's maximum rated output.

For an anode/blanket composite of 50 ft^2 (15 m^2), operating at 0.5 A/ft^2 (5.0 A/m^2), the anode lead needs to carry 25 amps. According to NEC, #10 American Wire Guage (AWG) would be required.

Typical system negative leads to the reinforcing steel should be #6 AWG. A minimum of two system negative leads must be installed per zone.

Electrolyte System

Pump

A 110-volt AC centrifugal pump, self-priming or magnetic drive, should be used for electrolyte recirculation. It should be selected and sized based on the system requirements. The pump should be capable of delivering 10 gal/min (38 l/min) per 1000 ft^2 (100 m^2) of treated area. The hydraulic head requirements should be considered when sizing the pump. Pump materials that come in contact with the electrolyte should be constructed of viton and polypropylene.

Electrolyte Reservoir

The reservoir should be sized to contain the volume of electrolyte determined in the system design. The reservoir should be polypropylene or other plastic that is suitably resistant to the electrolyte chosen. The reservoir should be covered.

Plumbing

Electrolyte distribution manifold piping and fittings should be Schedule 80 PVC. Schedule 40 PVC is not recommended. All pipe and fittings should be primed and glued with PVC cement. Others materials are suitable, but compatibility with the electrolyte should be verified.

Thick-walled tygon tubing or PVC garden hose is acceptable for electrolyte distribution hoses.

5

Pretreatment Procedures

Pretreatment procedures are procedures normally conducted before installation of the chloride removal system.

Half-Cell Potential Survey

A half-cell potential survey is normally conducted during structure selection (see chapter 2). If a potential survey has not been conducted recently, one should be completed before system installation. This survey will establish the probability for corrosion of the reinforcing steel before treatment. It provides baseline information that can be used for comparison after chloride removal has been completed and the steel has depolarized.

The survey should be conducted according to ASTM C 876-91, "Half Cell Potentials of Reinforcing Steel in Concrete," using 4-ft (1.2 m) spacing.

Chloride Analysis

Some chloride analyses are normally conducted during structure selection. Information from these analyses can be used for comparison after chloride removal has been completed. It is possible to estimate chloride removal efficiency from before- and after-treatment analyses, although not as accurately as from electrolyte analyses.

Chloride analysis of concrete before and after treatment is especially important when chloride removal is conducted using the sprayed cellulose fiber system. Since this system does not use a confined electrolyte, calculations based on electrolyte analysis are not practical.

Procedures and guidelines for testing chloride ion content are available in AASHTO T 260-84, "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials." It is recommended that at least two locations be sampled for every 1000 ft^2 (100 m^2) on large, relatively homogeneous structures. For nonhomogeneous structures such as most substructure columns, at least double that number of locations should be sampled. A minimum of 12 locations should be sampled for smaller areas. Before- and after-treatment samples should be taken close to each other. In the case of vertical surfaces, samples should be taken directly above and below each other. Concrete samples should be taken at 1/2-in. (10-mm) depth intervals to below the level of the reinforcing steel. Samples may be obtained either by coring or by collecting powder from drilling. Taking random samples both directly over reinforcing steel bars and between reinforcing steel bars is recommended.

Steel Continuity

A cursory check of electrical continuity of the reinforcing steel should have been done during structure selection. During pretreatment procedures, more detailed continuity testing should be conducted, and discontinuous steel must be made electrically continuous by continuity bonding. Chloride removal will not be effective where reinforcing bars are left discontinuous, and the process may accelerate corrosion in those areas.

Electrical continuity is best established by measuring the voltage between two embedded steel components with a high-impedence digital voltmeter. If the potential difference between the two components is less than 1.0 mV, it can be assumed that the two components are electrically continuous. As a general rule, five or more locations should be tested for each 1000 ft^2 (100 m^2).

Before chloride removal is conducted, all embedded metals found to be discontinuous must be electrically bonded. This bonding can be done with thermite welding, arc welding, or brazing. Wires may be used between the two components. The weld and any exposed copper should be coated with nonconductive, 100 percent solids epoxy.

