NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **313**

CORROSION PROTECTION OF PRESTRESSING SYSTEMS IN CONCRETE BRIDGES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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CORROSION PROTECTION OF PRESTRESSING SYSTEMS IN CONCRETE BRIDGES

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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation Research Board

This report includes the findings of a study on corrosion protection systems that can be incorporated into the construction of new prestressed concrete structures. The systems are intended to protect specifically against the chloride-induced corrosion of prestressing steel caused by the intrusion of salts from deicing chemicals or a marine atmosphere. Both pretensioned and post-tensioned methods of construction were considered. Promising design options were identified from the literature, and several were evaluated in the laboratory. Bridge designers, specification writers, materials engineers and scientists, corrosion engineers, manufacturers and suppliers of prestressing steel and hardware, producers of precast concrete members, and researchers working in the previously mentioned disciplines will find the report of interest.

The use of deicing salts or exposure to a marine environment can lead to chloride-induced corrosion of prestressing steel embedded in concrete bridge members—a problem that could ultimately cause major structural damage. This potential problem is further exacerbated in bridges where the prestressing steel is in close proximity to the deck or other exposed surfaces, such as in segmental bridges.

High quality construction reduces the potential corrosion of prestressing steel. Unfortunately, quality is often detrimentally affected by actual field conditions and less than ideal practices. Low-permeability membranes and overlays, concrete sealers, and various other methods of decreasing chloride intrusion are being used to provide some additional insurance against corrosion; however, confidence in the long-term protection of prestressing steel is lacking. More positive techniques are needed for the use of prestressing steel in a chloride-potential environment.

Protective techniques were investigated by the Northbrook, Illinois, firm of Wiss, Janney, Elstner Associates, Inc. (WJE) under NCHRP Project 4-15, "Corrosion Protection of Prestressing Systems in Concrete Bridges." WJE conducted a review of existing techniques, including some that showed promise but were not yet employed; all are documented in the report. The review also provided support for techniques that were pursued in laboratory experiments. These laboratory experiments helped WJE formulate the various recommended options that can be used in new construction for the protection of prestressing steel systems.

Protective techniques for bonded, post-tensioned concrete structures were deemed to be quite feasible from the outset. In bonded, post-tensioned concrete, the prestressing steel is encapsulated by a grout-filled duct, which provides a partial barrier to chloride intrusion. To enhance this protection, WJE experimented with the use, in various combinations, of plyethylene, galvanized metal, epoxy-coated metal, and bare metal ducts; uncoated and epoxy-coated prestressing strand and end-anchorage hardware; and corrosion inhibiting admixtures for grouts.

Pretensioned concrete presented different problems because the prestressing steel is in direct contact with the surrounding concrete. Therefore, the original intent was to perform feasibility studies for epoxy coating the prestressing steel strand, directly. However, before the actual research began, an epoxy-coated strand became commercially available. The feasibility of coating strands was no longer the issue, and WJE evaluated the performance of the available product.

In addition to corrosion resistance studies for both the post-tensioned and pretensioned systems, several mechanical tests were conducted on the ducts and prestressing strands. In these tests, WJE examined the friction between strand and duct walls, the abrasion of ducts and epoxy-coated strands, and the bond between ducts and concrete or grout.

Readers of the report should realize that besides the epoxy-coated strand, other commercially available products were used in the laboratory studies for the purpose of testing concepts. Even though individual products conformed to industry standards when available, overall materials and construction specifications based on performance were not specifically developed in this study. It is assumed that products of equal or higher quality will perform in a similar fashion. Nevertheless, products do vary, and caution must be exercised in interpreting and extending the findings of this research.

The appendices to the agency's final report are not published herein, but are contained in a separate report entitled *Supplement to NCHRP Report 313,* "Corrosion Protection of Prestressing Systems in Concrete Bridges, Appendices A, B, C, D, E, F." Copies of the agency-prepared supplemental report have been sent to all NCHRP sponsors, that is, the state highway departments. Others wishing to obtain the additional details found in the supplemental report (available for $10.00) should contact the Publications Office, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

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ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 4-15 by Wiss, Janney, Elstner Associates, Inc. (WJE). William F. Perenchio, Senior Consultant, was Principal Investigator. The major portion of the writing was by John Fraczek, Senior Consultant, and Donald W. Pfeifer, Vice President, both of WJE. The WJE Project Engineer was L. John Dondanville, formerly a Senior Engineer with WJE and now Director of Corporate Construction for Perry Drug Stores, Inc.

The work was performed under the direction of Messrs. Fraczek and Dondanville. J. Robert Landgren was responsible for the corrosion measuring systems used during the laboratory studies and W. Robert Hannen conducted the literature search; both are Senior Engineers with WJE. The following corporations donated materials and technical advice that contributed significantly to the success of these studies: DSI International, Lemont, Illinois; Florida Wire and Cable Company, Jacksonville, Florida; W. R. Grace and Company, Cambridge, Massachusetts; Hancor, Inc., Findlay, Ohio; Midwest Pipe Coating, Schererville, Indiana; Norcem Concrete Products, Inc., Long Island City, New York; Sika Corp., Lyndhurst, New Jersey; VSL Corp., Los Gatos, California; Charles R. Watts Co., Seattle, Washington.

CORROSION PROTECTION OF PRESTRESSING SYSTEMS IN CONCRETE BRIDGES

SUMMARY

An extensive literature search and a worldwide survey were undertaken to gather information on corrosion protection materials and techniques for pretensioned and post-tensioned, prestressed concrete bridge members. The reviewed information shows that the corrosion serviceability performance of prestressed concrete bridges has been quite good to date. Most designers and state highway departments believed that adequate clear cover with good quality concrete was the best protection for pretensioning strands. Similarly, most respondents indicated that post-tensioning tendons were best protected with a good set of grouting specifications that were rigidly enforced in the field.

Although overall performance has been good, corrosion serviceability could still be improved. In addition, the introduction of negative-moment intense segmental construction has brought with it new design details that may require enhanced corrosion protection measures. Recently developed measures that have been employed in construction in response to these needs include use of external tendons located within the box girder void; use of plastic duct or epoxy-coated metal duct for transverse deck prestressing; use of epoxy-coated anchorage hardware; and use of epoxy-coated prestressing bars and strands. In addition, some states are requiring or evaluating calcium nitrite, a corrosion inhibiting admixture for concrete, and others are assessing concretes with a condensed silica fume additive.

Following the state-of-the-art review on corrosion protection of prestressing steel, a year-long, accelerated corrosion test program was undertaken on bare and epoxy-coated prestressing strand using pretensioning and post-tensioning methods with traditional and new materials and hardware. These severe to very severe corrosion tests showed that epoxy-coated prestressing strand was remarkably corrosion resistant, even in the wedge/grip region of post-tensioned members or at locations of cracks in pretensioned concrete. These tests also showed that polyethylene duct and epoxy-coated steel duct were excellent chloride barriers, particularly when heat-shrink tubing was used to seal the post-tensioning duct joints. The epoxy-coated post-tensioning anchorages and chucks were also found to be generally corrosion resistant, although some localized corrosion occurred. Of particular importance is the chloride resistance of the total prestressing steel encapsulation system, because all three grout formulations tested were found to be highly permeable to chlorides. The two specialty grouts, modified with calcium nitrite and silica fume admixtures, were found not to contribute significantly to corrosion performance and, in fact, the silica fume grout system appeared to allow more severe corrosion than the traditional cementitious grout. As in the field, these hardened grouts were also found to contain voids even though simple, short length laboratory ducts were grouted using actual field grouting equipment. Thus, perfect grouting in the field appears very difficult to achieve and the emphasis on duct and duct joint performance is paramount.

While abrasion and damage occurred to some of these newer corrosion-resistant plastic materials, the abrasion and post-tensioning tests to assess damage susceptibility

were very severe in that a very small radius of curvature was used. Such damage and abrasion to the epoxy coating on the strand or to the polyethylene duct would be significantly less severe if straight ducts or ducts with more typical curvature were used.

Most of the newer materials tested in this program provided significantly enhanced corrosion protection when compared to traditional materials; however, these tests and the nationwide survey showed that traditional materials can provide good protection in normal environments, even with chloride present. On the other hand, codes have recently been modified to require lower permeability concrete and greater clear cover over the reinforcing and prestressing steel and its hardware. Thus, these new code provisions for better overall corrosion protection, supplemented by the newer materials evaluated in this severe test program, provide designers with opportunities to produce highly corrosion-resistant bridges using pretensioning and post-tensioning methods.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT

Exposure to deicing salts or a marine environment presents a potential problem of chloride-induced corrosion of prestressing steel and associated metallic hardware in concrete bridge members (*1–35*). This potential problem is exacerbated in the newer segmental bridges where these corrodible materials may be located in close proximity to the deck or other concrete surfaces exposed to chlorides.

Prestressing, which improves the long-term serviceability and strength characteristics of bridge members, can be accomplished by pretensioning or post-tensioning. Pretensioning utilizes highly stressed steel strands that are embedded directly in fresh concrete during the casting operation. Bond and force transfer to the hardened concrete is thus achieved without associated embedded metallic hardware. Post-tensioned concrete members require the same highly stressed steel strands or tendons, but they are usually located within hollow metallic ducts cast in the concrete and are stressed after the concrete has achieved the proper strength. The required ducts and tendon anchorage hardware can consist of corrodible materials. In bonded post-tensioning, the ducts must be grouted after the stressing operation to achieve bonded, composite structural behavior and encapsulate the bare prestressing steel in a protective, high pH grout.

Prestressing steel is subject to the same chloride-induced corrosion mechanisms that attack reinforcing bars (*1, 32, 35–38*). Steel, typically in a passive corrosion state in the highly alkaline environment of portland cement concrete or grout, is depassivated by chloride ions that penetrate through the concrete or grout. Such penetration can occur even through crack-free prestressed concrete (*32*). The consequences of corrosion of prestressing steel are potentially so serious that preventive measures beyond current common practice may be required. Low permeability membranes and overlays, concrete sealers, and various methods of decreasing the permeability of concrete are being used, but more positive steps are needed to instill greater confidence in the use of prestressing steel and its associated hardware in a potentially chloride-contaminated environment.

A number of surveys of the condition of prestressing steel in concrete bridges (*1–5, 27, 28*) have concluded that corrosion is not a common problem. Most instances of corrosion have been attributed to improper construction techniques or, to a lesser degree, poor design details combined with an aggressive environment. The surveys did note, however, that prestressed concrete bridges in the United States are relatively new, having been introduced approximately 35 years ago. Most of the surveys were conducted in the 1960s and, hence, did not reflect the effects of the substantial increase in the use of deicing salts that began about that time. Although no corrosion problems have been associated with segmental bridges to date, this type of construction has only been employed in the United States for about 15 years.

Because segmental construction incorporates design features that may not be representative of traditional prestressed concrete bridge construction, the historical corrosion performance of prestressed construction may not be totally applicable to segmental construction. The potential for corrosion-induced structural damage is enhanced in segmental construction because the deck is a vital structural element that typically contains significant amounts of prestressing steel. In addition, void-free grouting (*20, 21, 22, 23*) is very difficult to assure under actual field conditions and construction practices. The increasing concern of the design community with corrosion of prestressing steel in segmental bridges is evident in the recent specification (*39*) of relatively new protection techniques for such structures. For example, polyethylene ducts or epoxy-coated metal ducts have been specified for transverse prestressing in several bridges. Such features as additional concrete cover in segmental designs also reflect an increased awareness of potential corrosion problems. Consequently, a clear need exists to define new corrosion protection materials for pretensioned and post-tensioned bridge members.

CURRENT KNOWLEDGE

The objectives of the research conducted under NCHRP Project 4-15 were the identification of those techniques and materials that have been used or developed specifically to protect pretensioning steel and post-tensioning steel, ducts and anchorages from corrosion, and the evaluation of their long-term corrosion performance based on severe, accelerated corrosion tests. The knowledge gained during the last 15 years concerning corrosion protection of conventional steel embedded in concrete was thoroughly reviewed (*32, 40–49*) and applied to this study. The use of plastics for coating reinforcing bars, duct, hardware, tie wire, and prestressing strand can enhance the long-term serviceability of these various metals. The use of 100 percent plastic duct potentially can further enhance the corrosion protection of prestressing steels within grouted ducts. Corrosion-inhibiting calcium nitrite admixtures (*32, 49–53*) and silica fume admixtures (*30, 32, 54, 55*) have been successfully employed in concrete, and it was assumed that their use in grout could also potentially enhance the corrosion performance of bonded, post-tensioned members. These newly developing, potentially effective materials were identified, selected, and evaluated in this research.

RESEARCH APPROACH

State-of-the-Art Study

As noted earlier, the increasing concern over the potential for corrosion of prestressing systems in concrete bridges has resulted in the recent specification (*39, 56, 57*) of more stringent preventive measures. Gathering of current, state-of-the-art information was accomplished by direct contact with individuals having knowledge of corrosion of prestressing systems. An extensive search of the literature was also conducted, using the Highway Research Information Service and several major libraries. As the information was collected and evaluated, requirements for supplemental information became apparent and additional sources were sought.

This cumulative information was reviewed and summarized into the following subject areas concerning corrosion protection: (1) protection afforded by current standard practices (field experience, current specifications, segmental construction); (2) available measures for corrosion protection (protection of prestressing steel during shipping and storage, admixtures to improve the corrosion resistance of concrete or grout, ducts, metallic coatings for reinforcing steels, nonmetallic coatings for reinforcing steels, proprietary protection systems, protection by design).

The accelerated corrosion test program was then planned, based on a review of the foregoing information.

Accelerated Corrosion Testing

Materials. The one-year long, accelerated corrosion studies were undertaken on the following promising corrosion protection system components for post-tensioned or pretensioned concrete bridge members:

- Concrete or grout admixtures, particularly condensed silica fume and calcium nitrite.
- Plastic duct or epoxy-coated steel duct.
- Epoxy-coated prestressing strand.
- Epoxy-coated anchorage hardware.

For purposes of comparison, companion corrosion tests were conducted with traditional materials.

These measures could be used alone or in combination to tailor a corrosion protection system to the severity of the environment. All were currently available, and could be implemented immediately with little or no additional development. However, although several of these measures had already been installed in actual bridge constructions, their effectiveness in corrosion protection had apparently yet to be evaluated.

