Final Report

Corrosion Evaluation of Post-Tensioned Tendons on the Mid Bay Bridge in Destin, Florida

Prepared for

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EXECUTIVE SUMMARY

An on-site inspection of corroded post-tension tendons and acquisition of samples from these tendons were performed upon the Mid Bay Bridge on January 4 and 5, 2001. The primary focus of the study was upon Tendon 2 of Span 40-A and Tendon 4 of Span 37-C, although other tendons were visually examined and subjected to some testing also. The inspection included and the subsequent analyses were based upon the following:

1. Visual inspection, photographic documentation, and condition assessment of polyethylene ducts, grout, and tendons,
2. Determination of electrical continuity between strands,
3. Half-cell potential measurements in sound areas of grout,
4. pH measurements on exposed grout,
5. Chloride analysis of grout samples, and
6. Petrographic analysis of grout samples.

The visual inspection revealed 1) corrosion of cables and individual wires thereof that ranged from minimal to severe, 2) presence of three broken wires, 3) evidence that duct grouting had not been performed according to specification such that a) a cavity at the anchorage end opposite to that of pumping and macroscopic grout voids often occurred and b) grout quality was locally poor and spatially variable, and 4) cracking of the polyethylene duct.

The half-cell potential measurements indicated that there was no ongoing corrosion of cable exteriors at the time of the inspection for the locations upon the two tendons in question where the duct was removed. This was attributed to the grout having been dry and the relative humidity low. Active corrosion, as evidenced by presence of partially liquid, acidic reaction products, was observed upon previously exposed anchorage faces and cable ends. This, as well as corrosion of the cables within the ducts, resulted from 1) accumulation of excessive bleed water during grouting, 2) a negative effect upon bleed water corrosivity of the Intraplast-N expansive grout admixture (1) that was employed during construction, 3) presence of bleed water residuals that were possibly hygroscopic, 4) presence of cavities, grout voids, and local regions of high water-to-cement ratio (w/c) grout within the ducts that subsequently carbonated such that pore water pH was reduced, and 5) periods of high relative humidity and of moisture condensation, the latter occurring during times of cool or cold weather when temperature drops below the dew point.

A mechanism for the duct cracking has been theorized. Left unaddressed, the cracks will eventually lead to enhanced corrosion because of facilitated moisture, oxygen, and chloride access to the prestressing steel.

Specific recommendations are made that include, 1) experimentation to confirm the deterioration mechanism and to better disclose the role of influential variables, 2) development of improved methods for non-destructive inspect and condition assessment of post-tension tendons, 3) “surgical” autopsy by corrosion professionals of subsequently disclosed distressed tendons, and 4) revision of construction and inspection specifications associated with post-tensioning tendons.

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INTRODUCTION

The Mid Bay Bridge (Bridge Number 570091) is a 141 span, 3.6 mile long structure that spans Choctawahatchee Bay and connects Destin and Niceville, Florida on SR 293. The bridge is approximately eight years old and consists of a two lane undivided highway with shoulders on both sides. Figure 1 shows a perspective view of the bridge

Figure 1. View of the Mid Bay Bridge, Destin, Florida.

The superstructure is comprised of segmental precast concrete box girders that are held together by six post-tensioning tendons (three on each side) that span eight to nine segments and terminate at a metal trumpet type anchorage assembly that is cast into a bulkhead at each end. Figure 2 shows a photograph of the interior of a box girder, the six tendons, and the anchorage bulkheads. Each tendon is comprised of nineteen spirally wound 5/8 inch diameter seven wire strands within a grouted four inch diameter polyethylene duct. The tendons are inclined downward from one anchorage, pass through a deviation block mounted on the girder deck, proceed horizontally to a second deviation block, and from there proceed along an incline to the other anchorage. The ends of the anchorage assemblies are protected by cast-in-place grout (pour backs) that is coated on the exterior with a coal tar-epoxy mastic. Figure 3 shows an example of this.