Delaminated and Spalled Concrete Repair

Loose and delaminated concrete should be removed and patched prior to installation. Patches must age 28 days to allow the material to reach a stable resistivity.

Patch material should have a resistivity after curing that is similar to that of the surrounding concrete. Resistivity of the existing concrete can be estimated in the field using an AC resistance meter and the "Wenner Four Pin" method described in ASTM G 57-78. Resistivity of the patch material should not be more than 50,000 ohm-cm after 28 days of curing. Any patch material that meets these requirements, as well as commonly accepted specifications for normal patching, is acceptable.

Patches must contain no steel fibers, steel mesh, or other metallic embedments.

Crack Sealing

If a chloride removal system with a captive electrolyte is being used, cracks that may result in electrolyte loss must be sealed by epoxy injection. Procedures and guidelines for epoxy injection are given in ACI 503 R, "Use of Epoxy Compounds with Concrete."

If cracks are numerous or difficult to seal, the sprayed cellulose fiber system is recommended. This system does not require a confined electrolyte.

AC Power

The AC power source is usually provided in advance of system installation. A temporary service drop is satisfactory. A portable electric generator may be used when AC power is not readily available.

Safety Plan

An approved safety plan should be in place before initiating pretreatment procedures and system installation.

All workers are required to wear standard safety equipment. A material safety data sheet must accompany all chemicals. State and federal standards and regulations must be addressed.

Electrical hazard warning signs should be visibly placed near or on electrical components. Power supplies and portable generators should be secured to prevent access by the general public.

6

System Component Installation

The installation described in this chapter is for a column on land. Alternate system component installations are described in chapter 9 of this report. Components should be installed in an order that avoids interference with previously installed components. In general, the order should be as follows.

Wiring and System Negatives

The system negative (reinforcing steel or cathode) and system positive (or anode) leads should be rolled out separately, measured, labeled, cut, and bundled together. The bundled wires are lifted above the area to be treated and fastened to the structure. For neatness and safety, the bundles should also contain AC power cords for the pump(s).

Reinforcing steel for the system negative connections is exposed by chipping away concrete adjacent to the treatment area. The exposed steel is ground clean, drilled, and tapped for a 1/4-20 bolt connection. These connections can be left exposed during treatment, but the anode or electrolyte must not come in contact with the connection. Connections may be removed and patched or made permanent for subsequent measurements on completion of the treatment. Figure 6-1 shows a typical system negative connection.

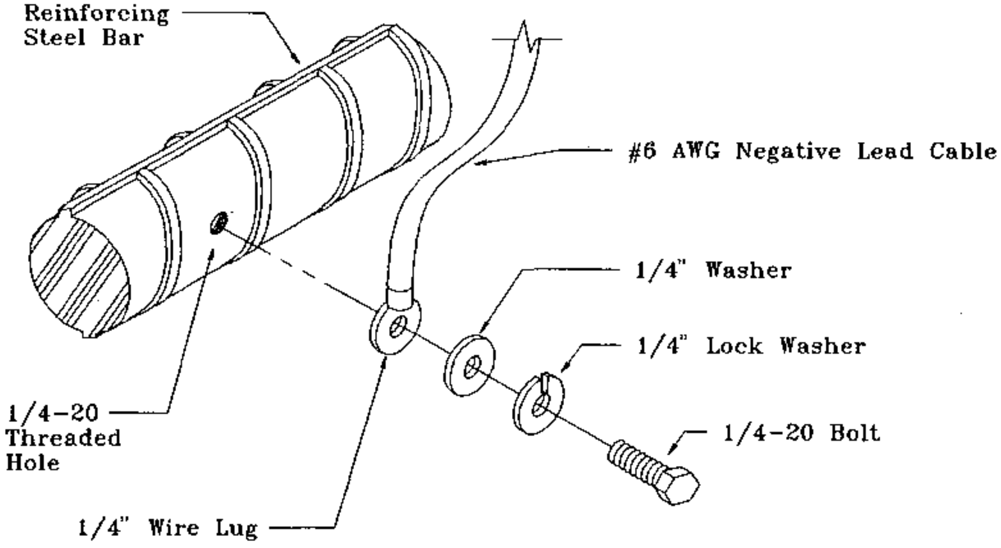

Figure 6-1. System Negative Connection

Electrolyte System

The electrolyte reservoir should be located central to the system to avoid unnecessarily long plumbing distances. The elevation of the reservoir must be such that the electrolyte can return by gravity. Burying the reservoir in the ground may be necessary. The tank must be sufficiently covered to avoid dilution by rainwater.