Corrosion protection for post-tensioning applications was evaluated with separate test specimens representing anchorage regions and duct regions away from the anchorage. These specimens used combinations of all of the protective measures cited earlier. Epoxy-coated prestressing strand was selected as potentially the most effective protective system for pretensioned members. It was evaluated using precast, prestressed beams.

Specimen Design. The anchorage is probably the most critical region of a post-tensioning tendon for corrosion protection. It typically includes components with different steel compositions, providing potential for galvanic couples. The gripping mechanism generally produces a complex stress state in the prestressing steel and the transition from duct to anchorage usually requires a joint which may not be watertight. Finally, anchorages may be located at the ends of structural elements, where exposure to chloride-laden moisture is common. Because of its importance, the corrosion testing emphasized the anchorage region for post-tensioned concrete. Three types of specimens were employed. The basic test specimen consisted of a fully assembled anchorage embedded near the top of the specimen. The top surface of the initially chloride-free concrete was alternately air-dried and ponded with a salt solution. The bottom region of the specimen contained four No. 11 bars to serve as the cathode of the test macrocell. To determine the possible existence of galvanic couples between the various steel components, companion specimens were cast with the anchorage components completely disassembled. Larger versions of the basic test specimen, containing both fully stressed and unstressed strands, were also tested to evaluate possible effects of state-of-stress on corrosion.

Three combinations of anchorage-duct-strand were employed in all of the post-tensioning anchorage specimens. These combinations were as follows:

- The industry standard—bare anchorage:galvanized steel duct:bare strand.
- New duct and anchorage materials—epoxy-coated anchorage:polyethylene duct: bare strand.
- New prestressing steel materials—bare anchorage: galvanized steel duct: epoxy-coated strand.

These specimens were intended to compare the performance or effects of the following:

- Uncoated (bare) anchorage vs. epoxy-coated anchorage.
- Galvanized steel duct vs. polyethylene duct.
- Uncoated (bare) prestressing steel vs. epoxy-coated prestressing steel.
- Stressed vs. unstressed prestressing steel.

A typical multistrand post-tensioning anchorage was tested. This anchorage was compatible with both bare and epoxy-coated ½-in. diameter prestressing strand. The post-tensioning anchorage specimens necessitated use of 1 in. by 3 in. oval duct for compatibility. Two-inch diameter round duct, considered more representative of the post-tensioning industry, was used for the remaining corrosion and mechanical tests.

Post-tensioned duct sections remote from the anchorage region were also simulated, by grouting unstressed bare prestressing strands in 2-in. diameter ducts, then subjecting the ducts to alternate air drying and soaking in a salt solution. Various combinations of duct and grout materials were employed for these specimens. Materials included bare steel, galvanized steel and epoxy-coated steel duct, polyethylene duct, normal cementitious grout, normal cementitious grout modified with calcium nitrite, and normal cementitious grout modified with condensed silica fume. All ducts had a joint at midlength to evaluate the effectiveness of an improved joint seal.

The joint at midlength in half of the post-tensioning duct corrosion specimens was sealed with standard duct tape. The joint in the remainder of these specimens was sealed with a heavy-wall, heat-shrinkable tubing developed for insulating and sealing electrical connections. When heated, the tubing shrinks and the thermoplastic adhesive-sealant internal coating melts and flows to provide a moisture seal.

Epoxy-coated strand (*11, 26, 32*) was selected for evaluation as a corrosion protection system for pretensioned members. Prestressed beams were cast with both coated and bare strand. The tops of these beams were also subjected to alternate air drying and ponding with a salt solution. Half of these specimens had flexural cracks initially induced and maintained during testing, while the other half were tested uncracked.

To produce very severe tests (*32, 43, 58*), the clear cover over the embedded prestressing steel and hardware was kept to a minimum value of about 1 in. in these pretensioned and post-tensioned specimens. The post-tensioning duct specimens were soaked directly in salt water without any exterior concrete protection.

Corrosion Measurements. An electrochemical corrosion cell typically consists of a combination of many microcell and macrocell interactions. Although the corrosion test specimens employed in this study were designed (*32, 43*) to promote the formation of macrocells between steel elements in concrete or grout increasingly contaminated with chloride and noncontaminated concrete, microcells and noninstrumented macrocells probably developed as well. The intent of the corrosion measurement techniques employed in this study was to identify the initiation of corrosion activity and monitor its subsequent development by the following three independent test procedures (*32, 59*): (1) measuring the corrosion current between various steel components or assemblies, (2) determining the instant-off potential or the back voltage (electromotive force) producing current flow between various steel components or assemblies, and (3) determining the copper-copper sulfate half-cell potential at predetermined locations over the various embedded steel components or assemblies in increasingly chloride-contaminated concrete. In addition, the AC resistance of the concrete or grout between various steel components or assemblies was periodically measured.

Chloride Contents. At the conclusion of the corrosion testing, concrete and grout samples at the level of the prestressing steel were taken for determination of chloride ion content. Comparison of these results with the chloride corrosion threshold provided an additional measure of protection system performance.

Visual Examination. On completion of the corrosion testing, all specimens were broken open and the individual elements were visually examined to assess actual performance. These visual examinations also served to confirm the validity and relevance of the electrical measurements.

Mechanical Testing

In addition to the accelerated corrosion tests, tests were performed to assess those aspects of mechanical performance considered critical to the effective use of these various new materials in prestressed concrete. These tests included creep, coefficient of friction and mechanical abrasion resistance of epoxy-coated strand and polyethylene duct, and bond and force transfer characteristics of epoxy-coated steel and polyethylene duct.

Creep Tests. Significant long-term creep of the epoxy coating on the 7-wire strand would result in significant stress losses in the strand during the service life of such pretensioned members. To determine if such creep is possible and, if so, its magnitude, the cracked and uncracked pretensioned beam corrosion specimens were instrumented to measure the creep properties of both bare and epoxy-coated strands relative to the concrete.

Friction and Abrasion Tests. Tests were undertaken to establish the relative friction losses associated with stressing epoxy-coated strand and bare strand in curved polyethylene duct and galvanized steel duct. These tests also determined if the stressing operation under very severe curvature conditions results in significant abrasion damage to either the epoxy coating on the strand or the polyethylene duct. The test configuration and procedures simulated the stressing operations in actual bridge constructions. A 15-ft radius of curvature was selected to represent minimum duct curvatures employed in post-tensioned bridges. The friction loss and abrasion damage performance of the following four strand and duct combinations were evaluated: (1) bare strand in galvanized steel duct, (2) bare strand in polyethylene duct, (3) epoxy-coated strand in galvanized steel duct, and (4) epoxy-coated strand in polyethylene duct.

Bond Tests. Tests were undertaken also to compare the bond and force transfer characteristics of polyethylene duct and epoxy-coated steel duct to those of conventional galvanized and bare steel duct. These tests consisted of pullout tests to determine the load-deformation behavior of a high-strength steel bar when grouted in these various 2-in. diameter ducts, which were cast in a large concrete block. The purpose of these tests was to determine if the four duct types could transfer 40 percent of the catalog ultimate tensile strength of four 0.6-in. diameter, 270-ksi prestressing strands to the concrete test block through the duct and grout materials. This nominal 100-kip force theoretically represents the maximum force to be transferred from the tendon to the concrete through the duct and grout materials.

The deformational behavior of the grouted duct was also measured to determine if the different ducts had significantly different stiffness and elasticity values when embedded in concrete.

CHAPTER TWO

FINDINGS

STATE-OF-THE-ART SURVEY AND LITERATURE SEARCH

A large portion of the information obtained was by direct contact with individuals active in corrosion prevention of prestressing systems. More than 200 letters were sent to addresses in this country and abroad. Also, presentations were made at meetings of selected committees of the Prestressed Concrete Institute (PCI) and the Post-Tensioning Institute (PTI). Letters were sent to selected members of these organizations as well as to the American Concrete Institute (ACI), the International Union of Testing and Research Laboratories for Materials and Structures (RILEM), and organizational and individual members of the Federation Internationale de la Precontrainte (FIP) Commission on Prestressing Steels and Systems. Another group contacted was the departments of transportation in the United States that frequently use prestressed concrete for bridges, and the Ministry of Transportation and Communication for the Province of Ontario, Canada. After the initial mailing, promising leads among the responses were pursued. About 90 replies to the letters were received, from North and South America, Europe, Asia, Africa, and Australia.

In addition to the letters and direct contacts, an extensive literature search was conducted by means of the Highway Research Information Service and the libraries of the Portland Cement Association, Northwestern University, the University of Illinois, and Princeton University. More than 130 relatively recent articles and publications were reviewed. As the search developed, additional leads were discovered. These were pursued through letters, telephone contact, and meetings.

Corrosion Protection Afforded by Current Standard Practice

Corrosion protection of pretensioned elements traditionally has been provided by use of high quality, low water/cement (w/c) ratio concrete and concrete cover. This same approach, but generally with somewhat higher w/c ratio concrete, coupled with established ducting and grouting procedures, also has served to protect bonded post-tensioned construction. The information obtained indicated that existing pretensioned and post-tensioned concrete bridge structures generally appear to be reasonably resistant to chloride ion-induced corrosion.

More than 12,000 prestressed concrete bridges were built in the United States between 1951 and 1966. These bridges, now in use for 20 to 35 years, have apparently shown only minor incidences of corrosion-related problems. Highway officials in the 14 states that collectively contain over half of these bridges reported no widespread problems, and those from only 3 states reported specific corrosion-related problems.

A 1982 survey of some 20 typical bridges on the Illinois Tollway system (*28*) found the precast, pretensioned concrete girders, stay-in-place deck slabs, and cylindrical piles typically to be in very good condition after 25 years of service.

The literature search found only a few citations of chloride-induced corrosion of prestressing steel. One 1977 survey (*4*) cited seven examples in bonded prestressed bridges. In each case, detrimental characteristics considered atypical of standard practice led to accelerated corrosion. An update of this survey in 1982 (*27*) found that corrosion incidents were usually associated with poor design details or execution, typically in aggressive environments. The major conclusion was that the 50 corrosion incidents reported, of which most involved improperly grouted tendons, represent a very small fraction of the prestressed concrete bridges in the United States.

Although of great concern because failure occurs suddenly, reported instances of stress corrosion or hydrogen embrittlement appear to be rare. At least two instances have been reported (*1, 10*); however, both involved aluminum in close proximity to the prestressing steel.

The failure of a post-tensioned bridge in the United Kingdom caused a sudden collapse (*29*). The 32-year old, simple span bridge utilizing nine I-beams, each consisting of eight precast segments post-tensioned together, collapsed under self-weight as a result of corrosion of the post-tensioning steel at the segment joints.

Reported instances of chloride-induced corrosion of prestressing steel in bridges generally have been due to a very harsh environment, poor design details, or poor construction practices as discussed below.

Performance in Harsh Environments. Corrosion problems in very harsh winter environments were reported both in Pennsylvania and Indiana with pretensioned adjacent box beam bridges. This type of bridge was built for a number of years with only an asphalt wearing surface and no waterproofing membrane. Without transverse post-tensioning, cracks soon developed along the joints. A number of these bridges exhibited deterioration of their soffits and wire fracture from corrosion of the strands. Florida also cited corrosion problems that were specifically limited to harsh coastal environments, particularly low profile bridges.

Early instances of corrosion in Japan were typically attributed to use of unwashed sea sand, instigating the first Japanese regulations on the salt content of sea sand used in concrete in 1974. The discovery in 1982 of six deteriorated coastal concrete bridges that were less than 15 years old led to a nationwide investigation of 920 concrete bridges within 500 m of the coast, over two-thirds being prestressed. This investigation found that 20 percent were adversely affected by chloride, and that conventionally reinforced and post-tensioned bridges had suffered greater corrosion damage than pretensioned bridges. A conclusion of the investigation was that wind-borne chloride, not the use of unwashed sea sand in the concrete, was primarily responsible for the corrosion.

A study of severe weathering of prestressed beams was reported by the U.S. Army Engineer Waterways Experiment Station (*14, 15, 16, 17, 18*). Pretensioned and post-tensioned beams were installed in the tidal zone at their Severe Exposure Stations in Maine and Florida in the late 1950s and early 1960s. The beams were maintained under various loading conditions and monitored over a period of years. Laboratory testing in 1969, 1973, and 1974 found relatively little corrosion damage to the post-tensioned wires, but significant damage to the pretensioned strands at the ends of the beams, where an epoxy pad used to protect the exposed ends of the strands failed. In addition, the pretensioned beams utilized mild steel bars with only ¾-in. concrete cover. This cover was quickly spalled off by corrosion of the bars. Inspection of the intentionally precracked beams revealed that most of the corrosion occurred at the beam ends or at crack locations. Visual observations of the post-tensioned beams in Maine indicated apparent good durability through 1978 (*19*). Examination of three of these beams in 1983 revealed that the chloride content of the grout was negligible and that the prestressing steel showed no loss of structural integrity (*31*), indicating that the metal ducts had effectively protected the post-tensioning steel from the seawater environment.

Detailing and Construction Problems. The most obvious examples of inconsistencies in typical construction practices involve the grouting of post-tensioning ducts. Studies in Ontario (*20*), Britain (*21*), and California (*22*) illustrate the large variations possible in quality and continuity of grout in existing structures, both new and old. In one Ontario bridge, the grout was of highly variable quality and incomplete, resulting in significant cross-sectional reduction of some wires because of corrosion. Another bridge, demolished after 23 years of use in a deicer environment, contained uniform and dense grout throughout the duct system. Only isolated instances of surface corrosion were discovered on the wires. Similar experiences have been reported in Denmark (*23*). Although high quality grouting is now typically the norm, consistent high quality in 100 percent of the duct is apparently difficult to achieve.

Another common detailing and construction problem cited was inadequate concrete cover or poor quality concrete over prestressing steel, ducts, or anchorages. One survey (*4*) listed this as a contributing factor in three bridges in marine environments. Two of these exhibited spalling of the concrete caused by inadequate cover over the duct. The third involved insufficient concrete compaction together with low cover.

In general, pretensioned elements appear to have better corrosion resistance than post-tensioned members, probably because of typically lower w/c ratio, higher strength concrete (*58*), in-plant quality control, and more complete encapsulation of the prestressing steel.

Corrosion in prestressed members resulting from the intentional addition of calcium chloride admixtures to the fresh concrete have also been reported.

Many responses expressed the opinion that quality workmanship and strict compliance with specifications were adequate protection in all but the harshest of environments.

