Evaluation of Corrosion Protection for Internal Prestressing Tendons in Precast Segmental Bridges

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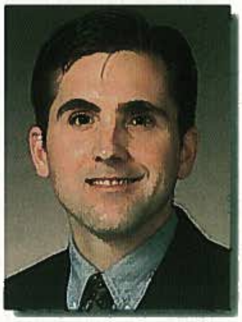

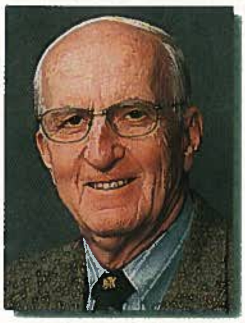

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A research program utilizing modified macrocell corrosion specimens was conducted to investigate corrosion protection for internal tendons in segmental bridges. Test variables were segmental joint type, duct type, joint precompression and grout type. Specimens were subjected to $4^{1}/_{2}$ years of exposure testing, after which selected specimens were removed for destructive examination. Dry joint specimens performed very poorly, as evidenced by corrosion currents measured during exposure testing and by tendon and duct corrosion observed upon destructive examination. Epoxy joints limited chloride penetration, preventing tendon corrosion and reducing duct corrosion. Plastic post-tensioning ducts performed very well, limiting strand corrosion to negligible levels. The research indicates that epoxy joints are required for the protection of internal tendons in aggressive environments, and that plastic post-tensioning ducts provide a significant improvement in tendon corrosion protection. Many of the conclusions and recommendations presented are not only specific to segmental construction but are applicable to all forms of internal, grouted post-tensioning tendons.

Precast concrete segmental bridge construction in North America normally consists of match-cast box girder segments post-tensioned for continuity. Post-tensioning may be internal bonded tendons, external tendons, or a combination of both. Current specifications[1] require the use of match-cast epoxy joints with internal tendons.

Epoxy joints were introduced to enhance force transfer across the segmental joint and to seal the joint against moisture entry. More recently, epoxy joints have been recognized as an absolute requirement for durability when internal tendons are used. The post-tensioning ducts for internal tendons are not continuous across the segmental joints in North American practice, and no special coupling of tendon ducts is made with match-cast joints.

Corrosion protection for bonded internal tendons in precast segmental construction can be very good. Within the segment, internal tendons are well protected by high quality concrete, duct and cement grout. General information on corrosion protection for precast, prestressed concrete is provided in a number of sources, including References 2, 3, 4 and 5. The potential weak link in corrosion protection for internal tendons in segmental construction is at the joint between segments, where the joint represents a preformed crack at the location of a discontinuity in the duct.

In saltwater exposures or in areas where deicing salts are used, the joint could possibly allow moisture and chlorides to reach the tendon and cause corrosion. Since the tendons provide structural continuity, failure of a tendon due to corrosion could lead to serious distress or collapse of the bridge.

The overall performance of precast segmental bridges in North America has been very favorable,[6] and there have been no reported cases of corrosion of internal tendons in precast segmental construction resulting from moisture penetration at epoxy joints. However, it has been argued that the lack of duct continuity at the segmental joint leaves the potential for moisture and chlorides to reach the prestressing tendon.

Recently, a number of post-tensioning tendon corrosion problems have come to light in North America, with the most notable occurring in several Florida bridges. While much of the information related to these tendon corrosion problems has not been formally published, some documentation is available directly from the Florida Department of Transportation. In addition, some discussion of the grout-related aspects of the corrosion problems is provided by Ronald.[7]

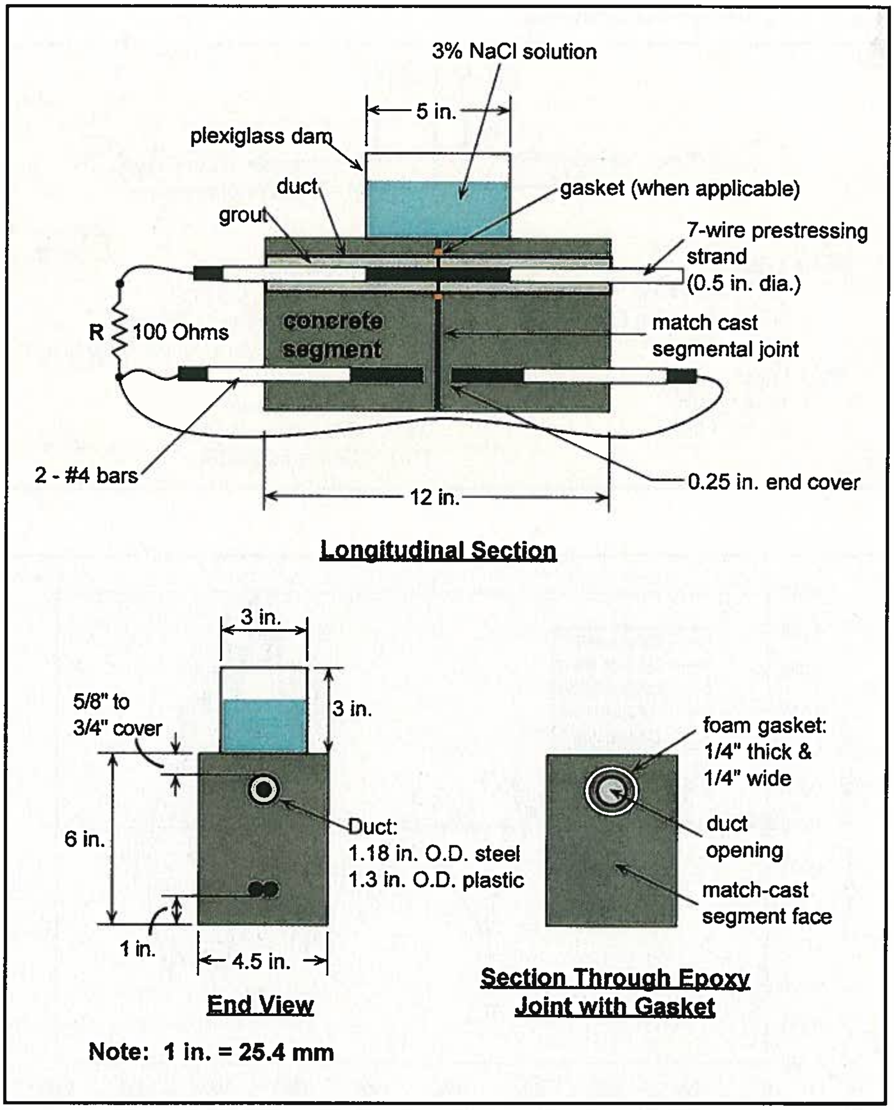


Fig. 1. Macrocell specimen details.

The recently discovered tendon corrosion problems in Florida and elsewhere involved a number of different forms of post-tensioned bridge construction. However, it is important to note that none of the problems were related to corrosion of internal tendons in precast segmental construction.

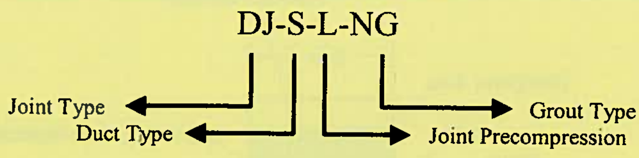
The tendon corrosion problems in Florida highlight the importance of attention to corrosion protection for grouted post-tensioning systems. The objective of the research described herein was to use laboratory corrosion tests to evaluate the potential for corrosion of bonded internal post-tensioning tendons with details typical of North American precast segmental construction.

This article provides a brief description of the test specimens and variables for the research study. Test data from $4^1/_2$ years of exposure testing are presented and discussed. One-half of the macrocell corrosion specimens were subjected to a complete destructive examination after the $4^1/_2$ year testing period. A detailed description of the autopsy process and findings is provided. Conclusions and recommendations suitable for implementation are presented based on the exposure testing and destructive examination.

TEST PROGRAM

The test program enlisted 38 modified macrocell corrosion specimens in 19 pairs. Four categories of variables were selected to evaluate typical details and protection measures in segmental construction.

Table 1. Specimen designation.



Joint Type:
DJ = Dry Joint
SE = Standard Epoxy
EG = Epoxy with Gasket

Duct Type:
S = Steel
P = Plastic

Joint Precompression:
L = Low: 5 psi (35 kPa)
M = Medium: 50 psi (345 kPa)
H = High: $3\sqrt{f'_c}$ psi (190 psi, 1310 kPa)

Grout Type:
NG = Normal Grout
SF = Silica Fume Added
CI = Corrosion Inhibitor

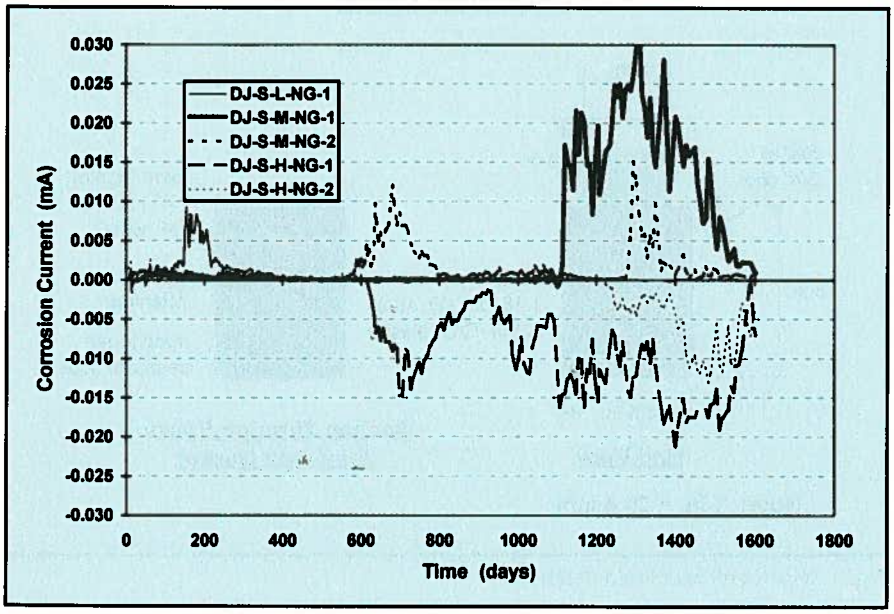


Fig. 2. Macrocell corrosion current: dry joint, steel duct, normal grout.