Electrolyte Distribution System

A PVC manifold (figure 6-2) is constructed to distribute the electrolyte to the columns. It is held in place above the treatment area by J-clamps. The manifold is connected to the outlet of the pump, and the lines feeding each column have a valve for flow regulation.

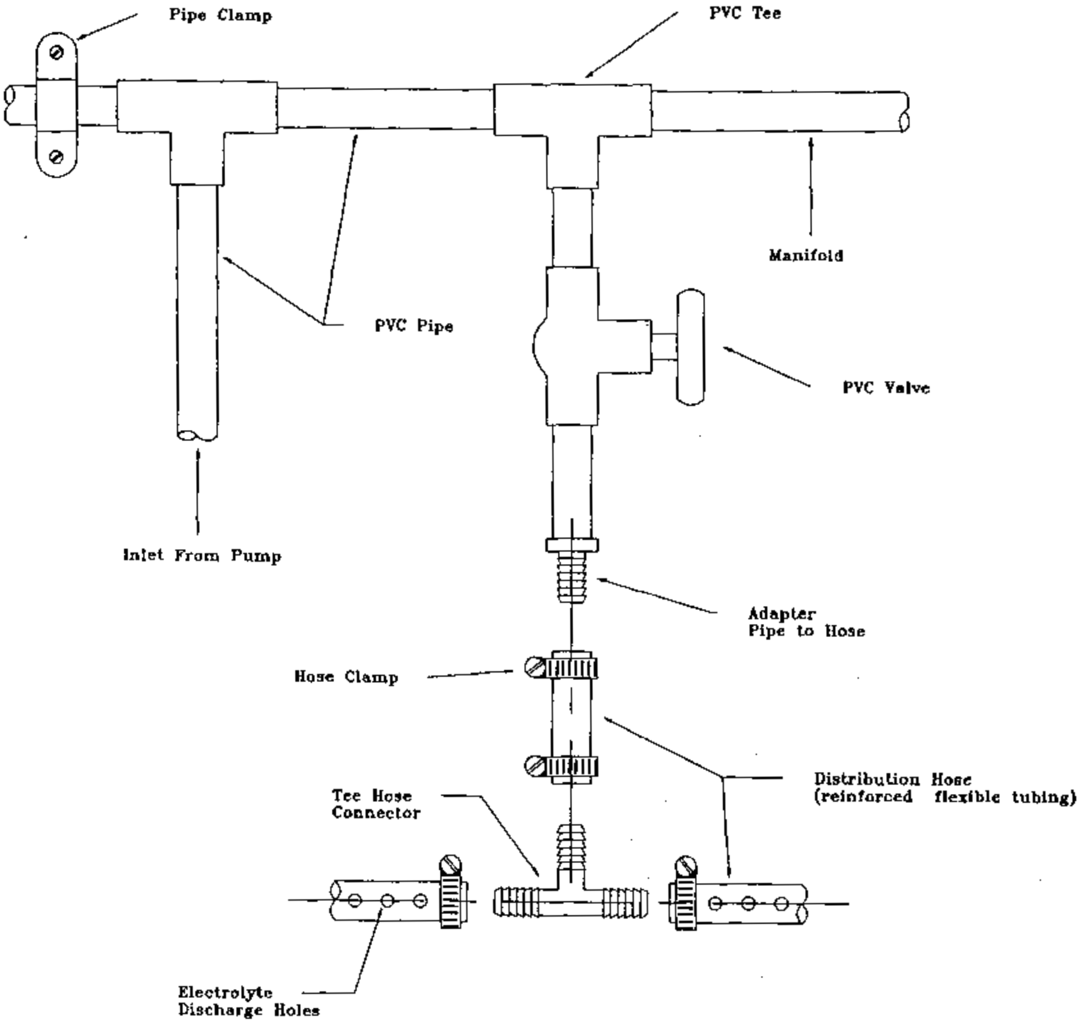

Figure 6-2. Electrolyte Distribution Manifold and Distribution Hose

The electrolyte distribution hose from the manifold (figure 6-2) ends in a loop around each column. The distribution hose has 1/8-in. (3.2-mm) holes are made at 4-in. (10-cm) intervals and is tucked into the top edge of the chloride removal blankets.

The pump should be mounted adjacent to the electrolyte tank and secured against vibration. A PVC union is usually used on each side of the pump to facilitate removal.

If the pump is not self-priming, a foot valve is used on the inlet to maintain prime.

Chloride Removal Blanket Installation

The chloride removal blanket assembly is described in chapter 3 and shown in figure 3-1. The dimensions of the assembly for column structures are 4 ft wide with the length determined by the circumference of the column.

An inner layer of Sorb_x is first wrapped around the column over the area to be treated. The blankets are wrapped and buckled to secure them to the columns.

A layer of plastic film is wrapped over the outside of the blankets in a top-to-bottom spiral to prevent electrolyte leakage and evaporation, and then bottom-to-top to prevent rainwater ingress. Plastic strapping is used to hold the wrap in place and to provide additional support. The top edge of the blankets must be protected from rainwater ingress.

Electrolyte Collection System

The rubber band, described in chapter 3, catches the electrolyte at the bottom of the area being treated. This process involves making a 1-ft wide (0.3-m) rubber band in situ to fit snugly around the column at the bottom of the blankets. The ends of a strip of 3/32-in. (2.4-mm) thick, 40-durometer rubber strip are vulcanized together after the strip was wrapped around the column. The bottom of the rubber band is sealed against the column with urethane caulk and secured with plastic banding. The top of the rubber band extends above the bottom of the lower anode blanket and is also banded securely. A plastic tube circumventing the column under the rubber band is used to channel electrolyte from all sides of the column to an exiting bulkhead fitting. The electrolyte is returned to the reservoir via a gravity return line. This collection assembly is illustrated in figure 3-3.

Electrical Installation

Power Supplies

The power supplies are positioned near the AC power source and wired. Circuit breakers should be open during installation. DC output should be routed to the current distribution box and labeled.

DC Wiring

All anode connections, discussed in chapter 3, are sealed with nonconductive putty and wrapped with vinyl electrical tape.

To facilitate data taking, monitoring and adjusting system currents, all anode blanket leads can be wired to a current distribution box. The system negative wires can be routed through this box.

Figure 6-3 shows a schematic of an installed chloride removal system.