Current Specifications. Guide specifications from California and Tennessee discuss protection of prestressing steel during shipping and placement, including packaging with a corrosion-inhibiting compound, adding lime to water used for flushing post-tensioning ducts, and limiting the time between installation of the post-tensioning steel and grouting of the ducts. Galvanized metal ducts are required by both States. California, on the basis of extensive studies, felt that their successful use of both pretensioned and post-tensioned bridge members for more than 25 years was in part because of strict enforcement of their construction specifications (*22, 60, 61, 62*). Most other responding states indicated that galvanized metal ducts were required.

Requirements for minimum concrete cover were either 1½ in. or 2 in. California indicated that their designers increase cover for conventional reinforcing in areas expected to receive deicing salts or in coastal environments, thus also increasing the prestressing steel cover.

For the past several years, Illinois has required the addition of calcium nitrite as a corrosion inhibitor for precast, pretensioned box beams used without a cast-in-place overlay or other protective covering. Other states are currently testing this admixture.

The AASHTO specifications do not require metallic ducts for post-tensioned systems (*57*). Performance requirements (e.g., pullout bond strength, grout penetration) for nonmetallic ducts, however, are equal to those of metallic ducts. If used, metallic ducts are to be of ferrous metal and may be galvanized.

Information from the Cement Research Institute in West Germany indicated that corrosion protection is typically afforded through the use of bitumen sealers or membranes on the deck surfaces and adequate concrete cover. In addition, very strict maximum water-soluble chloride limits in the concrete and grout have been established.

According to the Swedish National Road Administration, approximately 400 prestressed bridges have been built there since 1952. As in other European countries, corrosion protection for the deck is provided by a waterproofing membrane under the wearing course (*24*).

Available Measures for Corrosion Protection of Prestressed Members

Techniques that hold potential for enhancing the corrosion protection of pretensioned and post-tensioned bridge members can be divided into two approaches: those that enhance the concrete durability and those that directly enhance the corrosion protection for the prestressing steel and associated hardware. The durability of the concrete is admittedly important; however, a review of this large subject is beyond the scope of this study. Included here are techniques for protecting prestressing steel prior to encapsulation in grout or concrete; grout or concrete admixtures that may be used to inhibit corrosion; epoxy-coated metal ducts and plastic ducts; metallic and nonmetallic coatings for prestressing steel or anchorage hardware; proprietary corrosion protection systems; and design techniques that enhance corrosion protection. Because corrosion protection measures are being developed so rapidly, products or techniques in addition to those reported herein undoubtedly exist. A more complete discussion is presented in Appendix B.

Protection of Prestressing Steel During Shipping and Storage

The measures used to protect prestressing steel prior to its encasement in grout or concrete include special storage and handling techniques, packaging with inhibitors, and temporary inhibitor coatings.

Packaging of Prestressing Steel. Prestressing steel is generally packaged in a waterproof wrapping for shipment. When specified, a vapor phase inhibitor (VPI) is incorporated in the packaging. A commonly used VPI consists of dicyclo-ammonium nitrite crystals, which sublime to create a vapor that minimizes ongoing corrosion by forming an insoluble ferric oxide coating on the steel.

Temporary Protective Coatings. An earlier NCHRP corrosion study (*1*) included tests of commonly used temporary coatings. Two of particular interest were a water-soluble oil and a film produced by sodium silicate solution in water. The test results indicated that water-soluble oil, as well as other organic coatings, provided better corrosion protection than the sodium silicate film. However, the oil and organic coatings left residual films on the steel after a water rinse that were detrimental to the bond strength. The presence of the sodium silicate film or its residue did not adversely affect bond. The conclusion was that the sodium silicate coating was the most suitable temporary coating available. Despite these findings and continued questions of bond effectiveness, an emulsifiable (so called "water-soluble") oil has historically been the only type of temporary coating used on strand or wire tendons. Originally designed as a water-soluble metal-working coolant that contained rust preventive additives, this product has been used in both Europe and the United States for more than 20 years. An improved emulsifiable oil recently has been developed that is specifically designed as a corrosion preventive for bonded prestressing systems.

The present study identified other coatings that appear suitable for temporary protection of prestressing steel but are not in common use. One commercially available coating (a fast-drying, phosphoric acid phosphate resin) was tested specifically for use on prestressing strand. The coating was found to provide suitable short-term corrosion protection for shipment and sheltered jobsite storage without adversely affecting the bond characteristics of the strand (*6*). An alkali-resistant polymer coating developed for corrosion protection of mild steel reinforcement during storage, which does not affect the bond between steel and concrete, may also be suitable for prestressing steel (*44*).

Protection in Ungrouted Ducts. Climatic conditions in northern climates often dictate that post-tensioning ducts be grouted during warmer weather, at times leaving tensioned post-tensioning steel ungrouted for several weeks or months. The effects of this practice were studied by the Swedish National Road Administration. Five different corrosion protection methods were applied to ungrouted tendons in 26 ducts exposed to various climatic conditions at three different locations in Sweden for 3 years. The methods and their effectiveness were as follows (*25*):

1. Careful sealing of the ducts combined with drain pipes at the duct low points. These simple precautions resulted in relatively good corrosion protection.
2. Continuous flowing of predried air through the ducts. This technique provided better corrosion protection than the sealed and drained ducts.
3. Depositing a vapor phase inhibitor in the ducts. This measure afforded better protection than either of the two foregoing methods.
4. Eliminating oxygen from the steel environment by filling the ducts with nitrogen. Problems with connecting the gas tubes to the ducts and gas leakage made this method impractical.
5. Applying an emulsifiable oil on the tendons. This technique also produced good results.

After 3 years of exposure, the prestressing steel was tensile, fatigue, bend and stress-corrosion tested. Neither significant deterioration of the steel nor significant variations between the three test sites were discovered. In addition, measurements of the surface smoothness of the specimens did not reveal any significant difference between the five different protection methods.

Admixtures for Improving Concrete or Grout. Good quality dense concrete, with a minimum of 1-in. to 2-in. cover, previously has been considered effective protection against the ingress of chloride in all but the most severe exposure conditions. In severe exposure, additional protection, while maintaining the design cover, can be achieved by: (1) decreasing the permeability of the concrete or grout matrix, (2) increasing the durability of the protective oxide coating on the steel, or (3) precipitating or absorbing the chloride ion from solution as it approaches the steel.

Reducing the permeability of the concrete or grout slows or prevents the gradual migration of excessive amounts of aggressive anions, water, and dissolved oxygen toward the embedded steel and increases the electrical resistance of the concrete. The most common method of reducing concrete permeability is to use a lower w/c ratio concrete mix in combination with good consolidation and curing. Browne calculated that a w/c ratio of 0.40 combined with a cover of 2 in. over the steel would provide good protection for reinforced concrete for 50 years in a seawater splash zone (*63*). ACI Committee 201 recommends a maximum w/c ratio of 0.40 for concrete exposed to seawater or more than moderate concentrations of chlorides (*64*).

Research by the Federal Highway Administration (FHWA) (*43*) and Wiss, Janney, Elstner Associates, Inc. (WJE) (*32, 58*) indicates that chloride ion permeability to a 1-in. depth is increased by 500 to 600 percent when the w/c ratio is increased from 0.40 to 0.50, and by 1800 percent when the w/c ratio is increased from 0.28 to 0.50. These studies conclude that 1 in. of cover is inadequate protection against chloride-induced corrosion in conventional concretes with w/c ratios ranging from 0.60 to 0.28.

A w/c ratio of 0.40 or less may result in difficulties with concrete placement or consolidation. High-range water reducers are capable of producing concrete mixtures with much lower w/c ratios (0.35 or less) and good workability.

Use of condensed silica fume as a concrete or grout admixture is growing. Condensed silica fume with high-range water reducers enhances the workability and pumpability and reduces the segregation and bleeding of concrete or grout. The particles are spherical in shape and about 100 times finer than average cement or fly ash particles. The superior pozzolanic properties of this material allows the production of extremely low-permeability concrete, with compressive strengths as high as 18,000 psi. Very low w/c ratios of 0.20 to 0.40 are made possible by the water reducers. Concretes containing silica fume typically have electrical resistivities about two orders of magnitude greater than plain concretes. Research conducted at the Danish Corrosion Center (*54*) and WJE (*33*) has shown the value of this material in corrosion protection when employed in concrete. In the latter research, silica fume concrete specimens with 1-in. cover did not support corrosion after 44 weeks of accelerated testing, while similar conventional concrete specimens with w/c ratios ranging from 0.51 to 0.28 supported corrosion after 2 to 16 weeks of testing.

Corrosion-Inhibiting Admixtures. Corrosion inhibitors consist of substances placed in the environment surrounding a metal to prevent corrosion activity. Their methods of corrosion inhibition (*65*) are: (1) barrier layer formers, (2) neutralizers, (3) scavengers, and (4) miscellaneous mechanisms. Barrier layer formers are materials that tend to deposit themselves on or around the metal surface. They can be divided further into adsorbed layer formers, oxidizing or passivating inhibitors, and conversion layer formers.

Absorbed layer formers adhere strongly to the metal surface, creating a physical barrier. They have not been shown to be effective in concrete.

Oxidizing inhibitors (or passivators) constitute the category most commonly considered for use in concrete. They consist mostly of chromates, nitrites (NO_2) or nitrates (NO_3), which act by shifting the electrochemical potential at the steel surface out of the active region into a more positive passive region (*66*).

Recent studies have revealed that sodium nitrite and other alkali salts have adverse environmental effects as well as detrimental effects on the concrete matrix, including loss in concrete strength and adverse reactions with certain aggregates (*50*).

Further research led to the development of calcium nitrite $Ca(NO_2)_2$ as an effective and acceptable corrosion inhibitor (*51*). The nitrite ion acts by quickly oxidizing the ferrous metal ion to form an insoluble ferric oxide coating on the steel surface (*52*). As the chloride content near the surface of the steel increases, the effectiveness of the calcium nitrite is decreased because the nitrite ions are gradually consumed. A recent laboratory investigation (*32*) found that calcium nitrite did not significantly delay the onset of corrosion but substantially reduced the subsequent severity of the corrosion process.

Ducts. In bonded post-tensioning systems, the duct serves the primary function of forming the void through which the bar, strand, or tendon can be installed and stressed. To serve this purpose properly, the duct should have the following characteristics:

1. Impervious to mortar during concrete placement.
2. Sufficient strength to prevent crushing, puncture or other damage during duct installation or concrete placement.
3. Sufficient abrasion resistance and stiffness to prevent the prestressing steel from cutting or crushing the duct walls during tensioning.
4. Adequate chemical stability to avoid destructive reactions with the cement, grout, or prestressing steel.
5. Ability to transfer bond between the grout and the surrounding concrete.

Current practice typically uses corrugated ferrous-metal ducts to meet these requirements, usually galvanized to enhance their corrosion resistance. Recently, however, attempts to provide better corrosion protection in harsh marine environments or critical locations in large segmental structures have led to an additional requirement for post-tensioning duct. Dusts such as epoxy-coated metal or plastic, which resist the penetration of chloride or water, have been specified on several new bridges. Studies of epoxy-coated metal or plastic duct in bonded prestressing applications were not found in the literature. The information presented below was obtained from individuals involved in specifying, testing, or manufacturing such ducts.

The chemical stability of certain plastics has been questioned, particularly polyvinyl chloride (PVC) and other plastics containing chloride, based on concern that the plastic may decompose and release chloride ions within inches of the post-tensioning steel. Several chemists familiar with these materials and with concrete have indicated that this is a very real possibility in the highly alkaline concrete or grout environment.

The abrasion resistance and stiffness of plastic duct may also be problems. The basic reason for using plastic instead of metal for a duct is the presumed long-term ability of the plastic in preventing moisture and chloride from reaching the post-tensioning steel. A hole abraded in the plastic duct wall during threading or tensioning of the prestressing steel would seriously reduce this advantage. Also, the steel could crush the plastic duct walls over a period of time, either directly or through bond stresses in the grout. The effect of such behavior on the bond strength of the system is unknown and no published research was found. However, the pullout tests specified to date have not contained any deformation limitations.

Most concerns with use of plastic ducts for post-tensioning applications have apparently been resolved satisfactorily in Europe.

The basic strength, stiffness, and interior abrasion resistance of epoxy-coated metal duct remains unaffected by the exterior coating and the epoxies do not react chemically with the grout, cement, or metal components (*46*). Remaining questions include the abrasion resistance of the coating (i.e., damage during handling and installation) and the bond transfer characteristics.

Only one specification was received covering an actual application of epoxy-coated metal ducts (*67*). Smooth metal ducts, with a 1-in. by 3-in. rectangular cross section, were tested for "pullout" strength as required by the specifications. Again, the duct was required to transfer 40 percent of the minimum ultimate tensile strength, f_{pu}, of the grouted tendon in a duct length equal to its development length. The tests were completed to the satisfaction of the owner and designers.

Discussions with an applicator indicate that corrugated metal ducts may not be suitable for coating with epoxy. The applicator noted that epoxies prequalified for use on reinforcing steel, and most probably all epoxies, have insufficient ductility to bridge the spiral seam when the metal duct is flexed. These discussions indicate that epoxy coatings may only be suitable for bare, semirigid metallic ducts.

Metallic Coatings. Coating a metallic component with another metal having different properties can provide corrosion protection in two very different ways. The coating may be chosen for its hardness and noncorrosive properties to provide positive protection by shielding another metal from the corrosive environment. Conversely, a coating with a more negative galvanic potential than the base metal will protect nearby exposed surfaces of the base metal by acting sacrificially as an anode in an electrochemical corrosion reaction between the two metals. The normally less voluminous corrosion products will usually cover a small exposed area, stifling the corrosion reaction.

To be used on prestressing steel, a metallic coating must match certain physical characteristics of the bar, wire, or strand as well as provide protection from corrosion. A prior NCHRP study of this subject identified ten requirements which a metallic coating must meet to be effective with bonded prestressing steel (*1*). These include wear resistance during handling and placement, the ability to withstand wire elongation, good bond strength, and so on. The study concluded that no metallic coating could meet all of the requirements, and identified problems with candidate coating materials. Three metals have been developed as coatings for mild steel reinforcement, however, and attempts have been made to adapt them for use on prestressing steel. Galvanized (or zinc-coated) strand was used on the first prestressed concrete bridge built in the United States (*33*). Anodic to steel, zinc has been used for galvanizing since the early 1800s (*47*). Research on galvanized prestressing steel is summarized in *NCHRP Report 90* (*1*). That study concluded that a zinc coating appeared to be promising for corrosion protection of prestressing.