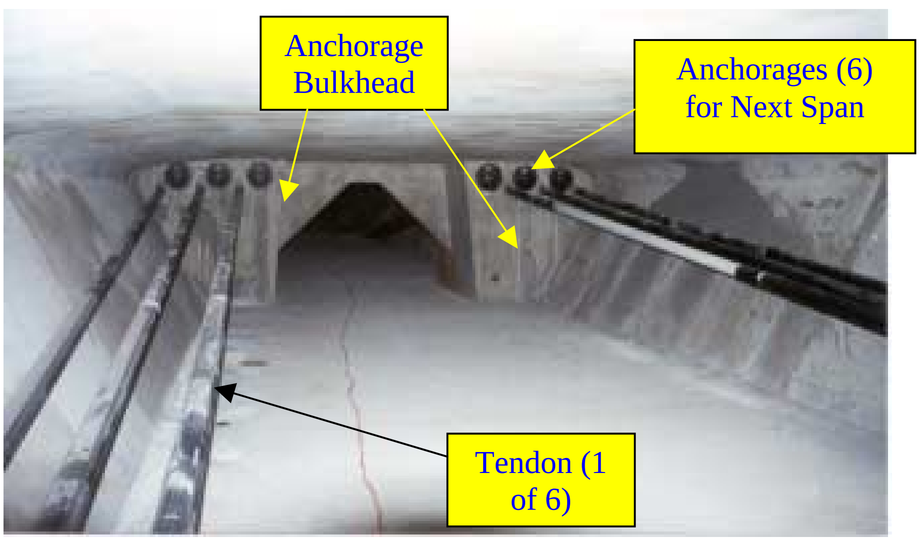

Figure 2. Typical view of the anchorage and the tendons.

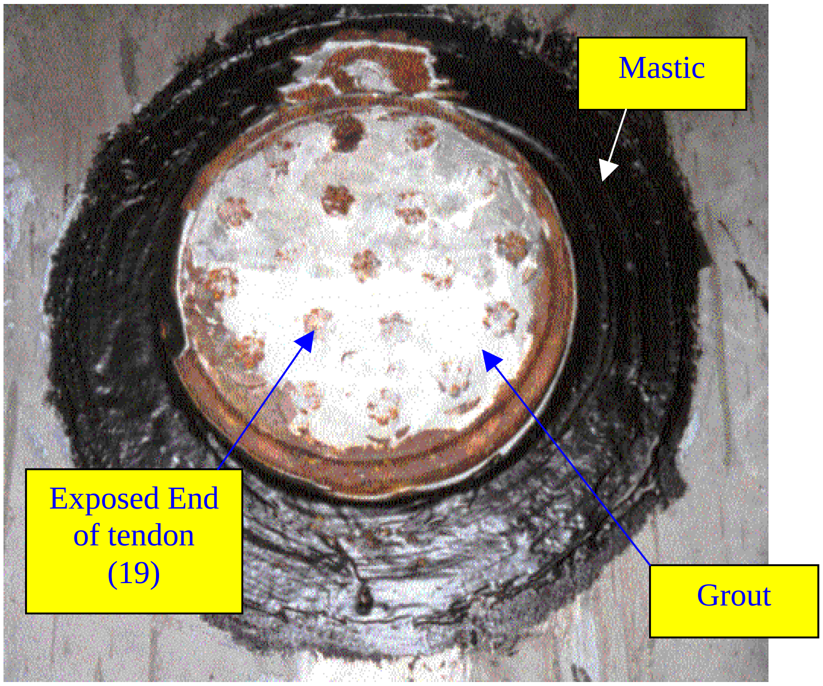

Figure 3. A typical end anchorage assembly.

BACKGROUND

General

Recently, as many as 11 tendons on the Mid Bay Bridge were replaced because of corrosion. Two other tendons were also found to exhibit corrosion, but the severity of damage upon these was not thought to warrant replacement. Additionally, many other tendons exhibit cracking of the polyethylene duct. It can only be concluded that corrosion is likely to be occurring on, not only these tendons, but possibly others as well. Left unchecked, such corrosion will reduce the cross section of individual wires in the strands and eventually result in strand fracture and tendon failure. As a consequence of these concerns, Florida Department of Transportation (FDOT) inspectors performed extensive inspection of all tendons on the bridge. The results of this and of repairs that have been performed have been reported elsewhere (2). The FDOT contracted with Florida Atlantic University (FAU) to determine 1) the specific factors that contributed to corrosion of these tendons, 2) any future monitoring needs, 3) the need for any corrosion related repairs, and 4) recommendations for further testing (if necessary). In turn, FAU retained Siva Corrosion Services, Inc. (SCS) as a consultant to assist in this evaluation.