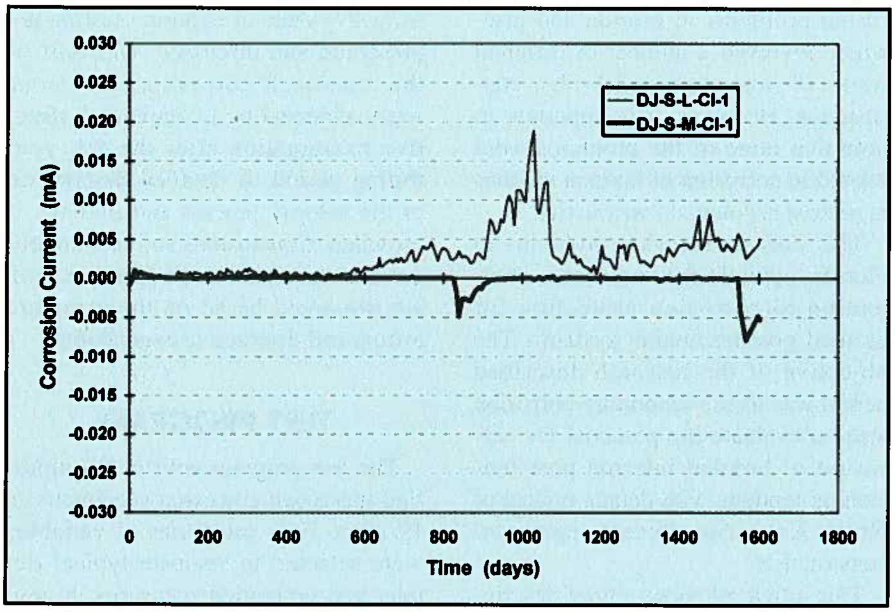


Fig. 3. Macrocell corrosion current: dry joint, steel duct, corrosion inhibitor in grout.

Macrocell Corrosion Specimens

Test specimens were based on the standard macrocell described in the American Society for Testing and Materials (ASTM) Standard G109.[8] The joint and tendon details investigated represent modern precast segmental bridge construction in North America. The modified macrocell specimen configuration is shown in Fig. 1.

Each specimen consists of two match-cast segments, with continuity between the segments provided by a $^1/_2$ in. (12.7 mm) diameter, seven-wire prestressing strand inside a grouted duct. The duct is not continuous across the joint, providing details typical of bonded internal tendons in precast segmental bridge construction. Due to the small size of the specimens, the tendon could not be prestressed effectively, and, as a result, stress corrosion was not considered in this research.

The pairs of match-cast segments are stressed together using external loading frames to simulate precompression across the joint due to post-tensioning. Two No. 4 (12.7 mm) mild steel reinforcing bars are used in the bottom of the specimen to represent segment reinforcement. The mild steel bars do not cross the transverse joint, which is consistent with precast segmental construction.

Following ASTM G109, the exposed length of the prestressing strand and mild steel bars was limited to 5 in. (125 mm) using epoxy paint. Electrical contact between the two layers of steel, necessary for macrocell corrosion, is achieved by wiring the protruding ends of the steel together as shown in Fig. 1. A resistor is placed in the wire connection to allow assessment of the corrosion current by measuring the voltage drop across the resistor (Ohm's Law).

Exposure conditions consist of a two-week cycle of two weeks dry and two weeks wet. During the wet period of the cycle, the top surface of the specimen is ponded with a salt solution.

Variables

The variables selected for investigation in this program cover four components of the precast concrete segmental bridge related to corrosion of internal tendons: joint type, duct type, joint precompression and grout type.

Joint type refers to the type of preparation or bonding agent used at the match-cast segmental joint. Variables investigated were dry joint (no bonding agent), epoxy joint and epoxy joint with a gasket around the duct connection. Dry joints with internal tendons are prohibited by the guide specifications for segmental bridges,[1] and were included only as a worst case example for comparison purposes.

The epoxy jointed specimens were assembled according to standard practice. Both match-cast faces were coated with epoxy and the segments were pushed together. The joint was precompressed at 50 psi (345 kPa) for 48 hours, after which the specimens were unloaded and reloaded to the desired level of precompression (see below).

In the epoxy/gasket joint, a foam gasket was glued to the face of one segment around the duct opening, as shown in Fig. 1, prior to application of the epoxy. The primary purpose of the gasket is to prevent epoxy from entering the duct during segment placement and initial stressing. In the epoxy joint without a gasket, the duct was swabbed out immediately after stressing to 50 psi (345 kPa) to prevent the epoxy from blocking the duct. Both techniques (gasket and no gasket) are used in current practice.

Duct types investigated were galvanized steel duct and plastic duct. Polyvinyl-chloride (PVC) pipe was used for the plastic duct due to size limitations. Although PVC pipe was used in the testing program, it is generally not permitted for use in concrete structures due to the potential for long-term breakdown of the PVC and associated release of chlorides over the service life of the structure.

Joint precompression refers to the level of prestress provided by the internal and/or external tendons in the bridge. Three levels of precompression were selected; 5, 50 and 190 psi (35, 345 and 1310 kPa). The lowest level of 5 psi (35 kPa) could represent the level of precompression encountered in a precast segmental column under self-weight. The precompression of 50 psi (345 kPa) is based on the AASHTO Guide Specifications.[1]

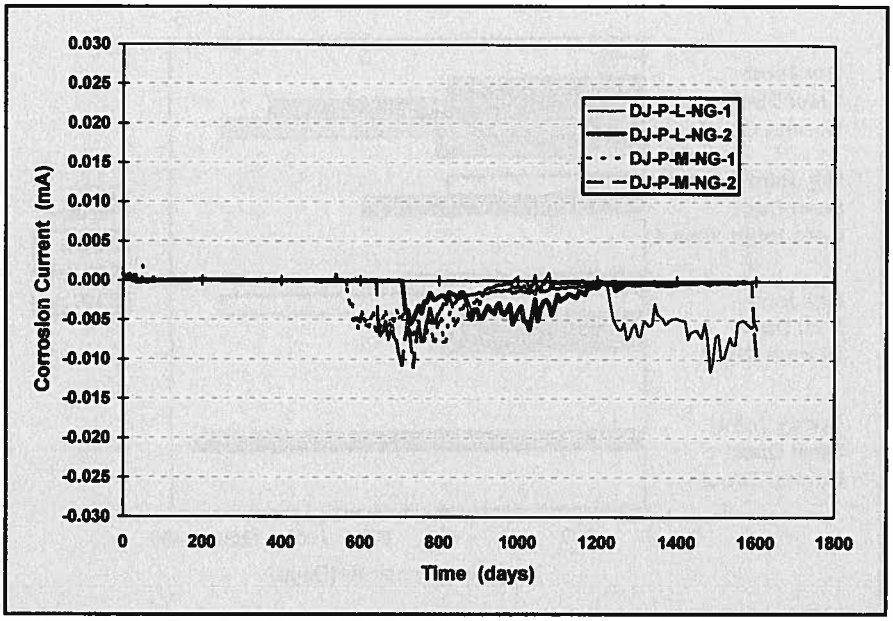


Fig. 4. Macrocell corrosion current: dry joint, plastic duct, normal grout.

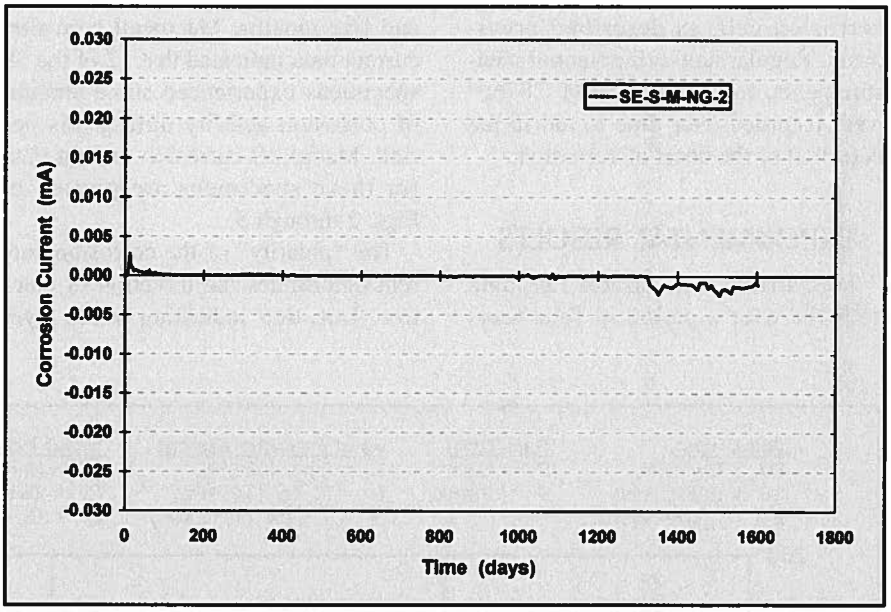


Fig. 5. Macrocell corrosion current: standard epoxy joint, steel duct, normal grout.

The highest precompression value of 190 psi (1310 kPa) corresponds to $3\sqrt{f_c'}$ psi ($7.88\sqrt{f_c'}$ kPa).

Three cement grout types were selected for evaluation: normal grout [plain cement grout, water-cement ratio (*w/c*) of 0.40], grout with silica fume [13 percent cement replacement by weight, water-cementitious material ratio (*w/cm*) of 0.32, superplasticizer added] and grout with a calcium nitrite corrosion inhibitor [water-cement ratio (*w/c*) of 0.40]. Details of the grout mix proportions are provided by West et al.[9]

A total of 19 specimen types were selected to address all of the variables. Each specimen type was duplicated for a total of 38 specimens. The notation used in the specimen designation is shown in Table 1.