Significant further research on zinc coatings has continued since that report, primarily in France. Investigations have concentrated on possible hydrogen embrittlement and mechanical properties of the coated steel. A reaction between the zinc coating and some cements releases hydrogen, reducing bond. Research has indicated that this undesirable reaction can be inhibited by addition of chromates to the cement (*8, 48*), or by dipping the galvanized steel in a chromate solution.

The galvanizing process also may affect the mechanical properties of the steel. Galvanizing of cold-drawn wire reduces its ultimate tensile strength, increases its ultimate elongation, and degrades its relaxation properties. Poor bond may result if the galvanized strand is not kept free of zinc carbonate prior to embedment in concrete.

Currently, galvanized 7-wire strand is produced by a number of manufacturers in the United States, with strengths ranging from 130 to 225 ksi. External prestressing tendons consisting of galvanized 7-wire strand have been used on at least two bridges in France, where research on such applications is continuing.

More noble than steel, copper typically does not corrode in the concrete environment. Therefore, any imperfection in the copper coating would cause the underlying steel to corrode rapidly at that location (*1*). However, recent studies of copper-clad steel reinforcement indicate that it may provide better corrosion protection than epoxy coatings. Nominal ½-in. diameter, copper clad 7-wire strand with a minimum ultimate tensile strength of 150 ksi is currently produced for grounding and guy-cable applications. Areas of concern in prestressed application include abrasion resistance of the coating, bond between the copper and concrete, and the need for isolation of other, uncoated, steel in the structure from the copper. Bond strength may be a potentially serious problem because copper salts severely retard the hydration of portland cement.

The corrosion-resistent properties of stainless steels have created interest in their use as a coating for steel in concrete. A number of manufacturers currently produce stainless clad mild steel reinforcing and solid stainless steel bars. Solid stainless steel reinforcing bars have been installed in an experimental program in Michigan (*40*). A ramp and one-half of a bridge at the I-696 and I-75 interchange incorporate the stainless bars. These same solid stainless steel bars provided excellent corrosion performance in extensive accelerated corrosion studies (*68*). Development of stainless-clad strand is being pursued by at least one manufacturer, but none is presently available commercially. One foreign producer advertises solid stainless strand. About 5,500 ft of nominal ½-in. diameter nonmagnetic stainless steel strand have been fabricated domestically for use in test piles for a Navy degaussing facility. Relaxation and bond tests of this stainless steel strand revealed characteristics similar to stress-relieved carbon steel strand. Fatigue properties and resistance to stress corrosion and crevice corrosion of stainless steel strand or cladding in a chloride-contaminated concrete environment need further study. Some promising test results on stainless steel prestressing strand have recently been reported, however (*34*).

Nonmetallic Coatings. Nonmetallic coatings for reinforcing steel can be organic or inorganic. Most research in the last 15 to 20 years has concentrated on the organic compounds.

In the 1970s, epoxy coatings for mild steel reinforcing were thoroughly tested. Certain formulations were recommended for experimental use in the United States (*46*). A significant number of bridges, as well as parking decks and other structures exposed to salts from deicing and marine exposures, have since been constructed using fusion-bonded epoxy-coated reinforcement. This protection technique also has been applied to high-strength prestressing bars in several bridge rehabilitation projects.

Epoxy-coated single and multistrand anchorages are now being employed in the construction or rehabilitation of bridges and parking structures (*42*).

Research also has focused in recent years on the use of epoxies to coat prestressing strand. As with metallic coatings, the principal questions involve bond characteristics and elongation capabilities. *NCHRP Report 90* (*1*) cited a number of references in which epoxy coatings were found to meet the bond and elongation characteristics necessary for prestressing.

At least one American manufacturer currently produces epoxy-coated 7-wire, 270-ksi, low-relaxation prestressing strand. It is produced with an epoxy thickness of 30 ± 5 mils, which has been found to result in an essentially holiday-free coating. Suitable bond between the strand and the concrete is attained by introducing frit onto the epoxy during the fusion bonding process. A great deal of testing (*11, 32*) has been done on this product, with very encouraging results. Details can be found in Appendix B.

Proprietary Protection Systems

Several systems for corrosion protection of prestressing steel are currently patented in the United States and abroad. The epoxy-coated strand described previously is a proprietary item, as are several systems designed for post-tensioning applications. All of the proprietary systems for post-tensioning incorporate the same basic concept for corrosion protection—total encapsulation of the prestressing tendon.

Single Strand Systems. At least two proprietary systems are available for single strand tendons. One of these, marketed by a Swiss firm, was developed for both bonded and unbonded strands. The system uses a plastic connector between the anchorage casting and the duct. Bonded systems incorporate grout fittings and either corrugated metal or plastic duct. This system has been employed throughout Europe since 1968. The manufacturer reports no corrosion problems despite extensive use.

A similar system for unbonded 0.6-in. diameter strand is marketed in the United States. This system employs polyethylene or epoxy-coated anchorage hardware and a connector sleeve with a greased and polyethylene-sheathed strand. A plastic grease cap is used at the end of the anchorage to achieve total encapsulation of the tendon.

Multistrand Systems. Developed in France, the one system identified was conceived for use in bonded post-tensioned offshore structures. The system is intended for use with multiple prestressing strands. It employs a steel pipe casing with plumbing-type connections as a duct. Galvanized pipe may be used. The trumpet portion is fabricated from a larger steel pipe that is welded to the bearing plate. A steel ring is welded to the anchorage side of the bearing plate. After the duct is grouted, a steel cap with a rubber O-ring seal is bolted to the ring. The cap, which contains inspection and vent ports and constitutes a permanent part of the anchorage, is then injected with grease or grout under pressure. The external surfaces of metal parts are then painted with epoxy and the anchorage is encapsulated in mortar or concrete.

Protection by Design

An alternate approach to corrosion-resistant materials or corrosion-inhibiting admixtures is the use of appropriate design details. Increased concrete cover and reduced concrete water-cement ratio traditionally have been used by American and European designers to enhance the corrosion protection of both mild and high-strength reinforcement. Relatively recently, however, innovative design concepts, such as external tendons located within the box girder void with provisions for future tendon replacement, have been introduced to limit potential corrosion liabilities. Discussion of these approaches to corrosion protection follows.

General. A number of corrosion problems reported with prestressed concrete elements have stemmed from poor design details. Such details have typically permitted chloride-laden moisture to penetrate to the prestressing steel, ducts or anchorage hardware, often resulting from poor drainage or ill-conceived joints. Consequently, proper attention to drainage details and a sensitivity to the corrosion vulnerabilities of prestressed elements can significantly enhance the durability of those elements.

Concrete Cover and Water-Cement Ratio. The effectiveness of concrete cover in protecting reinforcing steel from corrosion has been recognized and studied for many years. The 1940 *Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete* published by ACI (*69*) states, "Structures or structural elements exposed to the injurious action of corrosive liquids and vapors require special designs of protective coverings." The AASHTO Division II specifications have required 4-in. clear cover for concrete exposed to seawater for over 50 years. Current codes reflect these provisions in the same general way. The 1983 ACI 318, *Building Code Requirements For Reinforced Concrete,* says that, "In corrosive environments . . . amount of concrete protection shall be suitably increased. . . ." (*56*). The current edition of the AASHTO *Standard Specifications For Highway Bridges* contains similar requirements (*57*). For the first time, the 1983 ACI 318 code includes explicit provisions for maximum w/c ratio and the ACI *Commentary* suggests minimum concrete cover requirements for members exposed to deicing salts.

The use of deep concrete cover for main longitudinal tendons in segmental bridges has progressed rapidly. Designers of the West Seattle Freeway Bridge in Washington positioned the main longitudinal tendons below 3½ in. of conventional concrete plus 2 in. of dense concrete topping, and required extra protection for any steel (mild or high strength) above this level. Other designers have placed the main tendons entirely within the hollow core of the box girder section. This approach removed the tendon from possibly chloride-contaminated concrete and allows observation of and access to the tendon over the life of the structure. This method was applied to segmental construction in Florida in late 1980. A proposed Pennsylvania specification for segmental construction also recommends placing main tendons inside the hollow box (*39*).

Redundant Systems. The Pennsylvania specifications require that two extra tendons be installed as "contingency" tendons and that details be provided for the future installation of at least four others. One of the stated purposes for these provisions is their "future use in the substitution of defective or corroded tendons" (*39*). This concept, however, apparently has yet to be applied to an actual construction.

RESULTS OF THE ACCELERATED CORROSION TESTS

The initial task of this project identified the following materials as promising components in corrosion protection systems for post-tensioned or pretensioned concrete bridge members: (1) epoxy-coated prestressing steel, either strand, wire, or bar; (2) plastic duct or epoxy-coated semirigid metal duct; (3) epoxy-coated anchorage hardware; and (4) concrete or grout admixtures, particularly condensed silica fume or calcium nitrite.

These measures could be used alone or in combination to tailor a corrosion protection system to the severity of the environment. All were available, and could be implemented with little or no additional development. In addition, although several of these measures had already been installed in actual bridge constructions, their effectiveness in corrosion protection had yet to be compared and quantified.

Epoxy-coated prestressing strand was selected as potentially the most effective protection system for pretensioned members, and was evaluated using uncracked and cracked pretensioned beams. Enhanced corrosion protection for post-tensioning applications was evaluated with specimens representing anchorage regions and also with specimens representing duct regions away from the anchorage.

Pretensioned Beam Specimens

These eight specimens consisted of 6-in. by 10-in. concrete beams approximately 12 ft long containing two fully stressed strands. The top strand was epoxy-coated in half of the beams and bare in the other half, while the bottom strand was always bare. The central 6-ft region in half the beams was cracked prior

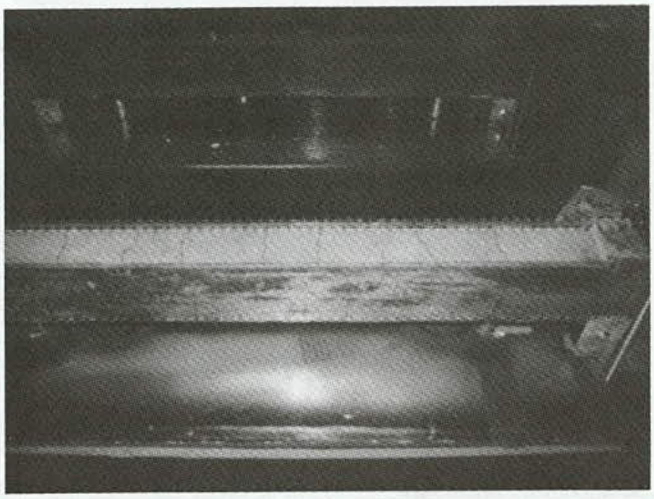


Figure 1. Typical cracks in pretensioned beams during corrosion tests.

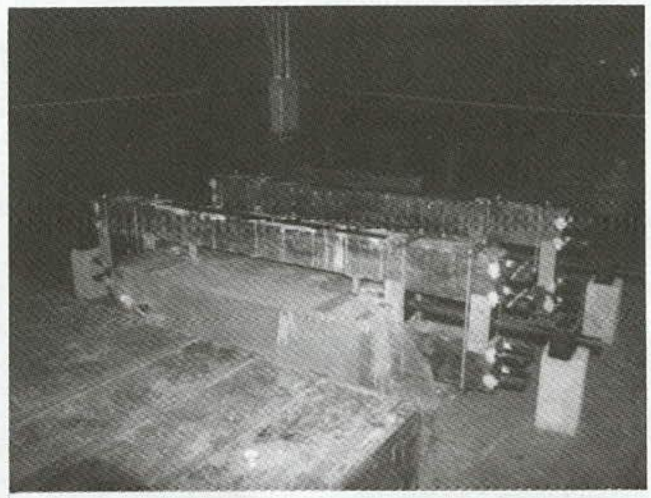


Figure 2. Pretensioned beam specimen under corrosion test simultaneous heating and saltwater ponding conditions.

to testing by subjecting the beams to flexural loading. This cracking was induced to ascertain if the epoxy coating on a highly stressed strand had sufficient ductility to bridge the crack and continue to provide corrosion protection at this critical location. Cracks were spaced about 6 in. on centers with widths at the top surface maintained at approximately 0.01 in. during the tests, as can be seen in Figure 1. The remaining four beams were tested uncracked.

Fabrication revealed two potential difficulties with the use of epoxy-coated strand. The first involved longitudinal cracking of the concrete over the epoxy-coated strand during detensioning when concrete covers of 3 in., 1 in., and 1½ in. were employed. Compressive strength of the concrete at detensioning was 4,000 to 4,500 psi. Such cracking occurred despite careful, gradual detensioning. Cracking did not occur over the bare strand with identical concrete cover. This problem was solved by enlarging the beam ends to provide 2 in. of clear cover over the epoxy-coated strand for about 2 ft at each end.

The second difficulty was sudden, partial release of the tensioning force by the chucks during the stressing operation. In the two or three occurrences of this problem, the epoxy appeared to strip away cleanly from the strand, exposing a ¼ to ½ in. length of wire. Examination of the wire revealed the presence of light corrosion products that apparently acted as a bond-breaker during the fusion bonding process, preventing adhesion of the epoxy to the steel. Such locations appeared to be random, typically involving a single wire over a length of 1 to 2 in.

The beams were tested in matching pairs, using a spit-like device to provide support and maintain crack widths. By rotation of the assembly, the test surface of one beam could be ponded with a 15 percent by weight solution of sodium chloride and water while the other beam air-dried at 100 F in an insulated enclosure. The assembly was rotated every 3½ days, resulting in a week-long wet/dry cycle, for 10 months. Figure 2 shows the pretensioned beam specimens under test. Additional details of the fabrication of these specimens, including procedures and materials, are provided in Appendix D.

Measurements of macrocell corrosion current, instant-off potential, and AC resistance between the top and bottom strand were routinely taken, together with copper-copper sulfate half-cell potentials over the top strand. Data for the four beams with only bare strands were generally similar. The only real distinction was that the majority of the half-cell readings exceeded −0.35 V at 30 days in the cracked specimens, but required 60 days to do so in the uncracked specimens. The corrosion current was significantly greater in the cracked beams with bare strands than in the uncracked beams. Beams with an epoxy-coated top strand typically had only one or two current readings other than zero during the duration of the tests and showed reversal of current flow during the test, indicating that the bottom bare strand was corroding. This was corroborated by examination of the strand at the end of the testing.