Scope of Work

The project team was charged with evaluating tendons in Spans 37 and 40 to determine the cause(s) of the corrosion. The work performed in the field included the following:

1. Comprehensive inspection and photographic documentation of the damaged and undamaged strands.

2. General characterization of the strands.

3. Acquisition of tendon and grout samples, to the extent these are available, for further evaluation,.

4. Performance of corrosion related measurements as required.

5. Chloride analyses of selected grout samples.

The field inspection, sample acquisition, and on-site analysis were performed on January 4 and 5, 2001. Analysis of data and samples took place during January-March, 2001.

FIELD INSPECTION

Visual Observations

General. The polyethylene (PE) duct of certain sections of Tendons 1-3 of Span 40-A and Tendons 4-6 of Span 37-C was opened for visual examination and sample collection. Observations that were made upon these tendons as well as others in this general part of the bridge are described below.

Polyethylene Duct. The PE ducts exhibited cracks at multiple locations along many of the tendons. An example of this is shown in Figure 4. Most of the cracks were along the inclined length between the anchorages and deviation blocks as opposed to the horizontal sections. Also, the cracks were concentrated in the top half of the duct circumference, particularly between 2 and 10 o'clock (12 o'clock was designated as the top of the duct). A general correspondence was found between occurrence of duct cracks and presence of an underlying grout void(s), meaning that the latter was also concentrated in the upper portion of the duct. These voids often extended along the tendon length and, in such cases, are termed void channels. The cause and significance of these elongated voids are discussed subsequently. The duct cracking is thought to have resulted from a combination of 1) the duct not meeting the construction specifications (2) and 2) circumferential tensile stresses that developed subsequent to setting of the grout during times of low temperature

Figure 4. Typical cracking of the PE duct.

when the duct contracted about the grout combined with bending stresses that resulted from the presence of the grout voids. Appendix A provides a detailed proposed mechanism that explains the observed grout void-duct cracking correlation. At the same time, FDOT personnel have reported that HDPE cracks on the Mid Bay Bridge do not necessarily correlate with grout voids. On this basis, voids are not necessarily a requisite for duct cracking.

Grout. The grout was represented as being based upon Type I cement with an upper w/c limit of 0.45 and Sika Intraplast-N expansive admixture. Cover around the tendons was non-uniform and varied typically from 0 to in excess of 1.5." Rust stains were observed on strands with no grout cover, although at least some of this corrosion was stated to have occurred subsequent to removal of the duct. The spatial location of such exposed strands was primarily between 8 and 4 o'clock . Glassy aluminum powder particles, a component of the expansive admixture, were observed on the surface of the grout. Small (one mm and smaller), extensive, non-uniformly distributed voids that were probably generated by the expansive admixture were apparent. Macroscopic voids were also apparent in many areas, as noted above. Periodic circumferential hairline shrinkage cracks were apparent in the grout along the entire length of tendons.

The grout was dry, and no moisture trace was apparent at any locations where the polyethylene duct was removed. A white powdery deposit was observed all along a void channel on the portion of Tendon 2, Span 40-A that had been opened. Figure 5 shows a photograph of this.