Measurements During Exposure Testing

Two forms of regular measurements were taken to evaluate corrosion activity. Macrocell corrosion current was determined by measuring the voltage drop across a known resistance in the

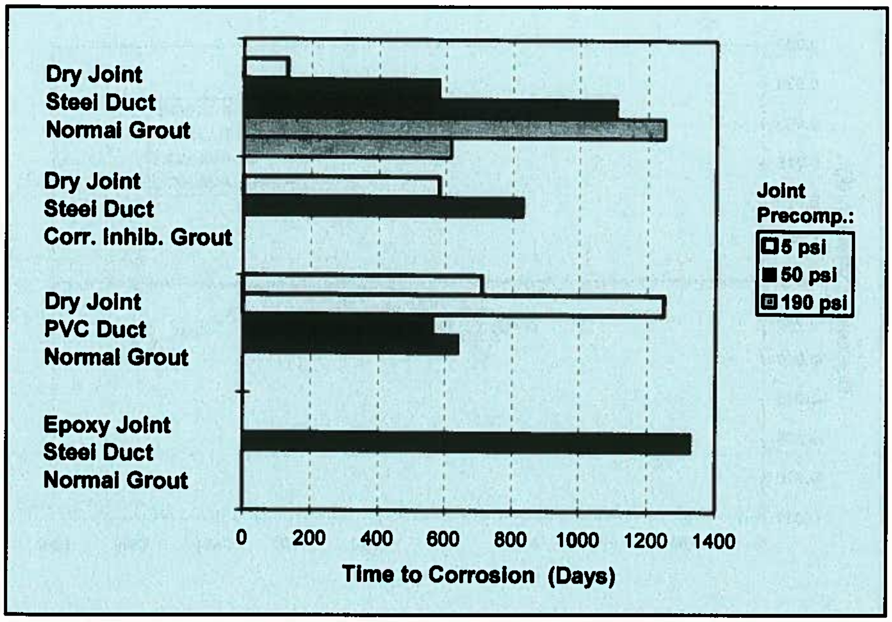


Fig. 6. Time to corrosion for specimens with corrosion activity.

corrosion cell, as described previously. Regular half-cell potential measurements, following ASTM C876,[10] were recorded over time to aid in the detection of the onset of corrosion.

EXPERIMENTAL RESULTS

This article summarizes test data gathered over a period of four years and five months. Macrocell corrosion current data indicated that 12 of the 38 specimens experienced some amount of corrosion activity during this period. Macrocell corrosion current data for these specimens are plotted in Figs. 2 through 5.

The "polarity" of the corrosion current determines the direction of electron flow, thus indicating which layer of steel is corroding or experiencing metal loss. Negative corrosion currents in Figs. 2 through 5 indicate that the mild steel reinforcing bars at the bottom of the specimen are actively corroding while the prestressing strand is acting as the cathode.

Of the 12 corroding specimens, only seven showed continued corrosion activity after four years and five months. Eleven of the 12 specimens with signs of corrosion had dry segmental joints, illustrating the poor level of protection provided by dry joints. One specimen with a match-cast epoxy joint showed an initiation of corrosion on the mild steel reinforcement, as indicated by the negative corrosion current in Fig. 5.

Time to Corrosion

The time to corrosion for each of the 12 specimens displaying corrosion initiation is plotted in Fig. 6. The time to corrosion ranged from 128 days for a dry joint specimen with galvanized steel duct and low joint precompression to 1330 days for the epoxy joint specimen with corrosion activity. Note that time to corrosion values are for the first detected corrosion activity, whether it occurred on the prestressing strand or the mild steel bars.

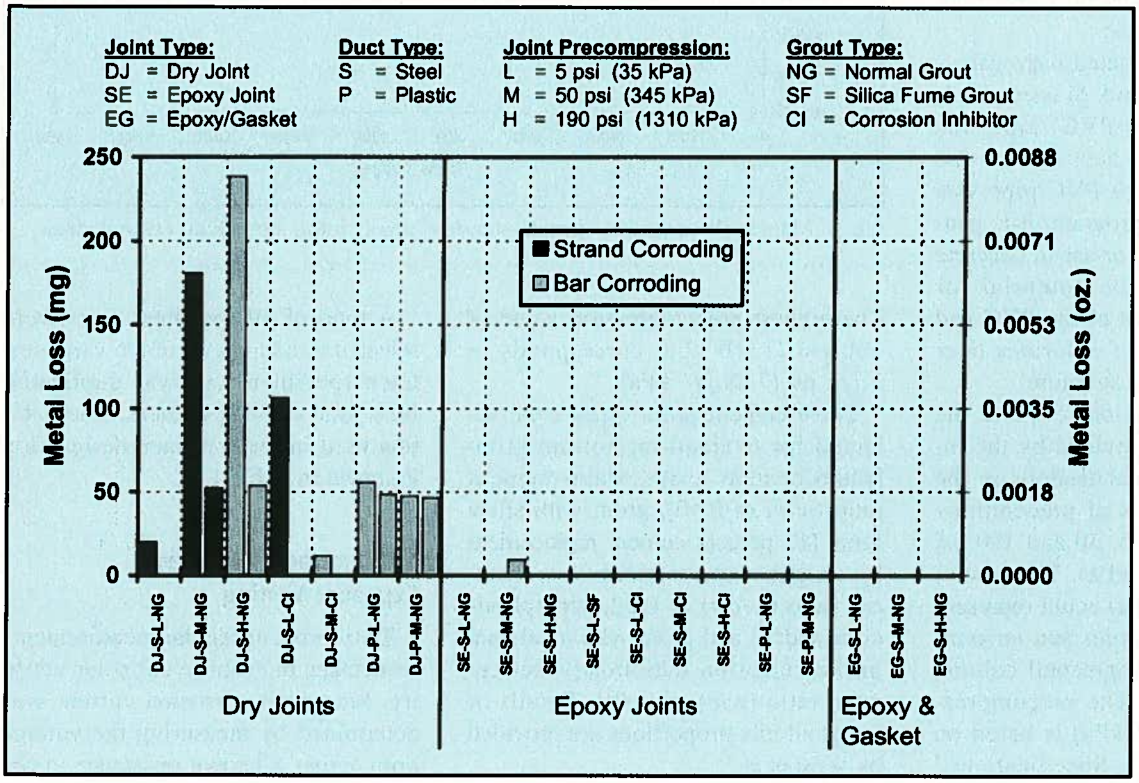


Fig. 7. Calculated metal loss for all specimens.

The times to corrosion in Fig. 6 do not appear to indicate any trends in the effect of the variables. Conceptually, a higher level of joint precompression might be expected to limit the entry of moisture and chlorides, providing better corrosion protection and longer times to corrosion. This trend is not supported by the data for the three levels of joint precompression investigated. In addition, the duct type and grout type do not appear to affect the time to corrosion based on the data to date.

Corrosion Severity

Calculation of the metal loss during corrosion allows a relative comparison of corrosion severity between specimens. The amount of steel consumed by macrocell corrosion is directly related to the total number of electrons exchanged between the anode and cathode. The amount of metal loss can be computed by numerically integrating the macrocell corrosion current over the duration of exposure. Based on corrosion science, one amp of corrosion current consumes 1.04 grams of steel (iron) per hour.[11]

Computed values of metal loss for all specimens are shown in Fig. 7. ASTM G109 defines failure for the macrocell corrosion specimen as a weighted average corrosion current of 10 mA (average calculated over the duration of testing). For an exposure duration of four years and five months, this would correspond to a metal loss of 0.014 oz (400 mg).

The most severe corrosion occurred in specimens with dry joints, galvanized steel ducts and normal grout, having a calculated metal loss of less than 250 mg (0.0088 oz). In general, the calculated values of metal loss are well below the failure limit of 0.014 oz (400 mg), suggesting corrosion activity to date is minor in almost all cases.

DESTRUCTIVE EXAMINATION

One specimen from each identical pair was removed from testing for destructive examination or autopsy after four years and five months of exposure testing. The objectives of the destructive examination were to obtain a visual evaluation of corrosion damage on the duct, strand and mild steel reinforcement, and to assess chloride ion penetration at locations adjacent to and away from the segmental joint.

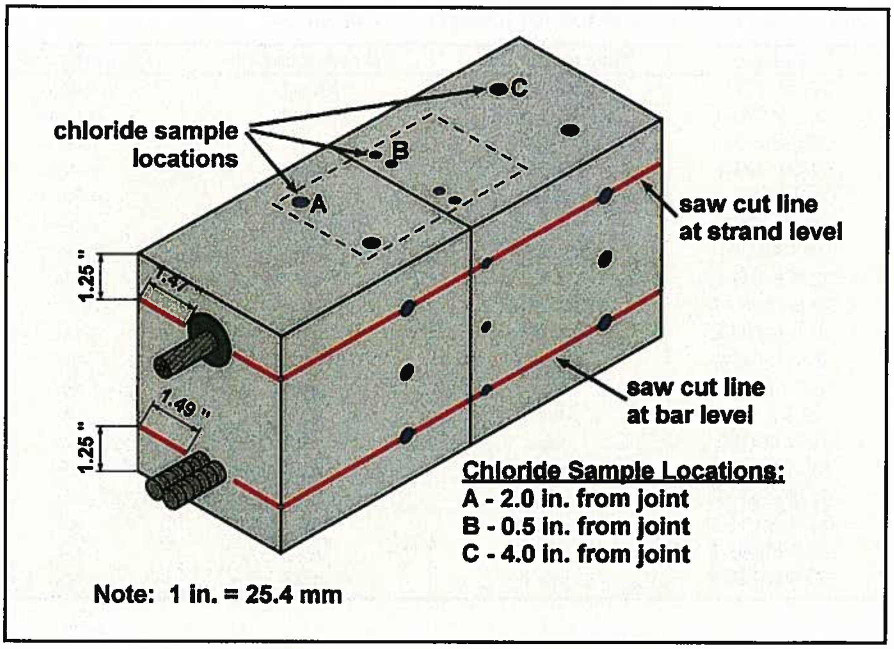


Fig. 8. Saw cut and chloride sample locations.

Procedure

The procedure for the destructive examination began with sampling of the concrete from selected specimens for chloride analysis. This was followed by cutting of the specimens to allow careful extraction of the duct, tendon and mild steel bars. Specimen condition was documented at each stage of the process.

Chloride Analysis — Concrete powder samples were collected to determine chloride ion profiles adjacent to the joint and away from the joint to examine the influence of joint type on chloride penetration. Sampling locations are shown in Fig. 8. Concrete powder samples were collected using a rotary hammer and following a procedure based on AASHTO T 260.[12] Samples were analyzed for acid soluble chlorides using a specific ion probe.