Measured AC resistance was generally three orders of magnitude higher in beams with an epoxy-coated top strand than in beams with bare strands. Instant-off potentials were proportionate with current and resistance in the beams with bare strands, but not in those with an epoxy-coated top strand.

At the conclusion of the corrosion tests, concrete powder samples were taken at the top surface of the top and bottom strands and analyzed for acid-soluble chloride content. The average chloride contents in the uncracked and cracked beams at the 1-in. depth were about 12 and 17 times the chloride corrosion threshold level of 0.03 percent by weight of concrete usually associated with reinforcing bars. Complete results are given in Appendix E.

Finally, the beams were destroyed and the strands removed for visual examination. No cracks, splits, or other imperfections were found in the coating on any of the four epoxy-coated strands, and no indications of corrosion were apparent on any of these coated strands. The four top bare strands all had heavy corrosion, and three had deep pitting. Corrosion of the top bare strand in cracked beams was somewhat more severe than in uncracked beams. All eight bare bottom strands had regions of corrosion. Additional details are given in Appendix E.

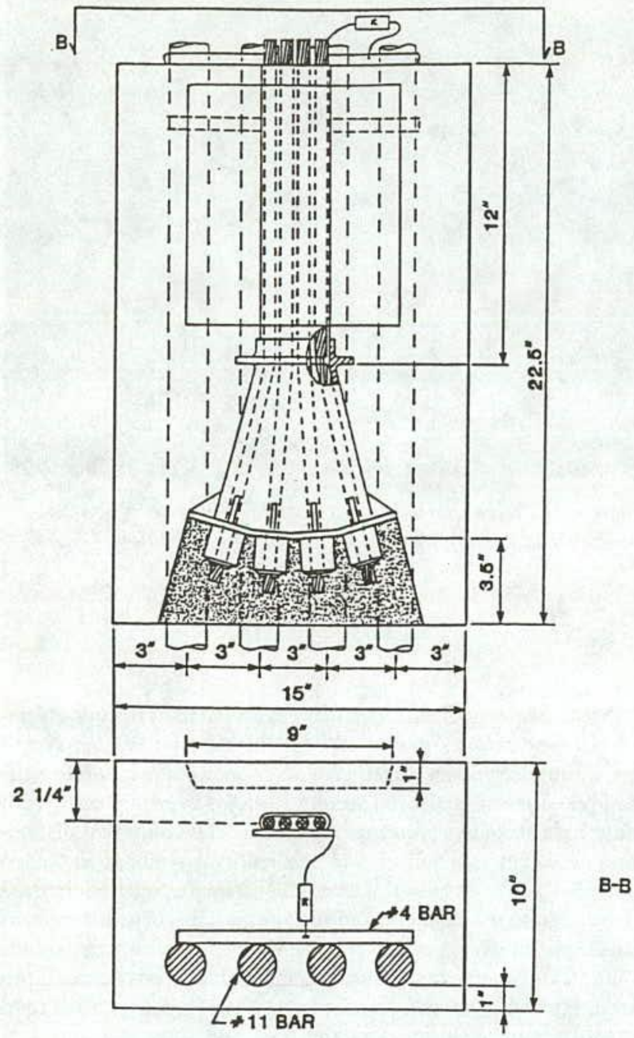


Figure 3. Small assembled anchorage test specimen for post-tensioned concrete corrosion study.

Post-Tensioning Anchorage Specimens

Three types of specimens were employed to study corrosion protection at post-tensioning anchorages: six small concrete specimens with assembled, unstressed anchorages; eight small concrete specimens with disassembled anchorage elements; and five large concrete members with fully stressed anchorages. The specimens with assembled anchorages incorporated all the significant elements of a post-tensioning anchorage, arranged as normally installed in an actual structure. Specimens with the anchorage elements disassembled were included to determine whether galvanic currents could develop between the individual metal elements comprising a typical anchorage assembly.

These specimens were intended to compare the performance of the following: (1) uncoated (bare) anchorage versus epoxy-coated anchorage; (2) galvanized steel duct versus polyethylene duct; (3) epoxy-coated versus bare prestressing strand, and (4) stressed versus unstressed prestressing strand.

All 19 specimens contained four No. 11 reinforcing bars near the bottom of the specimen, each with 1 in. of concrete cover. These bars were so positioned to serve as the cathode in a potential macrocell with the anchorage elements embedded near the top of the specimen. All strands, epoxy-coated as well as bare, were seated in the chucks by stressing to 80 percent of f_{pu}. Fabrication details, together with information on the anchorage, chucks, ducts, strands, grout, and concrete properties, are provided in Appendix D.

The accelerated corrosion testing consisted of weekly cycles of ponding with a 15 percent by weight solution of sodium chloride in water followed by air drying. After 3½ days of ponding, the solution was removed, the surface was rinsed with fresh water, and the specimens were air-dried at temperatures of 100 ± 10 F.

The corrosion current, instant-off potential and AC resistance between the anchorage elements and the No. 11 bars were routinely measured, as well as half-cell potentials at various locations over the post-tensioning anchorage elements. Specific details are provided in Appendix C. On completion of the testing, the specimens were evaluated by fracturing the concrete and/or grout and visually examining the embedded elements.

Small, Assembled Anchorage Specimens

Six small specimens with assembled, unstressed anchorages with dimensions and configuration, as shown in Figure 3, were tested, two each with the following combinations of elements: bare anchorage, galvanized steel duct, epoxy-coated strand; epoxy-coated anchorage, polyethylene duct, bare strand; and bare anchorage, galvanized steel duct, bare strand.

The last combination is considered representative of current practice and was to serve as the control. The corrosion current, instant-off potential, AC resistance, and half-cell potential data were virtually identical for the four specimens with a bare anchorage and galvanized steel duct, all indicating active corrosion after only 3 to 4 weeks of test. Data for the two specimens with an epoxy-coated anchorage and polyethylene duct indicated the onset of macrocell corrosion in 4 weeks, although the subsequent corrosion rate was appreciably less than in the other four specimens.

At the conclusion of the test period, rust stains were visible on the concrete surface of all four specimens with a bare anchorage and galvanized steel duct. These four specimens all had cracks over the chucks, and the two control specimens had cracks over the anchorage and duct as well. Examination of these specimens revealed that the galvanized ducts were heavily corroded. The top surface of the bare anchorages was also heavily corroded, with pitting. The chucks in all four specimens had red rust with some pitting on the outside surface, and most of the outside surface of the wedges was lightly corroded. The epoxy-coated prestressing strands were totally free of corrosion. The bare strands in one of the remaining specimens had light surface corrosion along their entire length, with concentrations at the chuck/anchorage and anchorage/duct joints, while those in the other had slight, spotty surface corrosion.

While the two specimens with an epoxy-coated anchorage, polyethylene duct and bare strand did not exhibit rust staining during the test, one developed a slight crack over the chucks that widened to $\frac{1}{64}$ in. at the end of testing. Examination of these specimens found the coated anchorages to be free of corrosion, except for a small rust spot on the flange of one. Although the chucks were also epoxy-coated, all exhibited significant corrosion, with 10 to 50 percent of the outside surface area of each chuck corroded. The most severe chuck corrosion occurred on the flat surface that bears against the anchorage. The bare strands in one of these specimens had some light surface corrosion near the duct/anchorage joint region, while two of the bare strands in the other had very light surface corrosion between the wires at the chuck/anchorage joint. The bare strand corrosion stopped where the strand became firmly embedded in the grout, except for minor corrosion at the duct/anchorage joint.

Large, Stressed Anchorage Specimens

Five post-tensioning anchorage specimens were tested with two of the four strands stressed to 70 percent of f_{pu}. These specimens were essentially 10-ft long versions of the small, assembled anchorage specimens described earlier, with the same concrete covers and general configuration.

The two outside strands were initially tensioned to 34 kip, or 80 percent of f_{pu}. The two remaining strands had the chucks at the test anchorage preseated to 80 percent of f_{pu}, and the strands were then tensioned to only 1 kip. The fully stressed strands were then restressed and shimmed at the dead end to recover seating losses and provide a strand tension of 29 ± 1 kip. The ducts were then grouted and the anchorage recess dry-packed prior to starting the corrosion tests.

Five large specimens with assembled, fully stressed anchorage assemblies were tested with the following combination of elements: bare anchorage, galvanized steel duct, bare strand (1 specimen); bare anchorage, galvanized steel duct, epoxy-coated strand (2 specimens); and epoxy-coated anchorage, polyethylene duct, bare strand (2 specimens).

The corrosion behavior of the three specimens with a bare anchorage and galvanized steel duct was similar to that of the corresponding small, assembled specimens. However, the average corrosion current was nearly twice that of the small specimens. The corrosion data from the two specimens with an epoxy-coated anchorage, polyethylene duct, and bare strands were surprisingly dissimilar. In addition, the data from either of these large specimens were inconsistent with those from the corresponding small specimens. However, the corrosion current, instant-off potential, and AC resistance data from one of these large specimens were similar to the corresponding small specimens for the first 18 weeks of test.

All three specimens with a bare anchorage and galvanized steel duct developed rust stains on the concrete surface by 18 weeks. Examination of these specimens revealed that the top surface of all bare anchorages was heavily corroded. The tops of the galvanized ducts were also completely covered with rust, and one duct had a few small holes. The chucks were lightly to moderately corroded on their outside surface, with no differences apparent between stressed and unstressed chucks. The outside surface of the wedges was also lightly corroded. Although the exposed ends of the bare strands were moderately to severely corroded, the lengths in the grouted anchorage and duct system were free of corrosion, as shown in Figure 4. The epoxy-coated strands were totally free of corrosion, again with no apparent difference between fully stressed and unstressed strands.

The two specimens with an epoxy-coated anchorage, polyethylene duct, and bare strand did not exhibit rust on the top

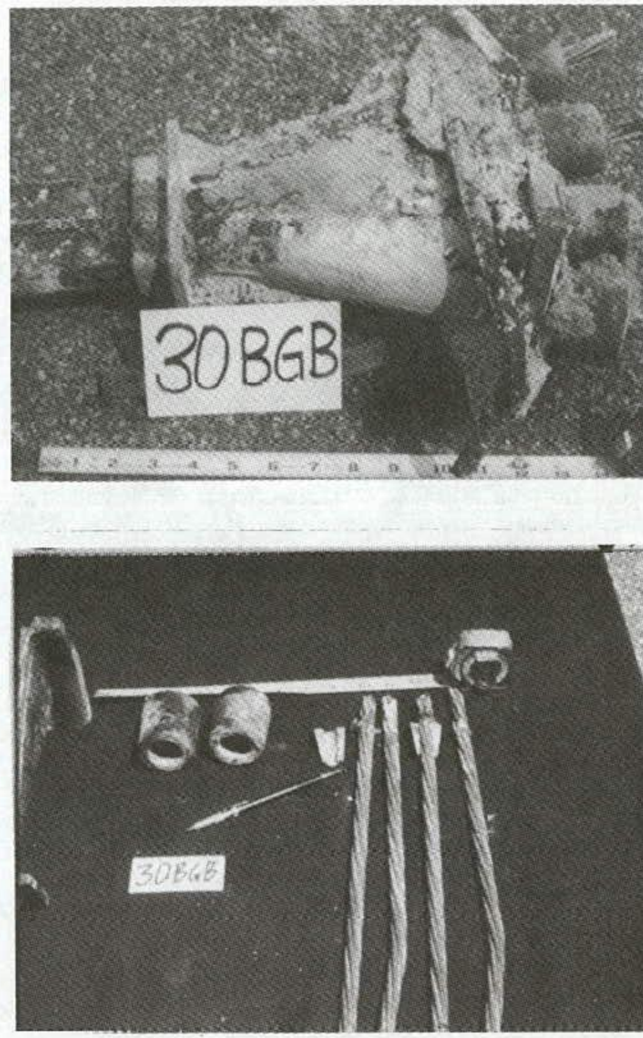


Figure 4. Condition of assembled materials from post-tensioned specimen 30BGB after corrosion tests.

concrete surface, although a large amount of corrosion products had leached through the vertical face of one specimen in the vicinity of one of the outside chucks. Examination of this specimen revealed that the ends of the bare strands protruding from the chucks were all very severely corroded, with deep pitting and broken wires. This corrosion continued into and through the wedge region. Surface corrosion was also evident on the bare strands at the duct/anchorage joint, with no differences apparent between stressed and unstressed bare strands. The chucks and wedges all had corrosion products on their outside and inside faces. Finally, the coated anchorage had very small regions of corrosion, possibly associated with damage to the epoxy coating prior to or during installation.

Examination of the other specimen revealed that although the ends of the two bare unstressed strands protruding from the chucks were severely corroded and pitted, and those of the two bare stressed strands were moderately corroded, the strand corrosion stopped at the wedges. Some slight surface rust was also visible on the bare strands in the region of the duct/anchorage joint. The bare strand corrosion stopped where the strand became firmly embedded in the grout system, except for minor corrosion at the duct joints. The anchorage itself was completely free of corrosion, as was the outside surface of three of the four chucks. The wedges generally had corrosion on their outside surface, but a clean inside surface.

Small, Disassembled Anchorage Specimens

Eight small specimens were tested with the individual metal elements comprising the anchorage regions totally separated and electrically discontinuous. These specimens were intended to determine the possible existence of galvanic couples between the various steel components comprising a typical anchorage. Figure 5 shows the arrangement of the various elements in one of these specimens prior to casting. Concrete covers over the individual metal elements were made identical to those in the small, assembled specimens. The test procedures and electrical measurements for these specimens were identical to those for the assembled specimens.

The three specimens with a bare anchorage, galvanized steel duct, and epoxy-coated strands all developed significant corrosion currents within 4 weeks of testing. The anchorage and duct in all three specimens were anodic and usually one or more of the chucks and wedges eventually became anodic. No current flows were associated with the strands. Half-cell data for these three specimens were characteristic of the corresponding assembled anchorage specimens.

The corrosion activity of the two control specimens with a bare anchorage, galvanized steel duct, and bare strands was high, similar to that of the specimens with epoxy-coated strands. In these specimens, however, significant corrosion currents developed in the strands by 4 weeks of test. The magnitudes of the corrosion currents were also similar.