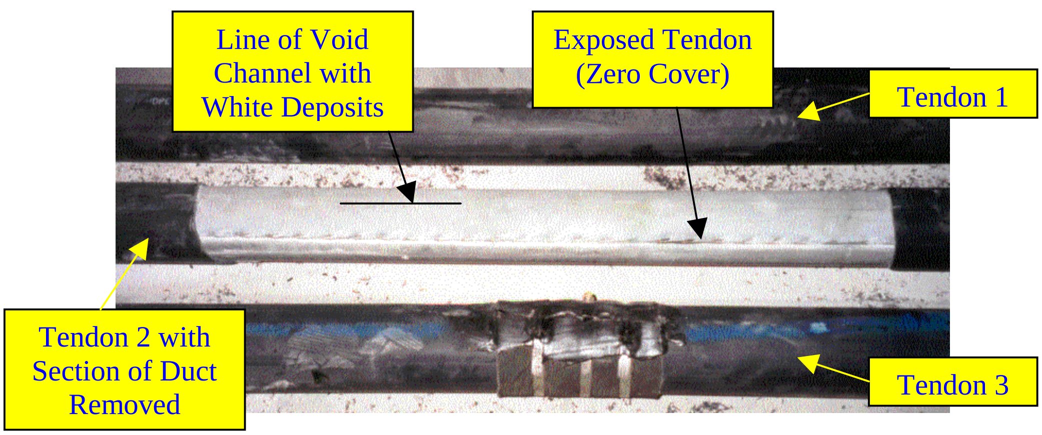

Figure 5. Void channel with exposed tendon as seen after removing the PE duct.

The quantity of white powdery deposit was directly proportional to the size (cross section) of the void channel. These channels and the corresponding white powdery deposit were mostly observed in the top half of the tendon but were also found in some cases to extend along the underside of individual cables or several closely grouped cables. The grout in the lower half of the tendon was typically dark gray, well consolidated, and showed no signs of segregation. The one observed exception was an eight foot long section of Tendon 2, span 40-A near the south end where the grout around the entire tendon was white chalky material. Figure 3 showed an example of this white grout as viewed on the anchorage end where light colored material is seen at the bottom and the dark at the top. Apparently, excessive bleed water collected here in conjunction with grout subsidence along the tendon. This, possibly in conjunction with eventual evaporation or reabsorption of bleed water into the grout, resulted in a cavity at the exit end. The pour backs were subsequently re-packed with a different grout material prior to the back face of the anchor plate being sealed (based on Bore Scope data (2)).

Tendons. Tendon sections for which portions of the duct had been removed, either previously in conjunction with the FDOT investigation or during this inspection, were examined for corrosion related damage. In this regard, Figure 6 shows a general photograph of corrosion along Tendon 4, Span 37-C. Likewise, Figure 7 provides a close-up view of Tendon 2, 40-A where wire pitting corrosion over a relatively broad length and one broken wire on each of three different strands were apparent. Two of the fractured wires exhibited corrosion damage but the third did not. The wire with no corrosion exhibited a well-defined cross section reduction (necking) as is indicative of ductile fracture. Corrosion deposits with small pits were observed on adjacent strands in localized areas. Failure of individual wires was primarily due to corrosion and a subsequent elevated tensile stress that resulted from the reduced cross section.

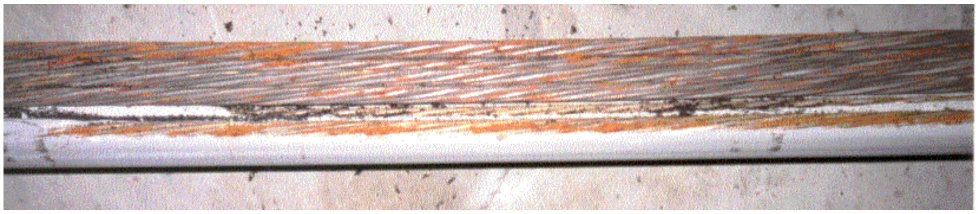

Figure 6. Typical corrosion observed on tendon 4 in Span 37-C.

Figure 7. Broken wire in one of the strands of Tendon #2 of Span 40-A.

Visual inspection of the tendon ends that extended beyond the back face of several anchorages for which the mastic and grout had been removed several months earlier revealed wet, acidic corrosion products, indicating that active corrosion was ongoing. It was represented that most of this corrosion had developed subsequent to these being exposed. Figure 8 shows a photograph of three tendon ends with corrosion products emanating from the wire intersticies. Note for the center tendon end, which is the only one in focus, that the cut end of the three upper wires is clean, but the ends of the lower wires are covered with corrosion products. The liquid nature of these corrosion products is an indicator that they are acidic, as determined by extensive past observations and experience of the investigators in similar and related situations. Dried corrosion products of this same type are apparent also as spherical rust particles along the base of the bottom cable wire in Figure 7. The possible significance of these observations is discussed subsequently.