Grout samples were also collected from selected specimens for chloride analysis. Samples were carefully removed from the strand at the location of the joint and at a distance of 2 in. (51 mm) from the joint. The grout pieces were crushed and ground into powder using a mortar and pestle. Grout powder samples were analyzed for acid soluble chlorides using a specific ion probe.

Longitudinal Saw Cuts — Two longitudinal saw cuts were made on each side of the specimens to facilitate removal of the duct/strand unit and mild steel bars, as shown in Fig. 8. An additional pair of longitudinal saw cuts was made at the midheight of selected epoxy joint specimens to evaluate the joint condition. Joint sections were examined for indications of voids in the epoxy, or the presence of moisture, salt, or corrosion products.

Autopsy Program

One specimen from each duplicate pair of specimen types was selected for destructive examination. Details of the 19 specimens selected for autopsy are listed in Table 2. This table also indicates the specimen condition at the time of autopsy, and whether chloride sampling was performed.

Evaluation and Rating of Corrosion Found During Destructive Examination

A generalized evaluation and rating system was developed in this research program to quantify the severity and extent of corrosion damage in the test

Table 2. Specimens selected for forensic examination.

Specimen	Time to corrosion	Corrosion location	Corrosion activity	Chloride samples	Midheight cut
DJ-S-L-NG-1	128 days	Strand	Inactive	A, B, C	n/a
DJ-S-M-NG-1	1110 days	Strand	Inactive	A, B	n/a
DJ-S-H-NG-1	615 days	Bars	Active	A, B	n/a
DJ-P-L-NG-1	1250 days	Bars	Active	A, B	n/a
DJ-P-M-NG-1	565 days	Bars	Inactive	None	n/a
DJ-S-L-CI-1	580 days	Strand	Active	A, B	n/a
DJ-S-M-CI-1	835 days	Bars	Inactive	A, B	n/a
SE-S-L-NG-2	n/a	n/a	n/a	A, B, C	Yes
SE-S-M-NG-2	1330 days	Bars	Active	A, B	Yes
SE-S-H-NG-2	n/a	n/a	n/a	A, B	Yes
SE-P-L-NG-2	n/a	n/a	n/a	None	No
SE-P-M-NG-2	n/a	n/a	n/a	None	No
SE-S-L-CI-2	n/a	n/a	n/a	None	No
SE-S-M-CI-2	n/a	n/a	n/a	None	No
SE-S-H-CI-2	n/a	n/a	n/a	None	No
SE-S-L-SF-2	n/a	n/a	n/a	None	No
EG-S-L-NG-2	n/a	n/a	n/a	A, B	Yes
EG-S-M-NG-2	n/a	n/a	n/a	None	Yes
EG-S-H-NG-2	n/a	n/a	n/a	None	Yes

specimens. The procedure is presented in a universal form with the intention of applying the same rating system to other situations.

The rating procedure involved subdividing the length of strand, mild steel reinforcement or galvanized steel duct into eight increments. The steel was examined at each increment, and a rating was assigned to describe the corrosion severity within that increment. The ratings for the eight increments were summed to give a total corrosion rating for the element that could be compared for different specimens. By assigning a corrosion severity at eight locations, both the extent and severity of corrosion is considered.

The corrosion severity rating system is essentially the same for prestressing strand, mild steel reinforcement and galvanized duct, with some modifications to reflect unique corrosion aspects of each type of steel. In general, the evaluation system doubles the severity rating for each category of increasing corrosion damage. A detailed description of the rating system and its application is provided by West et al.[9]

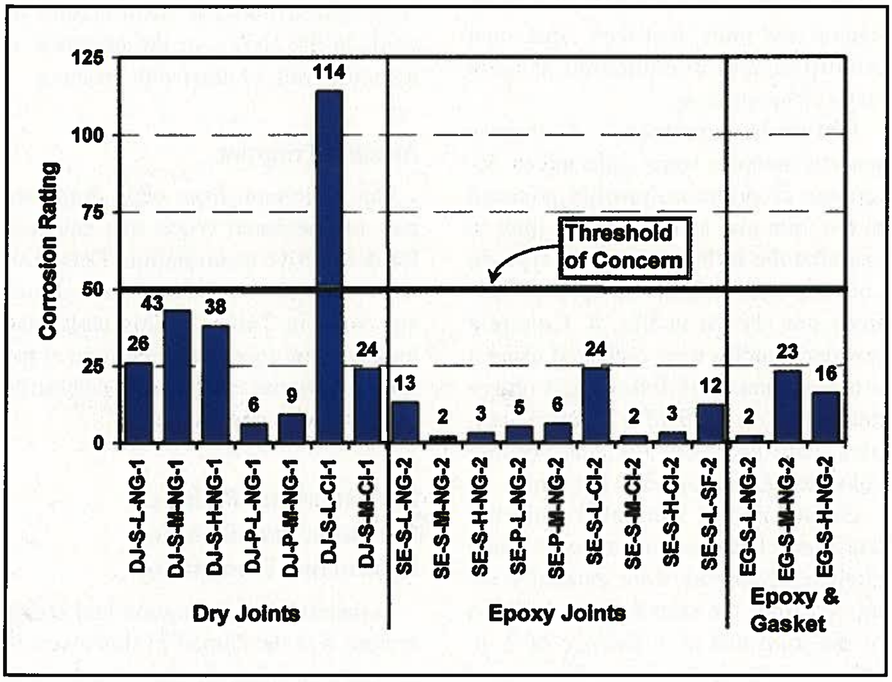


Fig. 9. Strand corrosion ratings for all specimens.

DESTRUCTIVE EXAMINATION RESULTS

Destructive examination of each specimen type revealed that corrosion damage to prestressing strand and mild steel reinforcement was not severe. Only one prestressing strand was found to have pitting corrosion, and no mild steel bars were found to have measurable area reduction.

Similar testing programs using ASTM G109 type macrocell corrosion specimens normally report severe corrosion damage and specimen failure in a test duration of less than $4^1/_2$ years. This observation highlights the overall excellent performance of the grouted post-tensioning system in this testing program. A detailed summary of the destructive examination results is provided for each specimen in Reference 9.

Corrosion Ratings

The strand, bar and duct corrosion ratings for all specimens are plotted in Figs. 9 through 11. A "Threshold of Concern" was assigned in the figures at a corrosion rating of 50 to indicate corrosion related deterioration deemed severe enough to warrant concern. The threshold of concern is useful to illustrate that in most cases the observed corrosion was negligible from a practical standpoint. In general, corrosion ratings greater than 50 corresponded to pitting corrosion for strands and bars, and holes in the galvanized steel duct caused by corrosion.

Specimen DJ-S-L-CI-1 [dry joint, steel duct, 5 psi (35 kPa) precompression, corrosion inhibitor in grout] had the most severe strand corrosion, with a corrosion rating of 114 (see Fig. 9) compared to the average of 19.5 and median of 12. This was the only specimen with a strand corrosion rating greater than 50.

Specimen DJ-S-H-NG-1 [dry joint, steel duct, $3\sqrt{f'_c}$ precompression (190 psi, 1310 kPa), normal grout] had the most severe mild steel reinforcement corrosion with a rating of 60 (see Fig. 10) compared to the average of 9.1 and median of 1. This was the only specimen with a bar corrosion rating greater than 50.

Specimen DJ-S-L-NG-1 [dry joint, steel duct, 5 psi (35 kPa) precompression, normal grout] had the worst duct corrosion with a rating of 528 (see Fig. 11) compared to the average of 122.9 and median of 79.

In each case, the specimen with the largest corrosion rating was several times higher than the average and median values. The average rating is larger than the median rating for all three ratings. The difference is largest for the mild steel bars, where the average is almost an order of magnitude larger than the median. These trends illustrate that the worst performance generally occurred in a limited number of specimens.

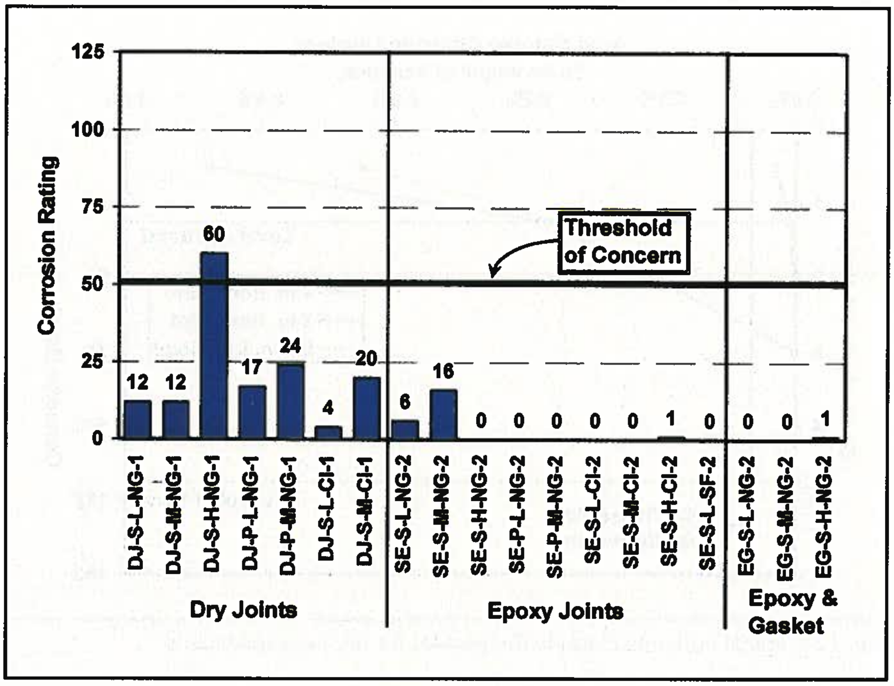


Fig. 10. Mild steel reinforcing bar corrosion ratings for all specimens.

Chloride Analysis Results

Concrete powder samples were collected from six dry joint specimens and four epoxy joint specimens for chloride analysis. In addition, samples were collected from the grout in these specimens for chloride analysis.

The chloride ion profiles in the concrete revealed distinct trends in chloride ion penetration in dry joint and epoxy joint specimens. In general, the dry joint specimens showed significantly higher chloride contents adjacent to the joint in comparison to measurements away from the joint. In the epoxy joint specimens, the chloride profiles were essentially the same near and away from the joint.