As with the corresponding assembled anchorage specimens, the half-cell potential measurements for these two control specimens were high and virtually identical to those from the bare

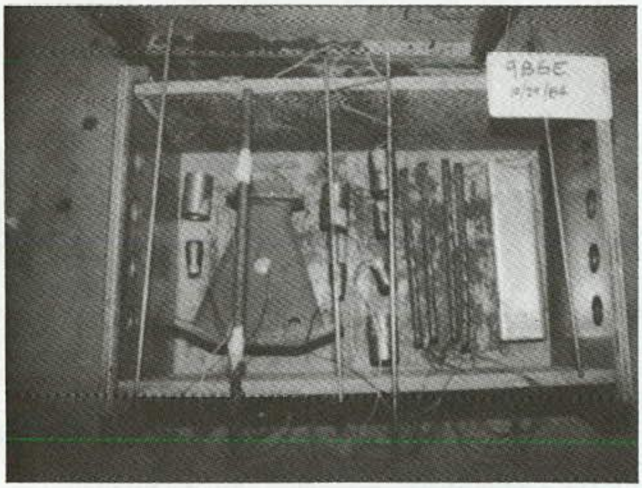


Figure 5. Element arrangement in small disassembled anchorage specimen prior to casting concrete.

anchorage, galvanized metal duct and epoxy-coated strand specimens.

The three specimens with an epoxy-coated anchorage and bare strands displayed varying corrosion behavior. Surprisingly, the epoxy-coated anchorage in all three specimens and one epoxy-coated chuck in two specimens developed significant corrosion currents during the test. One set of wedges in two specimens and two wedge sets in one specimen developed significant anodic corrosion currents. The remaining wedges remained cathodic for the duration of the test. All four bare strands in two specimens and two bare strands in one specimen eventually developed anodic corrosion currents. Apparently, because of the absence of the galvanized steel duct, whose early high potentials masked the readings of nearby bare steel elements, the half-cell measurements appeared to correlate better with the corrosion current measurements than in the other five disassembled anchorage specimens.

Examination of the small, disassembled anchorage specimens revealed good correlation with the electrical measurements. In particular, the amount of metal loss appeared to correlate well with the product of anodic corrosion current and time. At the conclusion of the test, the five specimens with a bare anchorage and galvanized steel duct all were similar in appearance, with rust stains on the top concrete surface and a crack as wide as $\frac{1}{16}$ in. over the flange of the bare anchorage. The top surface of the galvanized steel duct in each specimen was completely covered with rust, and 5 to 50 percent of the bottom surface was covered with iron or zinc corrosion products. The top surface of the anchorage was completely covered with rust in two specimens and 50 percent covered in the others.

Corrosion of the chucks and wedges was consistent with the measured corrosion currents. Identical elements subjected to essentially the same environment could be either anodic or cathodic in the corrosion process, with no apparent fixed pattern. Figure 6 shows two sets of wedges, one severely corroded and the other completely free of corrosion.

Examination of the three specimens with epoxy-coated strands revealed them to be totally free of corrosion, even in the wedge region. More than 50 percent of the top surface of all the bare strands in the other two specimens were severely corroded, with deep pitting.

Small regions of corrosion were observed under the epoxy coating of all three coated anchorages, corroborating the corrosion current measurements. Such corrosion of the anchorage is visible in Figure 6.

At the conclusion of the corrosion testing, samples of concrete powder were drilled from selected post-tensioning anchorage specimens at the level of the strands near the center of the specimen. These samples were analyzed for acid-soluble chloride ion content, as described in Appendix C. The mean chloride ion content by weight of the sample was found to be 0.543 percent, a value about 18 times the chloride corrosion threshold value.

During examination of the assembled anchorage specimens, samples of grout were removed from the duct, pulverized, and tested for acid-soluble chloride ion content in the same manner as the concrete powder samples. Chloride contents of grout from the polyethylene ducts were essentially zero, while those from galvanized ducts ranged from very low to as high as 0.09 percent chloride by weight of grout. These values are well below the chloride corrosion threshold for normal cementitious grout if, as assumed in this study, it is about 0.15 percent by weight of grout. Complete results are given in Appendix E.

Post-Tensioning Duct Specimens

These 32 specimens consisted of three 10-ft lengths of unstressed bare strand grouted in a 2-in. diameter by 9.5-ft long duct with a joint at midlength of the duct. The tests were intended to evaluate the effectiveness of various duct/grout corrosion protection systems in regions away from the anchorage. To provide a more severe test environment, concrete was not used around the ducts. These specimens were fabricated and tested to compare the following variables: (1) bare steel duct, galvanized steel duct, fusion-bonded epoxy-coated steel duct and polyethylene duct; (2) normal cementitious grout, cementitious grout modified with a calcium nitrite corrosion-inhibiting additive and cementitious grout modified with a condensed silica fume additive; and (3) duct joints sealed with either normal duct tape or heat-shrink plastic tubing. Details of these materials and the grout formulations used are provided in Appendix D.

Care was exercised during specimen fabrication to prevent direct contact between any of the metallic elements comprising the specimen. Electrical leads, soldered to one end of each element and connected together, provided electrical continuity between the elements.

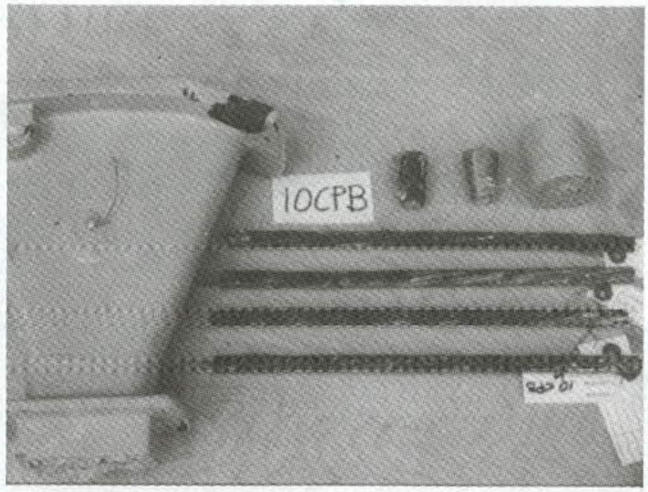
After fabrication, the specimens were placed in a 5 ft by 16.5 ft by 6 in. deep tank for corrosion testing. Testing, which began on average about 120 days after grouting, consisted of submerging the central 5-ft length of duct in a 15 percent by weight solution of sodium chloride in water for 3½ days and then air drying at 100 ± 10F for 3½ days. Figure 7 shows some of the duct specimens under test.

The test procedure was followed for 304 days, with measurements of corrosion current, AC resistance, and instant-off potential between each steel component (a strand or the duct) and the group of remaining components in the specimen typically made at about 60-day intervals. On conclusion of the tests, the ducts were cut open and the grout surface and strands were examined visually. Grout samples were also removed from the joint region and near the edge of the test region for chloride ion content determination.

Macrocell Corrosion Currents. The corrosion currents and instant-off potentials in the four specimens with polyethylene ducts were typically zero throughout the duration of the test. Specimens with metallic ducts developed corrosion currents within 30 days. Initially, anodic currents were associated with the ducts and cathodic currents with the strands.

The strands in the four specimens with epoxy-coated ducts did not develop measured anodic currents during testing. Current flow peaked at 30 to 90 days of testing and declined thereafter.

All specimens with bare steel duct and normal cementitious grout eventually developed anodic macrocell corrosion current flow in one or more strands. The corrosion current behavior of the calcium nitrite modified grout was essentially indistinguishable from that of the normal grout in bare steel ducts. The behavior of the silica fume modified grout was generally similar to that of the other specimens with bare steel duct, except the measured currents were typically about half in magnitude.



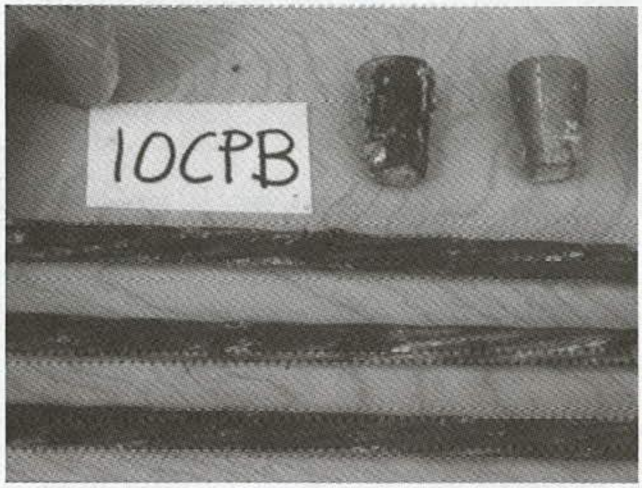


Figure 6. Condition of disassembled materials from post-tensioned specimen 10CPB after corrosion tests. Top photo: coated anchorage and chucks—bare strand and wedges; bottom photo: bare strand and wedges.

Figure 7. View of post-tensioning duct specimens under alternate soaking and air drying corrosion test procedure.

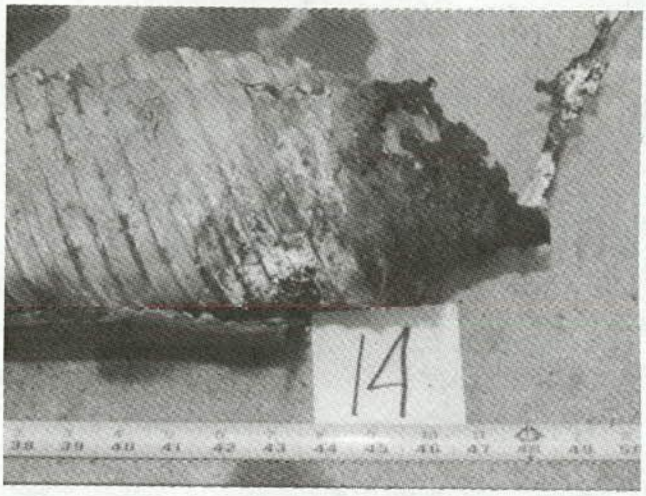


Figure 8. Appearance of galvanized duct at edge of test region after corrosion testing.

Specimens with galvanized duct generally exhibited different corrosion current behavior than those with bare steel duct. Three of the four specimens with normal grout did not develop any anodic macrocell corrosion currents in the strands. All four specimens with calcium nitrite modified grout eventually developed anodic currents in one or more strands, with such currents first being measured after 30 days of testing, in two of the specimens. The four specimens with silica fume modified grout were generally extremely low for the first 211 days, and then increased by about a hundredfold. Only one specimen developed anodic current flows involving the strands.

AC Resistance. With the exception of the polyethylene ducts, AC resistance between strands appeared to be independent of duct type. The calcium nitrite modified grout provided the lowest mean resistance between strands, averaging about 2 ohms and remaining relatively constant during the test period. The normal cementitious grout in metallic ducts averaged about 4.5 ohms and also remained reasonably constant. This normal grout in polyethylene ducts, however, had an initial mean resistance of 6 ohms that increased to over 8 ohms by the end of the test. Specimens with the silica fume modified grout had an initial mean resistance of over 110 ohms, or roughly 25 times that of the normal grout, that significantly declined with time to a final value of 15 ohms.

Chloride Contents. Except for the duct tape joint region, the chloride content analyses indicated that the polyethylene duct was impermeable to chlorides. Although the epoxy-coated duct permitted some penetration in this extremely severe test, the resultant value was only 0.027 percent by weight and far less than the assumed corrosion threshold of 0.15 percent.

The galvanized ducts appeared to be twice as effective in preventing chloride ion intrusion as the bare steel ducts. They were only about one-thirtieth as effective as the epoxy-coated ducts, however, and still permitted penetrations in excess of the assumed corrosion threshold.

The calcium nitrite modified grout had a higher chloride content than the normal cementitious grout with both the bare and galvanized steel ducts. The silica fume modified grout, on the other hand, had a chloride content of about one-fifth that of the normal grout.

While the joints were the weak link in the polyethylene and epoxy-coated ducts, the joint regions of the galvanized and bare steel ducts consistently had lower chloride contents than the location near the edge of the test area because these bare and galvanized ducts rusted through during testing. In these bare and galvanized steel ducts, the duct tape provided from modest to tenfold reductions, and the heat-shrink tubing from fivefold to over one-hundredfold reduction, in chloride ion penetration. In fact, no joint region in any specimen with heat-shrink tubing had a chloride content in excess of the assumed corrosion threshold. A comparison of the joints in all 32 specimens showed the heat-shrink tubing to be from 4 to 50 times, with an average of over 10 times, as effective as duct tape in reducing chloride ion penetration.

Visual Examination. Examination of the four specimens with polyethylene duct revealed that only one strand had any significant corrosion. The corrosion was very localized at a duct tape joint, where the strand was covered with only ⅛ in. of grout.

Strands in the four specimens with epoxy-coated steel duct also were free of corrosion. The ducts themselves, however, were all corroded along the spiral seams, apparently because of a break in the coating or incomplete coating at that location.

All bare and galvanized steel ducts rusted through in the test region. Figure 8 shows the appearance of a galvanized duct at the edge of the test region on conclusion of the corrosion testing. Despite significant variations in measured corrosion currents and chloride contents, the performance of the various galvanized and bare steel duct specimens as determined by visual examination of the strands was generally comparable, with all specimens having about the same average amount of strand corrosion. Surprisingly, the bare steel duct with silica fume modified grout specimens, however, had about 3 times the average amount of strand corrosion.

The visual examination of the grout in all 32 duct specimens also revealed the presence of voids up to 2 in. long and ¼ in. deep on the grout surface.

RESULTS OF THE MECHANICAL TESTS

A series of specialized mechanical tests was performed on the various corrosion-resistant materials to assess aspects considered critical to the effective use of these materials in prestressed concrete. Tests were conducted to evaluate: (1) relative creep movement over an 11-month period between bare strand and epoxy-coated strand in uncracked and cracked pretensioned members; (2) friction, mechanical abrasion and other damage resulting from handling and fully stressing epoxy-coated strand or bare strand in curved polyethylene duct or galvanized duct; and (3) bond and force transfer characteristics of bare steel duct, galvanized steel duct, epoxy-coated steel duct, and polyethylene duct when embedded in concrete.