Figure 8. Photograph of the exposed end of a tendon anchorage.

Corrosion Evaluation in the Field

General. Corrosion of steel (both regular and prestressing) embedded in cementiteous materials such as grout does not usually occur due to the high alkalinity of the pore water which promotes formation of a passive film upon the steel surface. This passive film is compromised, however, if the grout pH at the steel interface falls below about 10 or the chloride concentration rises above a threshold level (or a combination of the two). The predominant factor that causes a pH decrease is carbonation whereby atmospheric carbon dioxide reacts with cement alkali to yield carbonates. Carbonation generally progresses at a rate that is inversely proportional to quality of the grout (high grout quality – low carbonation rate), as defined predominantly by water-to-cement ratio (w/c). The time duration prior to passivity being compromised also increases with increasing grout cover. Once passivity is lost, active corrosion commences provided adequate moisture and oxygen are present. Passivity is not expected where steel is exposed at grout voids; and so corrosion can be ongoing here also in the presence of moisture and oxygen, irrespective of grout pH and chloride concentration (3).

Half-Cell Potential Tests. Active corrosion of atmospherically exposed steel in a cementiteous material is generally considered to be ongoing if potential is –350 mV versus a copper-copper sulfate electrode (CSE) or more negative. As a preliminary step to performing potential measurements upon grout embedded strands, the extent of electrical continuity between strands in Tendon 2 of span 40-A and Tendon 4 of span 37-C was determined at the anchors. All strands were found to be electrically continuous. Half-cell potential testing was performed on the two tendons just beyond the concrete anchorage blocks per ASTM C876-91 by making a direct metallic connection to a cable and placing a CSE upon the grout. The results of the readings that were acquired are presented in Tables 1 and 2. The half-cell potentials were more positive than –200mV CSE in all cases, indicating that active corrosion was not ongoing for the grout covered steel in the vicinity of the electrode position at the time of the measurements. This conclusion does not pertain to the void areas, however. Also, measurements were not

Table 1. Half-cell potential readings from Tendon 2, Span 40-A.

Location	Potential, mV vs CSE	Position of Half-cell	Comments
1	-44	top	Measurement location was along a ten foot span at the south end of the tendon. This area incorporated the broken wires, but no measurements were made in this immediate vicinity because of a lack of grout.
2	-48	top	
3	-55	top	
4	-107	top	
5	-92	top	
6	-132	top	
7	-132	top	
8	-62	top	
9	-72	top	
10	-76	top	
11	-96	bottom	Below broken wire.
12	-60	bottom	2' to the left of break.
13	-88	bottom	2' to the right of break.
14	-130	top	South incline within about five feet of the deviation block.
15	-129	top	
16	-131	top	
17	-127	top	
18	-127	top	
19	-126	top	
20	-139	top	Horizontal section between the two deviation blocks.
21	-140	top	
22	-141	top	
23	-140	top	
24	-140	top	

Table 2. Half-cell potential readings from Tendon 4, Span 37-C.

Location	Potential, mV vs CSE	Position of Half-cell*
1	-81	top
2	-32	top
3	-49	top
4	-50	top
5	-39	top
6	-48	top
7	-32	top
8	-52	top
9	-39	top
10	-51	top
11	-62	bottom
12	-40	bottom
13	-22	bottom
14	-22	bottom
15	-11	bottom
16	-24	bottom
17	-56	bottom
18	-10	bottom

- Measurements made along a 16 foot span midway along the north incline.

feasible at the location of the corroded, fractured wires of Tendon 2, Span 40-A because of an absence of grout here. In all probability, the apparent absence of potential measurements indicative of corrosion for steel in contact with carbonated grout was a consequence of the grout being relatively dry. There was no indication of any leaking joint(s) in the vicinity of where these measurements were made, and the strands were dry at the time of this inspection. The nature of the corrosion products on individual wires was consistent with these being previously moist (see above), perhaps during periods when temperature fell below the dew point.