Typical profiles for dry joints and epoxy joints are shown in Fig. 12 and Fig. 13, respectively. Values plotted in the figures are acid soluble chloride levels, expressed as a percentage of concrete weight (weight of sample). The chloride threshold for corrosion is indicated in the figures at 0.033 percent. This value is intended as a guideline only, and is based on the widely accepted chloride threshold value of 0.2 percent of the weight of cement.[13]

In the dry joint specimens, the chloride contents were well above the corrosion threshold over the depth of the specimen. In some cases, chloride con-

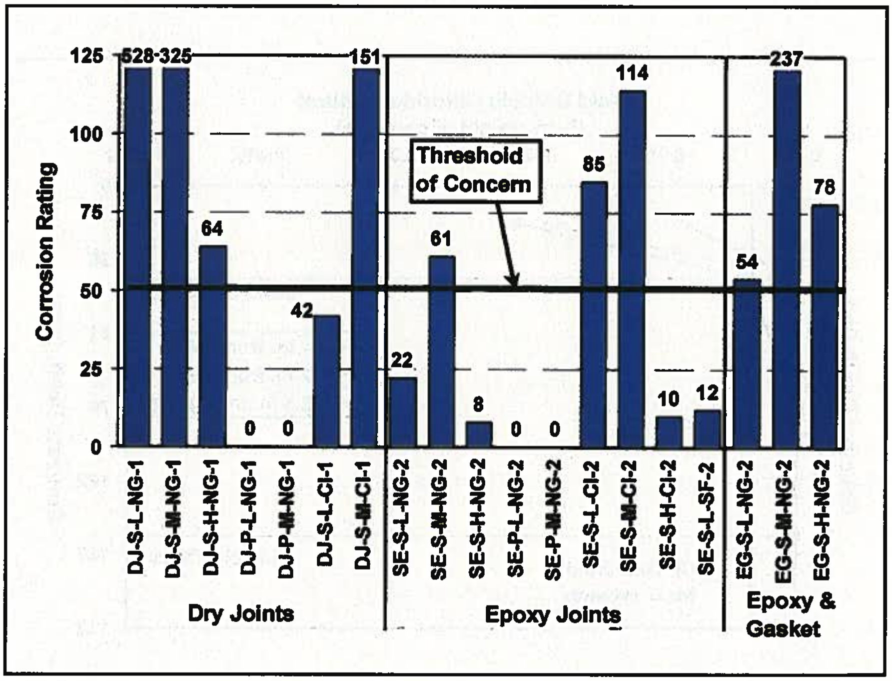


Fig. 11. Duct corrosion ratings for all specimens.

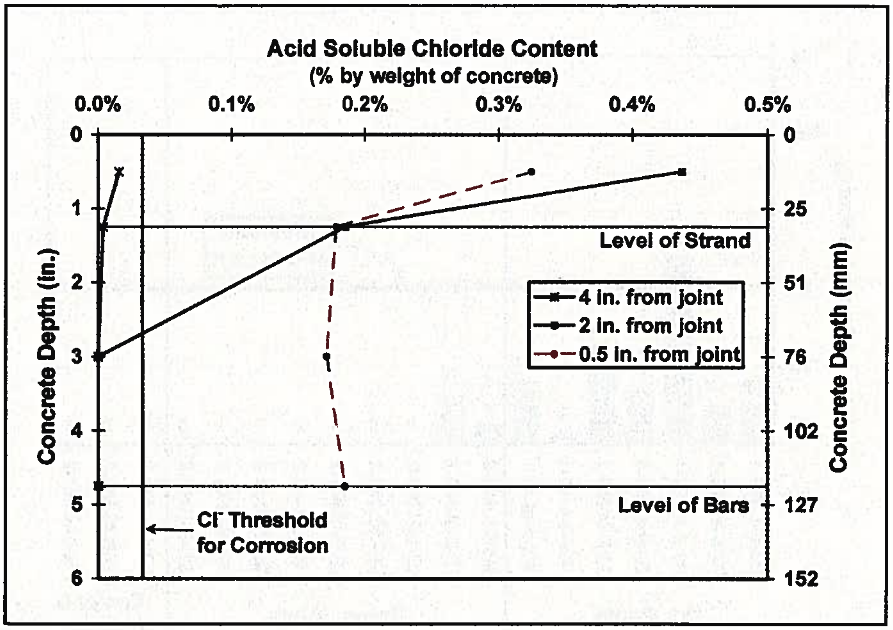


Fig. 12. Typical concrete chloride ion profiles for dry joint specimens.

tents at 2 in. (51 mm) from the joint were higher in the dry joint specimens in comparison to those with epoxy joints. Samples collected at Location C, 4 in. (102 mm) from the joint, showed negligible chloride levels in both dry and epoxy joint specimens.

The chloride profile for Specimen SE-S-M-NG-2 [epoxy joint, steel duct, 50 psi (345 kPa) precompression, normal grout] displays a discontinuity in the measurements adjacent to the joint, as shown in Fig. 14. Chloride measurements decrease to zero by midheight of the specimen, but increase dramatically at the level of the mild steel bars near the joint. This profile correlates with the observed corrosion on the mild steel at this location.

The most probable explanation for this result is that saltwater leakage from the ponded area ran down the exterior of the specimen to the bottom where it entered the concrete. The top surface and sides of the specimen are sealed with epoxy according to ASTM G109, while the bottom is not.

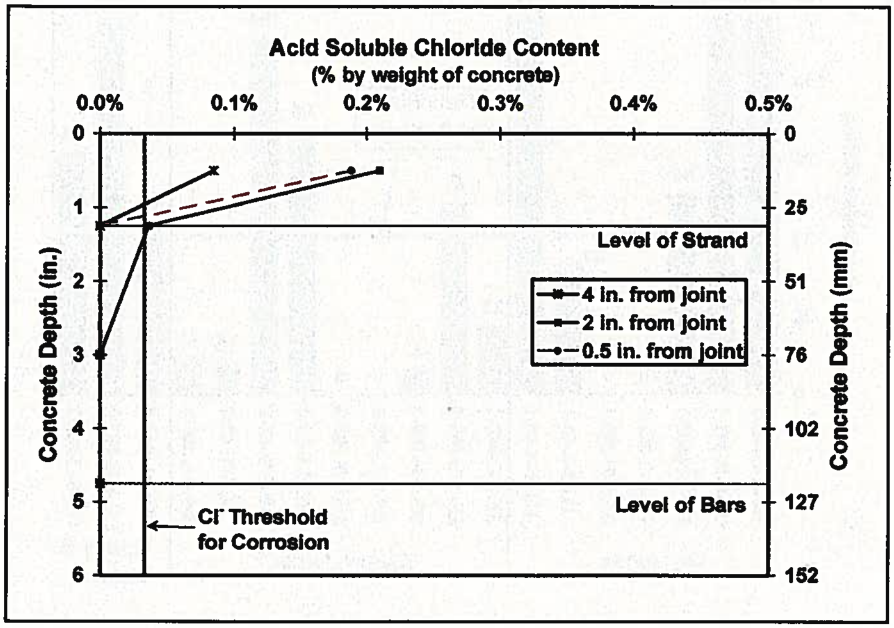


Fig. 13. Typical concrete chloride ion profiles for epoxy joint specimens.

This phenomenon is common in bridges, where moisture runs down the side of a member, and chlorides collect at the bottom of the member. The epoxy sealant on the top and sides of the macrocell corrosion specimens would amplify this effect, accounting for the increased chloride levels near the bottom surface.

The results of the chloride analysis on grout samples are shown in Fig. 15. The values are plotted as acid soluble chlorides, as a percentage of the grout weight. The chloride threshold for corrosion in grout is taken as approximately 0.14 percent by weight of sample. This threshold is based on a chloride threshold of 0.2 percent by weight of cement[13] and a water-cement ratio of 0.44. Note that the weight of cement is approximately 69 percent of the sample weight for a plain grout with a water-cement ratio of 0.44.

The dry joint specimens show very high chloride contents, particularly in the vicinity of the joint. The two dry joint specimens with steel ducts and low precompression (Specimens DJ-S-L-NG-1 and DJ-S-L-CI-1) also show large chloride contents inside the duct, 2 in. (51 mm) from the joint.

The dry joint specimen with a plastic duct, Specimen DJ-P-L-NG-1, showed a high chloride content at the joint, but only negligible chlorides 2 in. (51 mm) inside the duct.

The four epoxy joint specimens analyzed show very low or unmeasurable chlorides at the joint. At a distance of 2 in. (51 mm) inside the duct, all samples showed unmeasurable chloride levels for the epoxy joint specimens.

ANALYSIS AND DISCUSSION OF RESULTS

Four years and five months of exposure test data and destructive examination of 19 specimens provided a wealth of data to assess the variables investigated in this testing program. An analysis and discussion of the laboratory results are provided below in terms of the four groups of variables, namely, joint type, duct type, joint precompression and grout type. Additional observations are also discussed.

Effect of Joint Type

Of the four variable groups investigated, joint type appears to have the most significant effect on the performance of the specimens. In general, dry joints performed very poorly, with corrosion currents for 78 percent of the dry joint specimens indicating corrosion activity. The effect of joint type on the measured and observed results is described below.

Galvanized Steel Duct Corrosion — The extent and severity of duct corrosion was significantly affected by the joint type. The photos in Fig. 16 show typical corrosion of the galvanized steel duct in each of the three joint types, with two epoxy/gasket joint specimens shown to illustrate the varied conditions observed for this joint type.

The specimens in Fig. 16 have been cut open at the level of the duct, and the photo shows the top surface of the specimen and a top view of the duct still embedded in the concrete. The top surface of the concrete had a longitudinal crack due to corrosion in three of the four specimens shown. Note that the crack has been highlighted in the photo, and the black arrow indicates the joint location.

In general, the duct corroded area and corrosion severity were less for epoxy joints and corrosion induced cracking on the concrete surface was more severe for dry joints. Duct corrosion was centered on the segmental joint in all of the dry joint specimens. Corrosion was not centered on the joint in the standard epoxy joint, suggesting corrosion was caused by moisture and chloride migration through the concrete with no discernible influence from the joint.

Two of the three epoxy/gasket joint specimens autopsied indicated that the gasket interfered with epoxy coverage in the vicinity of the duct. When the joint was sound, as shown in the lower left photograph in Fig. 16, the duct corrosion in the epoxy/gasket joint was less severe than the dry joints and was not centered on the joint, similar to the standard epoxy joint. However, when epoxy coverage was not complete, severe duct corrosion and concrete cracking occurred, centered on the joint, suggesting that moisture and chlorides penetrated at the joint.