Creep of Epoxy-Coated Strand

Significant long-term creep of the epoxy coating on the 7-wire prestressing strand could produce losses in the strand during the service life of pretensioned concrete members. To determine the magnitude of the creep, duplicate pretensioned beams, each with two symmetrically placed, fully stressed strands were measured for long-term creep slippage of the strands into the end of the beam for 11 months. Half of the beams employed epoxy-coated and half bare top strands, and half were cracked and half uncracked. These eight beams were subjected to 3½-day air drying cycles at 90F to 110F followed by ponding with salt-water for 3½ days at 60F to 80F. The four cracked beams had 0.01-in. wide flexural cracks induced and maintained along the ponded surface at about 6-in. centers during the entire 11-month test period.

The measurements indicated that the epoxy-coated strands experienced minimal movement relative to the concrete beam ends during the test period in both cracked and uncracked beams. The average indicated creep movement in both cracked and uncracked beams was 0.006 in., ranging from 0.001 to 0.011 in., after 11 months of test. These data indicate that the creep of the epoxy coating as well as the strand itself was essentially zero.

The measurements of the bare strands indicated far greater creep movement with much more variability than the epoxy-coated strands. Indicated movements of the bare strand relative to the concrete beam ends at 11 months ranged from a minimum of 0.004 in. to a maximum of 0.137 in. The average value was 0.048 in., or 8 times that measured on the epoxy-coated strand.

Bare strands in cracked beams also behaved differently from bare strand in uncracked beams. The largest indicated movement consistently occurred in the bottom strand of the uncracked beams. This movement averaged 0.104 in., which was over twice that for bare strand in the tension zone of cracked beams. It is believed that this behavior is associated with the bottom strand being in the top region of the beam as cast, with the normal lower bond strengths associated with top reinforcing bars apparently also affecting these stressed bare strands.

These data show that the long-term creep movement of fully stressed bare strand is substantially more than that of the epoxy-coated strand, which contains a grit within the epoxy coating. This grit appears to dramatically influence both the bond strength and long-term creep behavior of epoxy-coated strand.

Friction and Mechanical Abrasion Tests

These tests established the relative friction losses associated with stressing epoxy-coated strand and bare strand in curved polyethylene duct and galvanized steel duct. They also determined if the stressing operation produces significant abrasion damage to either the epoxy coating on the strand or the polyethylene duct.

The test procedures simulated as much as possible the stressing operations in actual bridge constructions. The test setup consisted of two sets of four ducts cast into a 14-in. thick concrete slab in the shape of a quarter circle with an outside radius of 15.25 ft. The top four ducts were galvanized steel, and the bottom four ducts were polyethylene. Pairs of ducts were used to establish the relative performance of these four strand/duct combinations: bare strand in galvanized steel duct; bare strand in polyethylene duct; epoxy-coated strand in galvanized steel duct; and epoxy-coated strand in polyethylene duct. The ducts were nominal 2-in. diameter and identical to those used in the corrosion test program.

The test procedures consisted of first simultaneously pulling four 45-ft lengths of bare or epoxy-coated strand completely through each duct type to simulate normal strand installation. The strands were then removed and examined for abrasion. An individual strand was then pulled through the duct, anchored at the dead end and tensioned to approximately 80 percent of f_{pu} at the stressing end. Springs at the dead end were intended to significantly increase the relative movement between the strand and the duct during stressing, thus simulating a much longer length of strand. The strand was then gradually detensioned, removed from the duct and examined visually for abrasion damage. This test sequence subjected the ducts to multiple abrasive passes of the strand and two full-tension tests. The concrete cover over the ducts was then chipped off over a major portion of the duct length and the ducts were cut open to permit visual examination of their inside surfaces.

As described in Appendix F, the coefficient of friction between the strand and the duct was determined four times for each duct/strand combination by measuring the strand tension at both the stressing and dead end of the test fixture with load cells, then calculating the coefficient of friction from the expression:

$$T_x = T_o e^{-(\mu\alpha + kx)}$$

The data indicate that the polyethylene duct produced the lowest average coefficient of friction, with an average of 0.18 for bare strand and 0.205 for epoxy-coated strand. The coefficient of friction for epoxy-coated strand in galvanized duct averaged 0.40, or twice that in polyethylene duct. Bare strand in galvanized duct had an average coefficient of friction of 0.23. For purposes of comparison, bare strand in flexible galvanized duct is generally considered to have a coefficient of friction ranging from 0.14 to 0.22.

Normal pulling of the bare or epoxy-coated strand through the galvanized duct or polyethylene duct produced no significant damage to the strand.

Stressing of the strand to 80 percent of f_{pu} with significant slippage in the duct (slippage at the dead end was typically 5 to 8 in.) generally proceeded in a routine fashion for the bare strands in galvanized and polyethylene duct, as well as with the epoxy-coated strands in polyethylene duct. Visual examination of the bare strands stressed in polyethylene duct revealed no discernable effects on the strands, while bare strands stressed in galvanized duct appeared slightly scratched rather uniformly along their length after stressing. Epoxy-coated strands stressed in polyethylene duct had shreds of black polyethylene along their length, but otherwise appeared unaffected.

Stressing of epoxy-coated strand in galvanized duct produced a problem. The load at the jacking end increased smoothly to about 40 percent of f_{pu}, although it increased at the jacking end at a significantly greater rate than at the dead end. At a jacking force of about 0.4 f_{pu}, the coated strand suddenly slipped in the duct. This slippage was accompanied by a loud sound, considerable loss of force in the jack, and an increase in force at the dead end. Such sudden slippage typically occurred about eight times before reaching the final jacking end force of 0.80 f_{pu}.

Examination of the epoxy-coated strands after stressing in galvanized duct always revealed two or more locations where the epoxy coating was severely abraded. Abraded lengths generally ranged from about 2 to 6 in. At some locations, the epoxy coating was abraded completely through, exposing one or two wires of the strand.

Examination of the inside surface of the galvanized duct revealed a shiny "footprint" where bare strand had been bearing against the duct wall together with slight scratches. Galvanized ducts with epoxy-coated strands showed a larger, blue "footprint" of the strand, with traces of blue epoxy evident on the inside spiral duct seam at several locations.

The inside surface of the polyethylene duct tested with bare strand appeared shiny and compressed on the bearing side, with almost imperceptible signs of abrasion. Walls of the polyethylene ducts tested with epoxy-coated strand, however, showed very significant abrasion in places. Although none of the polyethylene ducts were abraded through, section loss was estimated to be 75 percent or more of the wall thickness. Additional details are provided in Appendix F.

Duct Bond and Force Transfer Tests

These tests compared the bond and force transfer characteristics of polyethylene duct and epoxy-coated steel duct to those of conventional galvanized steel duct and bare steel duct. They consisted of pullout tests to determine the load-deformation behavior of a high-strength steel bar grouted in these various ducts, which were cast in a large concrete block.

Three large concrete block specimens were cast for the pullout tests. Four 2-in. diameter, 48-in. long ducts were cast into each specimen using polyethylene, epoxy-coated steel, galvanized steel and bare steel ducts. A 1¼-in. diameter, 150-ksi threadbar conforming to ASTM A722 was grouted into each duct. Each bar was 72 in. long, with 48 in. embedded in the grouted duct. The grout consisted of 1 bag of Type I cement, 5 gal of water and 1 lb of a proprietary expanded, fluidifying and water-reducing admixture.

On the day of the pullout tests, the then 34-day old grout had an average compressive strength of 3,190 psi. Cylinder strengths for the concrete block specimen tested at the same time averaged 6,520 psi.

The test procedure consisted of loading the embedded bar in 10-kip increments and measuring the bar, grout, and concrete movements at each load stage. Each bar was eventually loaded to approximately 100 kip. A load of 93.76 kip corresponds to 40 percent of the f_{pu} of the four 0.6-in. diameter, 270-ksi prestressing strands typically used in a 2-in. diameter duct, and theoretically represents the maximum force to be transferred from the tendon to the concrete through the duct and grout materials.

Triplicate tests were conducted on each of the four duct types. The data reveal that all four types of duct displayed the same general behavior.

A comparison of the data indicates less apparent stiffness in the pullout tests with the bare steel duct and galvanized steel duct than with the other two duct types. Computation of an "average apparent modulus" results in a stiffness value of 1.965 million pounds per inch for the bare steel duct and 1.935 million pounds per inch for galvanized steel duct. The epoxy-coated steel duct had an average value of 3.159 million pounds per inch and the polyethylene duct had an average of 2.720 million pounds per inch. The threadbar/grout/duct system with epoxy-coated steel duct thus appears to have about 60 percent greater stiffness, and the polyethylene duct system about 40 percent greater stiffness, than the system average with bare and galvanized steel ducts.

When these 12 specimens were unloaded, the elastic recovery of the bar in all four duct types was quite high, averaging about 80 to 85 percent of the maximum bar movement at maximum load. When unloaded, the average residual upward movement of the bar from all 12 specimens was only 0.009 in., as compared to the average maximum upward bar movement of 0.048 in. at maximum load for the 12 tests. This shows that the duct type did not influence the elastic recovery behavior of the loaded bar embedded in grout in these various ducts.

These tests show that the four duct types can provide comparable bond and force transfer performance in resisting 100 kip of applied force in a length of less than 48 in. Of particular notice was the highly elastic behavior of the loaded bar on unloading, even though the applied maximum loads were generally in the range of 100 to 110 kip. During these 12 tests, failure of the duct or grout materials was not observed.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

GENERAL

The AASHTO and ACI design codes and specifications for reinforced concrete and prestressed concrete members have both been modified in recent years to provide better corrosion protection for embedded steel. These code revisions reflect the concern over the nationwide chloride-induced deterioration of concrete structures. These newer specifications require lower concrete w/c ratios and greater clear cover over the embedded steel to achieve greater resistance to the penetration of salt-laden water through the concrete. These major code changes recognize that extremely small amounts of chloride ion can initiate corrosion of steel, even in the highly alkaline environment of portland cement concrete. Previous codes did not fully recognize the vulnerability of reinforcing or prestressing steel to chlorides slowly penetrating the sometimes totally inadequate concrete cover and starting the corrosion process.

Since numerous prestressed concrete bridges were constructed with these older specifications, which allowed higher w/c ratio concrete and minimal clear cover at some locations, their apparently very good durability, as indicated by the results of the nationwide survey discussed in this study, is surprising. Because new prestressed concrete bridges will be designed and constructed using the newer design provisions for greater corrosion durability, these new bridges will be even more resistant to chloride-induced corrosion. All metallic reinforcing and hardware will be embedded deeper, in much lower w/c ratio concrete with chloride and water impermeability properties significantly better than in the past. Thus, designs using traditional materials for prestressing steel, ducts, anchorages, admixtures, and grouts should provide better performance in the future. These traditional materials can still be used in environments with some exposure to chlorides, but with greater emphasis on using even lower w/c ratios and greater clear cover than the minimum values suggested in the current codes. When severe chloride environments are encountered or anticipated, the newer materials evaluated in this study should be considered to provide extended service life for the structure without the need for expensive repairs.

TRADITIONAL MATERIALS

The traditional materials used for pretensioned and post-tensioned bridges are bare prestressing strand, galvanized steel duct, bare anchorages, bare chucks and wedges, normal cementitious expansive grout, and duct tape for sealing the joints in the ductwork system. The severe corrosion tests reported herein show that when embedded in concrete with minimal clear cover, the bare strand corroded severely in cracked and uncracked pretensioned concrete, while the same bare strand was better protected in grouted, post-tensioned concrete. This better protection in traditional post-tensioned concrete was initially provided by the galvanized duct, and finally by the grout as the galvanized duct corroded severely. The same severe corrosion also occurred on the bare post-tensioning anchorages, chucks, wedges, and protruding ends of the prestressing strand at the anchorage. Thus, all of the bare steel post-tensioning materials, except the grouted strand, were damaged by chloride ingress into the concrete, and cracking of concrete resulted.

This study reconfirmed the now well-established fact that crack-free concrete, either conventional or prestressed, is insufficient corrosion protection without adequate concrete cover. With the exception of the intentionally cracked, pretensioned beams, all of the concrete specimens employed in this study were initially crack-free. Although cracks allow for the rapid penetration of chlorides to the embedded steel, and hence the early initiation of corrosion at such locations, chlorides also penetrate sound, precompressed, crack-free concrete. With insufficient cover, these chlorides will eventually reach the reinforcement. In fact, a comparison of the cracked and uncracked pretensioned beams employed in this study, with 1 in. of clear concrete cover, showed that although corrosion of the prestressing steel was more severe in the cracked than in the uncracked beams, the difference was not significant. Thus, the level of precompression in prestressed concrete should not influence the selection of appropriate concrete cover for corrosion protection, except that the final level of precompression should be sufficient to prevent cracking.

Such severe corrosion of these traditional pretensioning and post-tensioning materials would not have occurred so rapidly had these materials been embedded deeply in the proper, low w/c ratio concrete suggested by present day codes. While some designers may still be tempted to use minimal clear cover over these traditional materials, these tests as well as other test programs prove that such metals will eventually corrode in the chloride environment so typical of many bridges. If minimal cover is absolutely necessary, newer and more corrosion-resistant materials should be used, even though the economics may be changed. Although such newer materials may be more costly, the additional costs will not approach the potential repair costs of these prestressed concrete bridges when corrosion damage influences the highly stressed tendons.

CORROSION-RESISTANT MATERIALS

The results of corrosion tests on newly developed corrosion-resistant materials for producing pretensioned and post-tensioned members have demonstrated that significant improvements in long-term corrosion serviceability can be achieved. Most of the metallic elements, i.e., strand, chucks, anchorage, and duct, utilized fusion-bonded epoxy coatings for corrosion protection. These epoxy coatings are the same or similar to materials used to coat conventional reinforcing bars. The epoxy coating for prestressing strand is a thicker and tougher epoxy formulation than that used on conventional reinforcing bars because of the abrasive stressing and handling operations to which prestressing strand is subjected. These tests found epoxy-coated prestressing strand to be remarkably tough and effective against corrosion in both pretensioned and post-tensioned applications. This toughness and elasticity were rigorously tested in the wedge grip region, where the wedge teeth could not penetrate the coating. It was also found effective at the "crack" locations in the pretensioned beams. While epoxy-coated strand is about twice as expensive as bare strand, the increased costs may be offset by other design considerations such as lower required clear cover. The technology now exists for the proper, fusion-bonded epoxy coating of prestressing steel, either strand, wire or bar. Use of this technology should certainly be considered when moderate to severe chloride environments are encountered, and potential repair of a structure is very difficult for access, economic or political reasons. However, because corrosion of highly stressed prestressing steel is such a serious technical problem, as well as an economic problem during repairs, these newer prestressing materials should be considered on their merits alone.