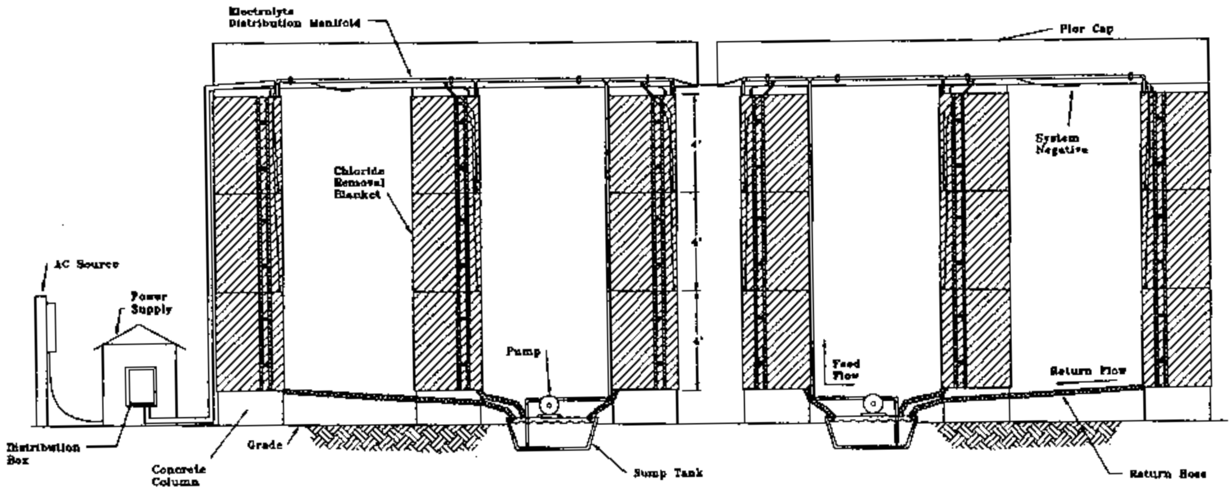

Figure 6-3. Schematic of a Chloride Removal System

7

System Operation, Maintenance, and Removal

Start-Up

First, the system must be started. The correct amount of water is added to the sump tank and circulated through the system. All fittings and seal points are carefully inspected for leaks. If any leaks are found, they must be repaired.

If no leaks exist, the flow rate is adjusted to the system, and the boric acid and sodium hydroxide are added.

Once the electrolyte has been prepared, it is circulated for about 30 minutes. This ensures that the electrolyte is well mixed and that buffer has reached all portions of the areas to be treated. The system is also checked for any new leaks. If needed, an electrolyte sample is taken at this time.

The amp-hour reading of the power supply is recorded. The power supply is turned on at zero current. With the voltage maximum set at 45 to 50 VDC, current is then gradually increased. If the output is limited by voltage, the power supply is set at 50 V and operated in constant voltage mode. If the output is limited by current, the power supply is operated in constant current mode. The power supply manual should be consulted.

Monitoring

The system should be monitored daily during treatment, and the following records should be made:

- date and time
- flow rate
- current
- voltage
- amp-hour reading
- electrolyte pH

It is important to maintain electrolyte flow. If flow slows or stops, the problem must be corrected before the treatment can continue. A flow switch to shut down the rectifier may be useful.

It is normal for current to decrease slowly during the chloride removal process. If a sharp decrease in current or increase in voltage is observed, a problem may have developed.

Wires, conductor bars, and connections should be checked. If the system has a distribution box, each subzone should be checked.

If the pH drops below 6, some hydroxide and boric acid should be added to the electrolyte until the pH is between 10 and 12.

The electrolyte should be sampled about twice per week for monitoring purposes.

End of Treatment

The end of the chloride removal process can be determined by the total charge passed or from the amount of chloride removed. If the total charge to be passed is fixed, the process is stopped when that amount of charge has been reached. If the electrolyte is analyzed for chloride, the process is stopped when the required amount of chloride has been removed. Minute changes in chloride removed relative to initial removal rates suggest that the process is not economically worth continuing.

A sample of the electrolyte may be obtained for posttreatment evaluations.

System Removal and Disposal

Electrolyte

After the system is shut down, 24 hours are allowed for the electrolyte to drain away from the anode blankets. The spent electrolyte is pumped into plastic drums and disposed of in accordance with applicable regulations.

Electrolyte System

Some items are reusable and should be saved for further treatments. All other materials should be disposed in accordance with applicable disposal and safety regulations.

The pump, electrolyte reservoir, and reusable fittings should be cleaned and saved for further treatments.

Electrical System

All electrical wiring and hangers should be removed from the structure and saved for further treatments. All other components and power supplies should be properly boxed for transport.

Anode Blankets

Plastic wrap and banding straps should be removed and properly disposed. The anode/blanket composites should be removed, rinsed, and allowed to dry completely. They should then be stacked, rolled up, and packed for transport.

The Sorb_x should be removed from the columns and properly disposed. Any remaining Sorb_x should be scraped off the surface of the concrete. Any holes made to install hangers and system negative connections should be cleaned and patched with approved materials.

The site should be completely clean at the end of the job.