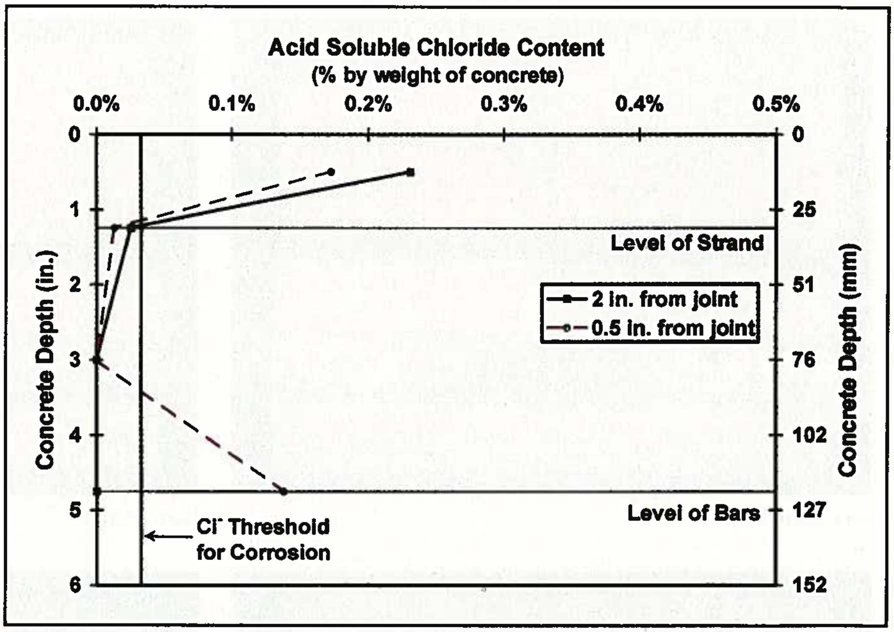


Fig. 14. Concrete chloride ion profiles for Specimen SE–S–M–NG–2.

These results indicate that the standard epoxy joint consistently provides the best corrosion protection. The results also indicate that the complications introduced in the process by adding gaskets could be counterproductive since corrosion protection was reduced when compared to the epoxy joint without a gasket.

Prestressing Strand Corrosion — Macrocell corrosion current data measured during exposure testing indicated that corrosion of the prestressing strand was only occurring in four specimens, all with dry joints. The prestressing strand corrosion found during the destructive examination would be considered very mild or negligible for all specimens with the exception of Specimen DJ-S-L-CI-1 [dry joint, steel duct, 5 psi (35 kPa) precompression, corrosion inhibitor grout].

In general, the strand corrosion

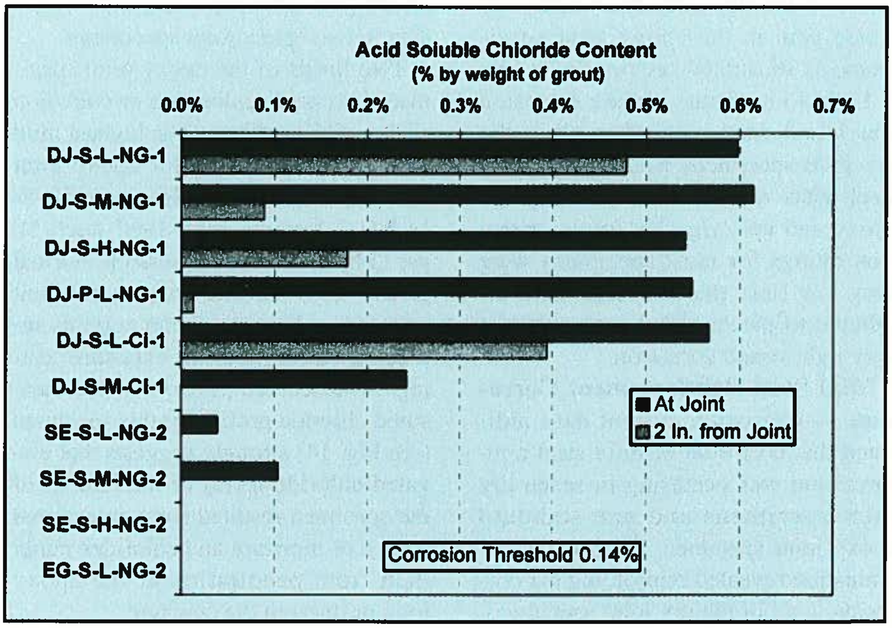
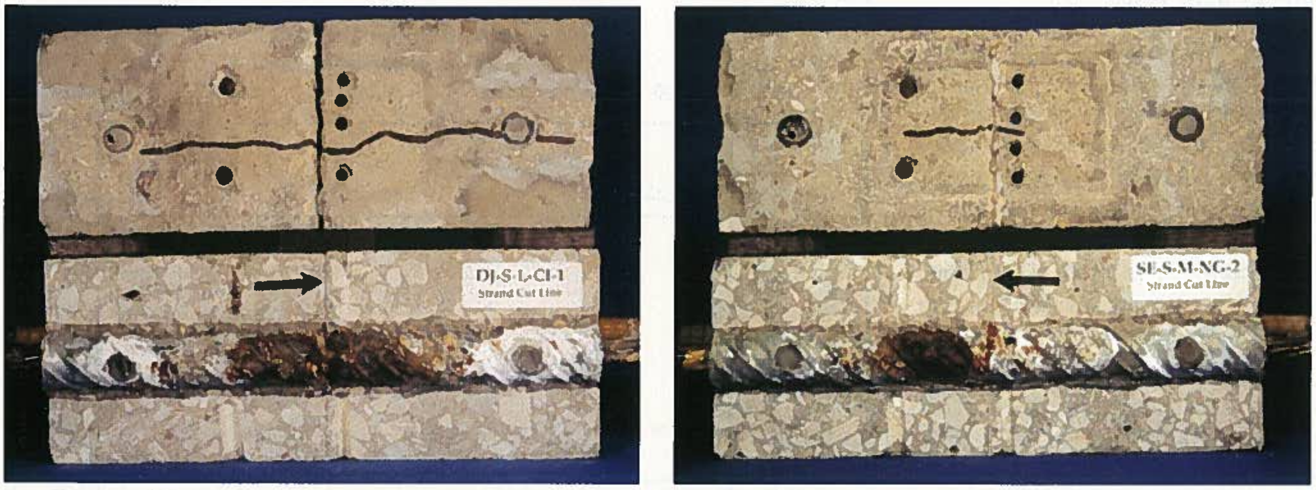
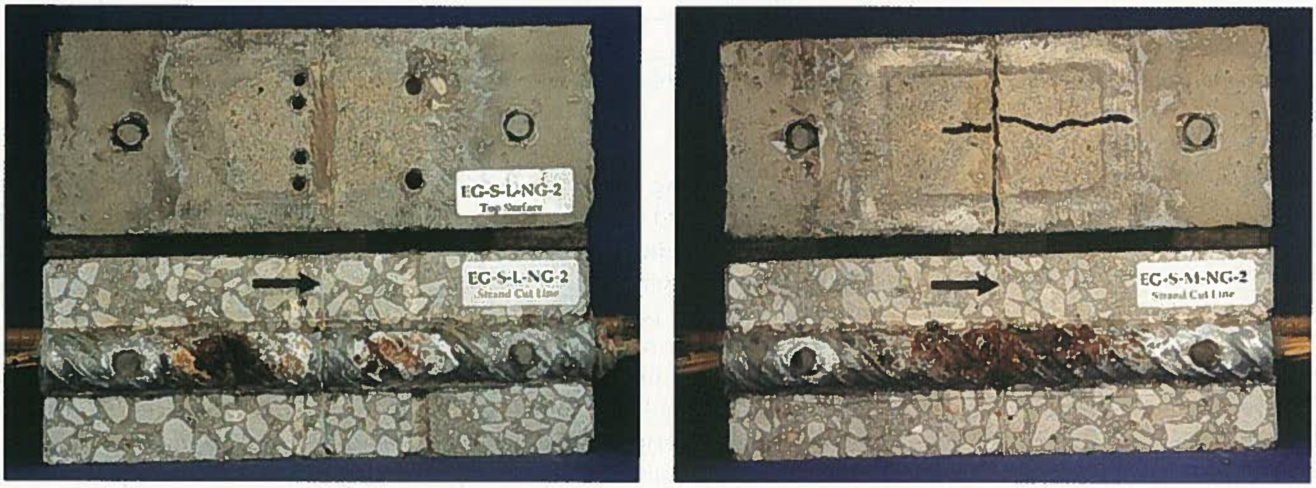


Fig. 15. Measured chloride contents in post-tensioning grout.



Dry joint

Epoxy joint



Sound epoxy/gasket joint

Poor epoxy/gasket joint

Fig. 16. Galvanized steel duct corrosion: effect of joint type.

found in the dry joint specimens was worse than in the epoxy joint specimens, as illustrated previously in Fig. 9. Light to moderate surface corrosion was found on the strand in all of the dry joint specimens where galvanized steel ducts were used. In the standard epoxy and epoxy/gasket joints, corrosion ratings for most specimens were very low (less than 10) and were attributed to patches of discoloration or very light strand corrosion.

Mild Steel Reinforcement Corrosion — Corrosion current data indicated that corrosion of mild steel reinforcement was occurring in seven dry joint specimens and one standard epoxy joint specimen. Destructive examination revealed reinforcing bar corrosion in all of the dry joint specimens, one small area of discoloration in two epoxy joint specimens and light corrosion in two epoxy joint specimens.

Two-thirds of the epoxy joint specimens had no discoloration or corrosion of the mild steel bars. The highest mild steel corrosion rating for epoxy joint specimens occurred in Specimen SE-S-M-NG-2 [epoxy joint, steel duct, 50 psi (345 kPa) precompression, normal grout]. This was the only epoxy joint specimen where corrosion currents indicated activity during exposure testing. As discussed previously, the measured chloride profile for this specimen (see Fig. 14) strongly suggests that elevated chloride levels at the bottom of the specimen resulted from an external source of moisture and chlorides rather than from penetration at the epoxy joint or through the concrete.