Despite some increase in cost, coating the anchorage hardware with fusion-bonded epoxy should always be considered for any environment where chlorides may penetrate to the anchorage. This study, as well as others, have demonstrated the vulnerability of the anchorage to corrosion damage. Corrosion of the anchorage will probably lead to cracking and disruption of the surrounding concrete, possibly resulting in overstress of the bearing region. In addition, anchorage locations are often difficult, if not impossible, to access and repair.

This study, one of the first to evaluate the total duct/grout/duct joint protection system, demonstrated the importance of this total system in preventing chloride penetration to the prestressing steel. As is apparent from Table 1, which compares chloride penetration in joints sealed with duct tape and heat-

Table 1. Chloride analysis of grout from post-tensioning duct specimens.

Duct specimen parameters			Acid-soluble chloride ion content, % by weight of grout	
Duct[1]	Grout[2]	Joint[3]	Average at joint	Average at quarter point
P	C	T	0.187	<0.006
P	C	S	0.037	
E	C	T	0.331	0.027
E	C	S	0.017	
B	C	T	0.491	2.536
B	C	S	<0.009	
B	N	T	0.417	2.951
B	N	S	0.053	
B	S	T	0.208	0.525
B	S	S	0.032	
G	C	T	0.123	0.925
G	C	S	<0.008	
G	N	T	0.159	1.877
G	N	S	0.012	
G	S	T	0.149	0.203
G	S	S	0.038	

[1] P = Polyethylene, E = Epoxy-coated steel, B = Bare steel, G = Galvanized steel

[2] C = Normal cementitious, N = Calcium nitrite modified, S = Silica fume modified

[3] T = Duct tape, S = Heat-shrink tubing

shrink tubing, joints between duct segments and the connection of the duct to the anchorage may be weak links in the duct corrosion protection system. Use of improved materials such as heat-shrink tubing to seal such joints represents extremely cost-effective insurance to preventing possible corrosion of the prestressing steel at such locations. Better joint seals may also result in fewer blockages during grouting operations. Although not addressed in this study, improved techniques for sealing joints in precast segmental construction should be pursued.

Use of polyethylene duct or fusion-bonded epoxy-coated steel duct will permit the use of traditional concrete covers, hence not altering typical member span/depth ratios or dead load, while still providing significantly enhanced corrosion protection. As shown in Table 1, the polyethylene duct demonstrated total chloride impermeability in extraordinarily severe tests where the ductwork system was soaked directly in salt-water without any concrete protection. These plastic ducts may prove to be economical when compared to traditional metallic duct materials because they have a low coefficient of friction and can be used with minimal concrete covers if the joints remain watertight.

While the two specialty grout formulations did not provide significantly improved corrosion protection during the very severe corrosion tests when compared to the traditional grout, the cumulative data from these tests show the importance of proper grout specifications and grouting procedures at the site. It is this high pH grout that provides the final line of defense against chloride that may eventually reach the bare strand, wires, or bar in post-tensioned concrete. Breach of this defense would require much longer periods of time in real life exposure than it did in these accelerated tests.

The calcium nitrite-modified grout was more permeable to chlorides than the conventional grout, as shown in Table 1, and the corrosion performance was essentially the same as conventional grout. Thus, the corrosion inhibiting quality of this admixture was not clearly evident under these test conditions. Although Table 1 indicates that the silica fume-modified grout was much less permeable to chlorides than conventional grout, its performance in preventing strand corrosion was equal to or worse than the calcium nitrite-modified grout or the conventional grout. On the basis of these tests, the use of traditional cementitious grout formulations, with their moderate costs and long history of use, appears to be appropriate for the foreseeable future.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Many designers believe that adequate concrete cover, combined with high-quality concrete or grout, constitutes the most suitable corrosion protection system for bare prestressing steel and its associated hardware. Yet, because of the nationwide corrosion problems, the design codes have been modified in recent years to require lower water/cement (w/c) ratios and increased clear cover over the reinforcing and prestressing steel for concrete in a potentially corrosive environment. Although corrosion protection based on this traditional design approach has generally been good with prestressed concrete bridges, the performance of certain bridge members when in a severe chloride environment, such as piling in seawater, or with inconsistent grouting in post-tensioned members, has sometimes been disappointing. Furthermore, the introduction of segmental construction has brought with it new design features as well as potentially increased risk of corrosion. Experience is limited with negative-moment intense segmental construction in a corrosive environment brought about either by heavy use of deicing salts or severe exposure to seawater.

Because the potential corrosion effects on highly stressed prestressing steel, either pretensioned or post-tensioned, are so serious, the corrosion tests described in this report were extraordinarily severe. This severity provided significant corrosion performance differences between the newer and traditional materials in a short time. The newer materials that exhibited very good performance during these severe to very severe tests were: epoxy-coated prestressing strand; epoxy-coated post-tensioning anchorages and hardware; epoxy-coated steel duct; polyethylene duct; and heat-shrink tubing for duct joint seals.

The severity of the tests and the unexpectedly high chloride absorption characteristics of three high-quality, relatively low w/c ratio grouts (normal, calcium nitrite modified, and silica fume modified) produced corrosion of bare strands in all three grout systems whenever salt-water was able to gain access through a duct joint or a badly corroded duct. These tests clearly demonstrate why conventional post-tensioning ducts need to be protected by adequate clear concrete cover of low w/c ratio, and that the duct joints can be a very weak link in the corrosion protection system. On the other hand, heat-shrink tubing used to seal the duct joints outperformed normal duct tape seals by a wide margin and, in fact, produced essentially water- and chloride-tight joints under these conditions.

The polyethylene duct and the epoxy-coated steel duct provided comparable performance under very severe testing. Both provided essentially total protection for the bare strand when used with the heat-shrink tubing to seal the duct joint. The polyethylene and epoxy-coated steel duct specimens had chloride contents in the grout after the testing, which were about 1 to 3 percent of those measured in either the bare steel duct or galvanized steel duct specimens. The traditional bare steel ducts and galvanized steel ducts deteriorated badly when similarly exposed. However, the performance of the galvanized steel duct was superior to that of the bare steel duct, with a resultant chloride content in the grout of about 50 percent that of the bare steel duct specimens.

These tests also confirmed the vulnerability of the anchorage region to corrosion damage and the difficulty in achieving perfect grouting of post-tensioning systems. Because post-tensioning anchorages typically represent relatively massive steel embedments, inadequate corrosion protection can lead to severe cracking of the concrete in the anchorage region. The prestressing steel within the anchorage, however, should remain protected for a much longer period than the anchorage, if properly grouted. This study showed that an epoxy coating on the anchorage and associated hardware generally provided very good to excellent corrosion protection. It also indicated that the end of the anchorage may require additional corrosion protection than that traditionally provided by dry-packed mortar.

The epoxy-coated prestressing strand demonstrated excellent corrosion performance in both pretensioned and post-tensioned applications. The epoxy coating was never breached, even in the wedge grip region of the post-tensioning anchorage, providing complete corrosion protection for the prestressing steel during very severe corrosion testing. The epoxy coating showed essentially zero creep relative to the concrete when the strand was fully stressed in a pretensioned concrete beam and, yet, had sufficient ductility to bridge cracks induced in the beam without itself cracking. Use of this corrosion-resistant material in precast elements, however, may require some attention to concrete cover and strand spacing to avoid cracking the concrete on detensioning.

Although the new protective materials provided very good to excellent performance, a significant conclusion of this study was that the post-tensioning industry standard consisting of a bare anchorage, galvanized steel duct with duct taped joints, bare prestressing strand and normal cementitious grout adequately protected the encased bare strand from corrosion when embedded under only about 1 in. of concrete cover. At the conclusion of the test, this concrete cover had a chloride content of some 18 times the chloride corrosion threshold and was cracked by corrosion of the galvanized duct and bare anchorage. When this traditional duct system was soaked directly in salt-water, however, the corrosion protection afforded to the grouted bare strand was dramatically reduced because of the more rapid corrosion of the galvanized duct.

As expected, no apparent differences in the corrosion behavior of fully stressed and unstressed strands were found in this study. In addition, although the individual elements (including the strands) comprising a post-tensioning anchorage could be either anodic or cathodic as various corrosion cells developed, specified metallic elements were never consistently anodic nor cathodic. Thus, all unprotected metallic elements comprising the anchorage have the potential to corrode in a chloride environment.

Abrasion and damage to softer materials, such as epoxy and polyethylene, can result during handling and stressing operations, particularly with extreme duct curvatures. Such damage may be minimized by the selection and use of tougher or thicker layers of these materials. This philosophy was used during the development of the commercially available, epoxy-coated 7-wire prestressing strand, which has an epoxy coating thickness about 4 times that commonly found on epoxy-coated reinforcing bars. While this extra thickness provides added protection against physical damage and corrosion, very sharp edges, such as inside seams of corrugated steel duct, can cause damage to the epoxy coating, exposing bare steel during post-tensioning. Such damage, together with a resultant high coefficient of friction, will probably preclude use of epoxy-coated strand in corrugated steel duct when duct curvature is extreme. Such damage to epoxy-coated strand did not occur in polyethylene duct and should not occur in smooth, semirigid steel duct. The abrasion behavior of the polyethylene duct in these studies suggests that 60 mils may be a reasonable minimum wall thickness for such ducts used for post-tensioning applications.

The tests for bond and force transfer of fully grouted polyethylene duct and epoxy-coated steel duct showed results that were essentially equal to or better than traditional bare steel duct or galvanized steel duct. Thus, these newer materials may be directly substituted for traditional duct with no apparent differences in resultant structural behavior.

It therefore appears that the use of the more chloride-resistant polyethylene duct or epoxy-coated steel duct in combination with bare strand, heat-shrink tubing or some other watertight material for all duct joints, and a conventional grout results in the most economical, enhanced corrosion protection system for post-tensioned members. When greater protection is required, polyethylene duct should be considered.

When the maximum corrosion protection is desired, the use of the epoxy-coated prestressing strand should be considered for both pretensioning and post-tensioning methods, while considering the construction and handling problems discussed herein. With post-tensioning methods, the use of epoxy-coated strand should be limited to plastic duct or smooth, semirigid metallic duct with reasonable ductwork curvatures.

SUGGESTIONS FOR FUTURE RESEARCH

Pretensioning Method

The use of the relatively thick epoxy coating on 7-wire prestressing strand results in a tough and durable corrosion protection system. However, because of its thickness of about 35 mils, significant lateral expansive forces are created during the strand detensioning process. If the clear concrete cover over the coated strand is minimal (i.e., about ¾ in. to 1 ½ in.), cracking of the concrete directly over the coated strand can occur during detensioning. The relationship between epoxy coating thickness, clear concrete cover, and cracking needs to be explored. Such information is needed for thin, precast, pretensioned bridge members such as stay-in-place bridge deck slabs and sheet piling. Because most corrosive bridge environments will dictate significant clear cover of 2 ½ in. to 4 in., this lateral expansion property of the epoxy coating should not be a problem with normal-sized bridge members, although it needs to be recognized with respect to lateral confinement reinforcement.

Because most pretensioned bridge members are also cured overnight using accelerated heat curing procedures, the ability of the epoxy coating on the strand to transfer the prestressing loads into the members during detensioning operations, when the members may still be warm to hot, may need to be investigated.

Also, considering the relatively thick coatings used on prestressing steel and the sometimes high concentration of strands in prestressed members, thermally induced expansion of the epoxy coating could cause disruptive forces to develop before the concrete has gained significant strength during the initial curing period. This subject also could be pursued.

Because published data on the threshold chloride content at which bare prestressing strand begins to corrode are not well defined, it is recommended that additional chloride threshold studies be undertaken for prestressing steel.

Post-Tensioning Method

This study showed that improvements in the duct system provide the best corrosion protection with the least impact on stressing operations. Heat-shrink tubing for sealing the duct joints was very effective; therefore, this or other suitable watertight materials should be tested further under actual field conditions, particularly at anchorage-to-duct joints. Tests on other waterproofing tapes, other than duct tape, should also be undertaken to compare their effectiveness against heat-shrink tubing. Further tests are also suggested on different formulations of polyethylene duct as well as other plastic duct materials to determine their thickness and toughness requirements to minimize abrasion damage during handling, concreting, and post-tensioning operations. The possibility of combining the chloride resistance of polyethylene duct with a thin steel liner for abrasion resistance should be explored.

The results of the foregoing suggested research should produce continuing improvements in the corrosion protection provided by the post-tensioning ductwork system in cast-in-place bridges. It can also be used for within-segment ductwork joints of precast, segmental bridges. The joint between precast segments and the connections for ductwork from one segment to the other, however, need research to develop better corrosion protection for the prestressing steel at these critical locations. This subject was not addressed in the present study.

The fusion bonding process for malleable iron castings should be reviewed to eliminate or minimize apparent local defects in the epoxy coating system. The epoxy formulations may need better toughness and bond properties, and possibly be used with a greater thickness.

The anchorage region should also receive further corrosion protection research. Different coatings for the anchorage should be investigated. An improved technique or material for better protecting the exposed ends of the strands at the anchorage in the field should also be developed. The tests in this study showed clearly the vulnerability of the drypack mortar used in post-tensioned anchorage assemblies.

Grouting materials and methods still need further improvements to lower the chloride permeability qualities and to eliminate, if possible, voids in the hardened grout. Neither of these ends was achieved in this research, even though three different formulations of grout were evaluated and grouting was done under controlled laboratory conditions. In one instance, the very ineffective protection afforded to bare strand by encasement in silica fume-modified grout was surprising in light of other recent studies. It is conceivable that although the addition of condensed silica fume was beneficial, the dosage employed in the particular grout formulation tested may have negated the benefits. Additional work in this area may be productive.

In this same area of improved grouting formulations, research on the chloride corrosion threshold for various grouts would prove helpful both in selecting a grout formulation for use and in assessing the severity of existing corrosion damaged, post-tensioned concrete bridges.

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APPENDIXES—A THROUGH F

Appendixes A through F are not published herewith, but are contained in a separate volume, as submitted by the research agency to the sponsors. A limited number of copies of the appendix materials in the agency final report on Project 4-15, "Corrosion Protection of Prestressing Systems in Concrete Bridges," are available on loan, or for purchase at a nominal cost, upon written request to the NCHRP. The Contents are listed here for the reader's convenience.

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