8

Posttreatment Procedures

Treatment Evaluations

Structural

Posttreatment testing is conducted to determine the effectiveness of the chloride removal process and its effect on the concrete structure. First, a visual inspection is made. Concrete etching might indicate that the electrolyte flow was restricted in certain areas of the system. The location and magnitude of cracks should also be noted, even though chloride removal is not believed to cause cracking.

Technical

A potential survey of the structure may be taken in accordance with ASTM C 876. Interpretating the results in the usual way is not appropriate since all the reinforcing steel has been strongly polarized. The purpose of the survey is to assess the distribution of current during treatment. If distribution of current has been good, all potentials will be strongly negative (≈ -1000 mV versus saturated calomel electrode) and roughly equal. If current distribution has been poor, there will be areas where the steel potentials are less negative. These areas have received less total charge.

Concrete powder samples should be taken for chloride analysis in accordance with AASHTO T 260. For complete evaluation, samples should be taken at different depths and at locations both above and between the reinforcing steel. Sampling locations should correspond to pretreatment sampling locations so that the effect of the treatment can be determined. Comparing pretreatment and posttreatment samples to accurately determine the amount of chloride removed is usually difficult since chloride contamination of concrete is not homogeneous. This problem can be minimized by comparing samples taken very close to each other and in vertical lines on vertical surfaces.

Cores can be taken after treatment for petrographic analysis and compared with pretreatment cores. Such cores should contain steel, if possible. Petrographic analysis is especially important if the concrete contains alkali-silica reactive aggregate.

Surface Treatment

Chloride removal will not prevent the future ingress of chloride. Following chloride removal, application of an effective concrete sealer is recommended. The sealer should be selected and applied in accordance with agency practice and manufacturers' instructions. When choosing a sealer, it should be recognized that there will be retreatment problems. Recommended sealers include silanes; siloxanes; and 30 percent solids, two-component epoxy.

Follow-Up Inspection

Follow-up inspections may consist of a visual survey, delamination survey, potential survey, linear polarization corrosion rate measurements, and chloride analysis. Inspections are recommended for the first year after chloride removal and every two to three years thereafter.

9

Alternate Systems

This chapter will identify the differences between the system already discussed and two alternate chloride removal systems.

Ponded Electrolyte System

System Design

This system is used on a horizontal or near-horizontal surface such as a bridge deck.

A dam made of concrete block or other suitable material, is constructed around the perimeter of the area to contain the electrolyte, and a catalyzed titanium mesh anode is used. A pond approximately 2 in. (5 cm) deep is recommended. This depth holds approximately 650 gal (1650 l) of electrolyte per 1000 ft^2 (300 m^2). If the slope of the deck is too severe, weirs can be built to maintain sufficient electrolyte depth.

A cover over the treatment area is recommended to prevent dilution or evaporation of the electrolyte. A constant electrolyte level should be maintained throughout the treatment.

System Removal and Disposal or Reuse

The electrolyte is pumped into plastic drums and disposed of in accordance with Environmental Protection Agency regulations or other appropriate regulations. The anode is stored for reuse on additional projects.

The perimeter dam can be removed without harming the concrete surface, and the rubble is disposed.

Cellulose Fiber Without Electrolyte Recirculation

System Design

This system is applied principally to vertical surfaces. Cellulose fiber is wet sprayed onto the structure, a steel anode is installed over the fiber, and more cellulose fiber is sprayed to cover the anode. Periodic wetting of the surface with water is necessary to maintain an electrically conductive path between the anode and concrete. This proprietary procedure is commercially known as the NORCURE™ process and is marketed by CPS (Concrete Protection Services). A description and evaluation of this process is reported in SHRP Report Number SHRP-C-620.

A catalyzed titanium mesh anode has also been used in this system.

Equipment

Equipment for handling and spraying cellulose fiber is needed. The dry fiber is air blown out the center of the application nozzle and is wetted by limewater that is sprayed around the perimeter of the nozzle.

System Operation and Maintenance

The fiber is wet when installed so the system can be energized after all electrical connections are made. However, the fiber must be rewetted daily or as necessary by spraying it with limewater.