Chloride Penetration — Chloride penetration was higher for dry joint specimens in all cases, as illustrated previously in Figs. 12 and 13. Chloride profiles in the epoxy joint specimens suggested no influence from the joint.

Chloride analysis performed on samples from the grout showed very high chloride contents for dry joint specimens, even at distances of 2 in. (51 mm) from the joint. Grout chloride contents in the epoxy joint specimens were very low or negligible.

The measured chloride profiles for the dry joint specimens illustrate an increased potential for corrosion of the mild steel reinforcement within the segment. Although dry joints are not permitted with internal tendons, dry joints are commonly used in precast segmental construction with external tendons. The chloride test data suggest

(a) Outside surface of duct (joint location at left end) (b) Inside surface of duct (joint location at left end)

Fig. 17. Severe duct corrosion damage.

that corrosion protection of mild steel reinforcement adjacent to the joint face should not be overlooked when dry joints are used.

Grouting — Grout leaked into the joint region in five of the seven dry joint specimens. The extent of the leak ranged from very minor around the duct opening to almost 80 percent of the joint face covered with grout in one specimen. No grout leakage was found in the standard epoxy joint and epoxy/gasket joint specimens.

Effect of Duct Type

Duct Corrosion — Galvanized steel ducts were corroded in all cases, with an example of typical corrosion damage shown in Fig. 17. Duct corrosion led to concrete cracking along the line of the duct on the top surface of the specimen in eight of the fifteen specimens with galvanized steel ducts. No cracks were found in specimens with plastic ducts.

Galvanized steel ducts were perforated by corrosion action (corroded through) in nine of fifteen specimens, allowing direct ingress of moisture and chlorides. Plastic ducts were not affected by exposure testing, and remained intact as a barrier in the corrosion protection system.

The concrete cover in the macrocell corrosion specimens was lower than would be allowed by specification, and this contributed to the severe galvanized duct corrosion in a short period of time. However, the test results indicate the potential for corrosion problems when using galvanized ducts in aggressive exposures, and the relative performance of the galvanized and plastic ducts is not affected by the low cover.

Table 3. Effect of grout type – strand corrosion ratings.

Specimen	Grout type	Strand corrosion rating	Comments
DJ-S-L-NG-1	Normal grout	26	Light to moderate corrosion
DJ-S-M-NG-1	Normal grout	43	Light to moderate corrosion
DJ-S-L-CI-1	Corrosion inhibitor	114	Light to moderate corrosion with pitting on three wires

Prestressing Strand Corrosion — Little or no strand corrosion was found in dry joint and epoxy joint specimens with plastic ducts. Strand corrosion ratings for the four plastic duct specimens autopsied were all less than 10, and were attributed to discoloration found on the strands. Light to moderate surface corrosion and some pitting was found on the strands in galvanized steel duct specimens with dry joints.

Reversed Macrocell — Macrocell corrosion current data for the four dry joint specimens with plastic ducts indicated that the mild steel bars were corroding instead of the prestressing strand. Destructive examinations performed on two of the plastic duct specimens confirmed that the mild steel reinforcement was the primary corrosion site (anode). This data suggests that the plastic ducts provided improved corrosion protection for the prestressing strand in the dry joint specimens, and, as a result, the mild steel reinforcement became the preferential site for corrosion.

Effect of Joint Precompression

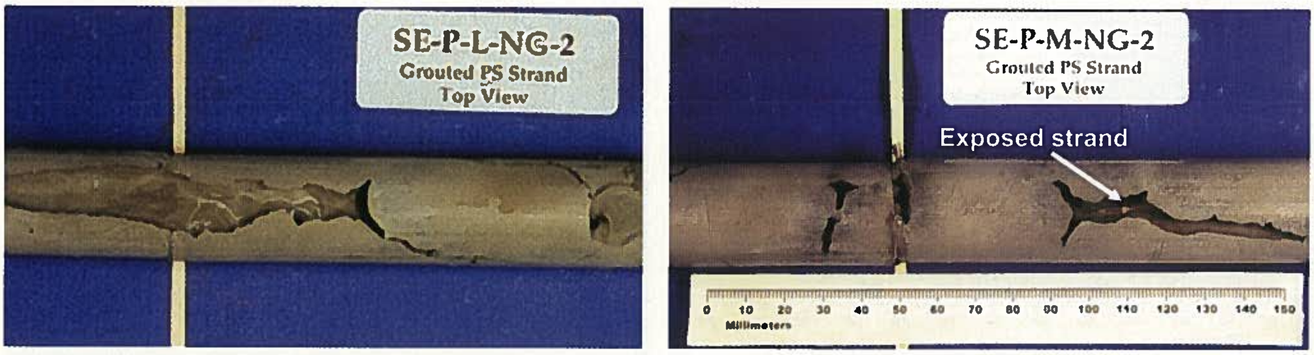
The three levels of joint precompression investigated show no clear, consistent trends in strand, duct or mild steel reinforcement corrosion.

Effect of Grout Type

Measured macrocell corrosion currents indicated that the prestressing strand was corroding in four specimens. Three of these four specimens were autopsied, with the observed strand corrosion ratings listed in Table 3. The most severe corrosion, including the only pitting corrosion, was found in the specimen with a corrosion inhibitor admixture in the grout. Based on this limited data, there does not appear to be any improvement in corrosion protection when a calcium nitrite corrosion inhibitor is used in cement grout.

The dosage of corrosion inhibitor used in this testing program was the same dosage normally used for concrete (approximately 4 gal. per cu yd of concrete or 20 Liters/m^3 of concrete). This dosage was based on the direct recommendations of the manufacturer's representative at the time of specimen construction.

The effectiveness of calcium nitrite



Void caused by entrapped air or incomplete filling

Void caused by lack of grout fluidity

Fig. 18. Typical grout voids.

corrosion inhibitor is related to the ratio of calcium nitrite solids to cement solids. Due to the higher cement content of grout in comparison to concrete, the dosage used in this testing program may be too low for the corrosion inhibitor to be effective. In spite of this, it is very concerning that calcium nitrite appears to have worsened corrosion in comparison to plain grout.

Other research has found calcium nitrite corrosion inhibitor to be detrimental to corrosion protection when used in cement grouts. Koester[14] performed anodic polarization tests on grouted prestressing strand to investigate the corrosion protection provided by various cement grouts.

In these tests, it was found that calcium nitrite significantly reduced the time to corrosion in comparison to plain grout, and had no effect on corrosion rate after the initiation of corrosion. The calcium nitrite dosage was adjusted to account for the higher cement content in grout for those tests. Calcium nitrite has shown good results when used in concrete.[5,11,15] However, further investigation may be warranted before calcium nitrite corrosion inhibitor should be used in cement grout.

The grout containing 13 percent silica fume was used only in specimens with a standard epoxy joint. Macrocell corrosion currents did not indicate an initiation of corrosion in these specimens. Destructive examination of Specimen SE-S-L-SF-2 [epoxy joint, steel duct, 5 psi (35 kPa) precompression, silica fume grout] found small areas of light corrosion on the prestressing strand and a total corrosion rating of 12. These data do not indicate a positive or negative effect of using silica fume in cement grout for the reported exposure period.

Grout Voids

Voids were found in the grout of all 19 specimens autopsied. In some cases, the shape and appearance of the voids suggested that the voids resulted from insufficient fluidity. In other cases, voids appear to have resulted from air pockets, bleed water collection, or as a result of incomplete filling of the duct during grouting. In most cases, observed voids were small or shallow. However, in several cases, voids were extensive and deep and the prestressing strand was exposed. Examples of typical voids are shown in Fig. 18.

Normally, a grout void that does not expose the prestressing tendon would not be deemed a concern. However, during the destructive examination it was discovered that five specimens had holes corroded through the galvanized steel duct at the location of a void. In two of these specimens, large holes in the duct corresponded directly to the voids in shape and size, as shown in Fig. 19.

These findings suggest that the presence of a void in the grout may lead to more severe corrosion of the galvanized steel duct. The duct is intended to provide corrosion protection for the tendon, and thus holes in the duct will effectively eliminate the duct as a protective barrier for the tendon.

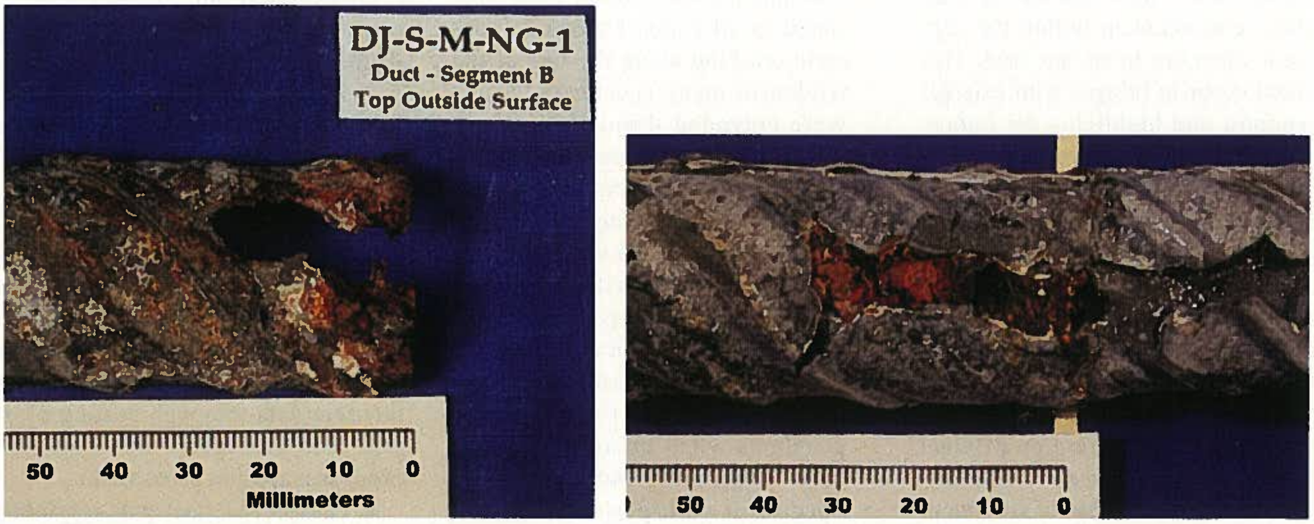
The importance of grouting to overall corrosion protection of the post-tensioning system often receives comparatively little attention during the design, construction and inspection of post-tensioned structures. Grout voids and poor grout quality are frequently significant factors in tendon corrosion problems, as evidenced recently by some high-profile post-tensioning problems in prestressed concrete bridges in Florida.