An operating current density of approximately 0.1 A/ft^2 (1.0 A/m^2) is recommended. The process is continued until significant decrease in current is obtained at 40 VDC. This decrease occurs after approximately 60 $A\text{-}hr/ft^2$ (600 $A\text{-}hr/m^2$) of charge has passed and after three weeks of operation.

System Removal and Disposal or Reuse

The cellulose fiber is scraped off the structure and disposed properly. The steel embedded in the fiber is dissolved throughout the process, and only a minimal amount remains to be disposed of with the fiber.

If a steel anode is used, there is staining on the structure. This stain may have to be removed by blast cleaning with sand or other suitable abrasive.

References

1. Stratfull, R.F. "Experimental Cathodic Protection of a Bridge Deck." *Transportation Research Record 500.* 1974, pp. 1-15.

2. Federal Highway Administration. *1991 Status of the Nation's Highways and Bridges: Conditions, Performance and Capital Investment Requirements.* July 2, 1991.

3. Han, M.K., M.J. Snyder, P.D. Simon, G.O. Davis, and B. Hindin. *Cathodic Protection of Concrete Bridge Components.* Quarterly Report SHRP-87-C-102B. SHRP, National Research Council, Washington D.C., 1989.

4. Lankard, D.R., et al. *Neutralization of Chloride in Concrete.* Battelle Columbus Laboratories, Report No. FHWA-RD-76. FHWA, U.S. Department of Transportation, 1965.

5. Morrison G.L., et al. *Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis.* Report No. FHWA-KS-RD 74-1. Kansas Department of Transportation, 1976.

6. Bennett, J.E., et al. *Electrochemical Chloride Removal and Protection of Concrete Bridge Components, Volume I: Laboratory Studies.* Report No. SHRP-S-657. SHRP, National Research Council, Washington D.C., 1993.

7. Bennett, J.E., et al. *Electrochemical Chloride Removal and Protection of Concrete Bridge Components, Volume II: Field Trials.* SHRP, National Research Council, Washington D.C., 1993. Forthcoming.

8. ACI Manual of Concrete Practice. *Corrosion of Metals in Concrete.* ACI 222R-85, Detroit, Michigan, 1989.

Concrete and Structures Advisory Committee

Chairman
James J. Murphy
New York Department of Transportation (retired)

Vice Chairman
Howard H. Newlon, Jr.
Virginia Transportation Research Council (retired)

Members

Charles J. Arnold
Michigan Department of Transportation

Donald E. Beuerlein
Koss Construction Co.

Bernard C. Brown
Iowa Department of Transportation

Richard D. Gaynor
National Aggregates Association/National Ready Mixed Concrete Association

Robert J. Girard
Missouri Highway and Transportation Department

David L. Gress
University of New Hampshire

Gary Lee Hoffman
Pennsylvania Department of Transportation

Brian B. Hope
Queens University

Carl E. Locke, Jr.
University of Kansas

Clellon L. Loveall
Tennessee Department of Transportation

David G. Manning
Ontario Ministry of Transportation

Robert G. Packard
Portland Cement Association

James E. Roberts
California Department of Transportation

John M. Scanlon, Jr.
Wiss Janney Elstner Associates

Charles F. Scholer
Purdue University

Lawrence L. Smith
Florida Department of Transportation

John R. Strada
Washington Department of Transportation (retired)

Liaisons

Theodore R. Ferragut
Federal Highway Administration

Crawford F. Jencks
Transportation Research Board

Bryant Mather
USAE Waterways Experiment Station

Thomas J. Pasko, Jr.
Federal Highway Administration

John L. Rice
Federal Aviation Administration

Suneel Vanikar
Federal Highway Administration

11/19/92

Expert Task Group

John Apostolos
California Department of Transportation

Robert Girard
Missouri Highway and Transportation Department

Richard Kessler
Florida Department of Transportation

Carl Locke, Jr.
University of Kansas

David Manning
Ontario Ministry of Transportation

Paul Virmani
Federal Highway Administration