The findings of this research program illustrated that even under "laboratory conditions," grout voids may be encountered if proper materials and procedures are not followed. Recently published guide specifications for grouting of post-tensioned structures[16] and new research efforts[17,18] should help to mitigate grouting problems.

Mechanism for Reversed Corrosion Macrocell

The polarity of the macrocell corrosion current data indicates that eight of the 12 specimens with corrosion activity have developed reversed corrosion macrocells where the mild steel reinforcing bars are corroding (anodic reaction) instead of the prestressing strand. The development of a reversed macrocell in typical macrocell specimens is not common, and may be attributed to the transverse segmental joint. The use of a dry joint is particularly severe, as indicated by the experimental data.

A possible mechanism for reversed macrocell corrosion is shown in Fig. 20. The dry joint allows rapid penetra-



Corroded duct with large hole corresponding to grout void

Grout surface with large void – Note corrosion product accumulated in void

Fig. 19. Hole in duct corresponding to grout void.

tion of chlorides to the bottom layer of steel. The small end cover for the bottom bars [0.25 in. (6 mm)] provides little protection from lateral migration of the chlorides, and the steel becomes quickly depassivated. It is assumed that the prestressing steel benefits from the additional protection provided by the grout and duct, and the corrosion macrocell develops.

It is likely that the added protection for the prestressing tendon is primarily due to the extra thickness of the grout over the strand in comparison to the end cover for the bars. Although the duct is discontinuous at the joint, it may also contribute to corrosion protection.

The occurrence of a reversed macrocell was confirmed by destructive examination. Corrosion of the mild steel reinforcement was found in each of the five autopsied specimens that had shown negative macrocell corrosion currents during exposure testing. Chloride profiles (where available) also indicated that chloride levels were in excess of the corrosion threshold at the level of the bars in these specimens.

SUMMARY OF TEST RESULTS

The majority of corrosion activity after $4^{1}/_{2}$ years of extreme, accelerated exposure testing has occurred in specimens with dry joints (11 of 12 specimens with corrosion). Exposure testing is continuing for 19 specimens (one of each specimen type). Continued exposure testing may provide additional results to assist comparison of variables, and may change the conclusions presented in this paper. The primary findings of the research program are listed below.

Overall Performance

- Overall performance of the segmental macrocell corrosion specimens in this program is very good, with only minor corrosion detected in a limited number of specimens.
- Metal loss calculations indicate that prestressing strand corrosion over the exposure duration is minor or negligible.
- Possible strength degradation in the form of pitting corrosion on prestressing strand was found in only one specimen.

Segmental Joints

- All significant corrosion occurred in specimens with dry joints. Seventy-eight percent (11 of 14) dry joint specimens displayed corrosion activity. Specimens with dry joints showed increased chloride penetration and increased corrosion of galvanized steel duct, prestressing strand and mild steel reinforcement.
- The mild steel reinforcement is corroding instead of the prestressing strand in seven of the 11 dry joint specimens with corrosion activity. This occurrence is attributed to penetration of chlorides at the dry segmental joint and indicates a possible

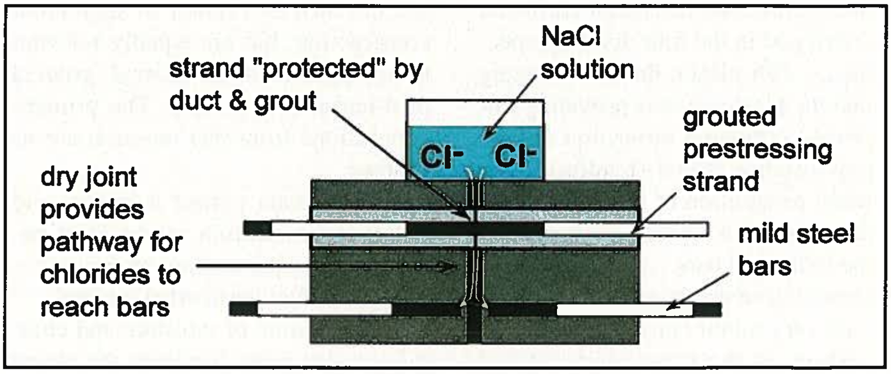


Fig. 20. Probable mechanism for "reversed" macrocell corrosion.

increased corrosion threat for mild steel reinforcement within the segment when dry joints are used. This could occur in bridges with external tendons, and highlights the importance of clear cover over the ends of longitudinal bars in the segments.

- One out of 24 specimens with epoxy joints has shown corrosion activity. Autopsy of this specimen confirmed that the mild steel reinforcement was corroding rather than the prestressing strand. Measured chloride profiles for this specimen suggest that corrosion resulted from an external source of moisture and chlorides (leakage of dam on top of specimen) rather than from penetration at the epoxy joint or through the concrete.
- Corrosion of the galvanized steel duct was reduced in extent and severity in specimens with epoxy joints. Only very minor prestressing strand corrosion was found in specimens with epoxy joints. The experimental data indicate that thin epoxy joints provide substantially improved corrosion protection for internal tendons in segmental construction.
- The use of gaskets in epoxy joints may interfere with epoxy coverage on the joint. Autopsied epoxy/gasket joint specimens revealed incomplete epoxy coverage near the duct openings, leading to increased chloride penetration and duct corrosion. The observed deficiencies occurred in carefully controlled laboratory conditions, and could possibly be worse under field conditions.

Ducts for Internal Post-Tensioning

- Strand corrosion was not detected during exposure testing in any epoxy joint specimens with plastic ducts. Reversed macrocell corrosion developed in the four dry joint specimens with plastic ducts, indicating that the plastic duct is providing improved corrosion protection for the prestressing strand (tendon), even when penetration of chlorides at the dry joints has caused corrosion of the mild steel bars.
- Destructive examination revealed only very minor corrosion or discoloration on the prestressing strand from specimens with plastic ducts.
- Galvanized steel ducts were corroded in all cases, leading to concrete cracking along the line of the tendon in many specimens. Ducts were corroded through in nearly two-thirds of the specimens, eliminating the duct as corrosion protection for the prestressing tendon. The concrete cover in the test specimens was lower than specification, contributing to the poor performance of the galvanized duct in a short period of time. However, test results indicate the potential for durability problems when using galvanized ducts in aggressive exposures.
- Specimens with plastic ducts and epoxy joints had the best overall performance in the testing program in terms of strand, mild steel and duct corrosion.

Joint Precompression

- The range of joint precompression investigated did not affect the time to corrosion or corrosion severity.

Grouts for Bonded Post-Tensioning

- The most severe corrosion of the prestressing tendon was found where a calcium nitrite corrosion inhibitor was used in the grout.
- Two specimens with silica fume in the grout (and epoxy joints) did not show corrosion activity.

CONCLUSIONS

After $4^1/_2$ years of severe exposure testing and destructive examination of one-half of the test specimens, a number of significant conclusions can be drawn. While the focus of this research was on precast segmental construction, several of the conclusions are not strictly related to segmental construction, but are equally relevant to all applications of internal, grouted post-tensioning tendons. The primary conclusions from this research are as follows:

1. Dry joints permit moisture and chloride penetration at the joint between segments, compromising corrosion protection for internal tendons.

2. Penetration of moisture and chlorides at dry joints increases the extent and severity of corrosion of mild steel reinforcement and galvanized steel post-tensioning ducts within the segment.

3. Properly constructed thin epoxy joints prevent chloride penetration at the segmental joint.

4. Thin epoxy joints substantially improved corrosion protection for internal prestressing tendons, and for galvanized steel ducts and mild steel reinforcement within the segments.

5. The use of a gasket around the duct opening in a thin epoxy joint may interfere with thorough coating of the joint face with epoxy, and could compromise corrosion protection.

6. Galvanized steel post-tensioning ducts provide only limited corrosion protection for internal tendons, and may corrode through in severe exposure conditions or when low concrete cover has been provided.

7. Plastic ducts provide a significant improvement in corrosion protection, limiting prestressing tendon corrosion to negligible levels and eliminating concrete cracking due to duct corrosion.

8. Joint precompression up to $3\sqrt{f_c'}$ psi ($7.88\sqrt{f_c'}$ kPa) does not appear to influence corrosion activity.

9. Test results suggest that the use of a calcium nitrite corrosion inhibitor should be carefully investigated prior to use in cement grouts.

10. The presence of grout voids may increase the extent and severity of both tendon and duct corrosion.

RECOMMENDATIONS

Based on the results of this laboratory research program, the following recommendations are made regarding corrosion protection for internal post-tensioning tendons in precast segmental bridges. Similar to the research conclusions, some of the recommendations are not specific to segmental construction, but are applicable to all forms of internal, grouted post-tensioning tendons.

1. Match-cast dry joints should not be used with internal tendons in any environment where exposure to chlorides may occur, including applications where chloride-bearing deicing chemicals are used and marine (saltwater) environments.

2. Where dry joints are used with external tendons, the face of the segment should be considered as an exposed face. Accordingly, concrete cover for mild steel segment reinforcement adjacent to the joint face should meet the same cover requirements as required elsewhere in the structure to minimize corrosion due to penetration of moisture and chlorides at the dry joint.

3. Match-cast thin epoxy joints should be used in all applications where corrosion of the internal tendons is a concern.

4. Proper application of epoxy to the joint faces during the construction process is critical to corrosion protection at the joint. Thus, this step in the construction process must receive an appropriate level of attention from all construction and inspection personnel involved.

5. The use of gaskets around the duct opening in epoxy joints should be avoided. As an alternative, ducts should be swabbed immediately following segment placement and initial stressing to prevent epoxy from blocking the duct.

6. Plastic post-tensioning ducts should be used for all internal tendons in applications where corrosion is a concern, including marine exposures and environments where chloride-bearing deicing chemicals are used.

7. Proper grout materials and procedures should be utilized to minimize grout voids and improve corrosion protection. Significant advances in the state-of-the-practice for grouting have been made recently. Guide specifications are provided in Reference 16.

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