While active corrosion was ongoing upon the outer anchorage faces and upon contiguous strand ends that had been exposed several months earlier (see Figure 8), such corrosion was not active at the time of this inspection upon strands, even previously corroded ones, that were exposed by removal of the duct and, in some cases, grout. This difference is attributed to a greater concentration of hygroscopic material within the cable intersticies than upon the exterior wire surfaces. It must be expected that corrosion of the strands per se within grout voids or where grout has carbonated will reinitiate during periods of high humidity and, particularly, during times of moisture condensation.

pH Measurements

pH measurements for grout samples were performed in the field using a Germann, Co. spray indicator that provides a progressive color change over a relatively broad pH range from acid to base. The accuracy of this method is approximately plus/minus one pH unit. The determinations were performed on both previously exposed and freshly exposed grout surfaces. The former were represented as having been exposed in October, 2000 or before (2). Measurements performed upon these were designated as "prior." Afterwards, the same areas were abraded with a wire brush such that fresh grout was exposed. The surface was then blown clean of all powdery material, and the pH of the freshly exposed surface was measured. These measurements were recorded as "after." Table 3 summarizes these pH results.

Table 3. Summary of field pH measurements.

Span	Tendon	Area	Position	pH		Depth for Alkalinity Loss, inches	Comment
				before*	after**		
40-A	1	1	top	12 +/- 1	12 +/- 1	< 1/64"	Note 1
40-A	2	1	top	8 +/- 1	12 +/- 1	1/4"	Note 2
40-A	3	1	top	11 +/- 1	12 +/- 1	< 1/64"	Note 3
40-A	2	1	bottom	8 +/- 1	8 +/- 1		Note 4
40-A	2	2	top	9 +/- 1	12 +/- 1		
40-A	2	3	top	10 +/- 1	12 +/- 1		
37-C	4	1	top	8 +/- 1	12 +/- 1	1/4"	Note 5
37-C	5	1	top	12 +/- 1	12 +/- 1	< 1/64"	Note 6
37-C	6	1	top	12 +/- 1	12 +/- 1	< 1/64"	Note 7

Note	Comment
1	Trace void channel @ 12 o'clock (top). No white powder deposit. Void channel @ 6 o'clock 6 feet long. No white powdery deposit.
2	Void channel @ 12 o'clock, 15 feet long from the anchor. Three broken wires @ 9 o' clock - 4 feet from the anchor. Grout is white up to 8 feet from the anchor but changes to dark gray beyond.
3	Void channel @ 12 o'clock with trace white powdery deposit.
4	pH measured @ 6 o'clock (bottom). pH of 8 +/- 1 up to 8 feet from anchor but increases to 12 +/- 1 beyond. Grout color changes from white to dark gray.
5	Void channel with exposed strand @ 2 o'clock and 9 o'clock. Significant white powdery deposit @ 12 o'clock. Significant white powdery deposit @ 12 o'clock with void channel.
6	Void channel @ 12 o'clock with exposed strand. Trace white powdery deposit along void channel.
7	Void channel @ 9 o'clock with exposed strand. White powdery deposit @ 12 o'clock.

Tendon 2 in span 40-A and Tendon #4 in Span 37-C were exposed in October, 2000.
Tendons 1 & 3 in span 40-A and Tendons 5 & 6 of span 37-C were exposed on 1/4/2001.
* pH was measured on freshly exposed surface but before cleaning with a wire brush.
** pH was measured on freshly exposed surface but after cleaning with a wire brush.

The pH measurements upon the grout of Tendons 1 and 3 of Span 40-A indicated no loss of alkalinity except within a thin surface layer about 1/64” deep. The pH of the white powdery material at the top of Tendon #2, Area 1 was in the range of 8±1 prior to cleaning with a wire brush and was 12±1 after cleaning. In the corresponding bottom region, the grout was carbonated with a pH of 8±1 to a depth of about ¼”. It is within this latter region that the cable wires were broken. The pH was 12±1 once the grout transitioned to the dark gray region. Figure 9 shows a photograph of this.

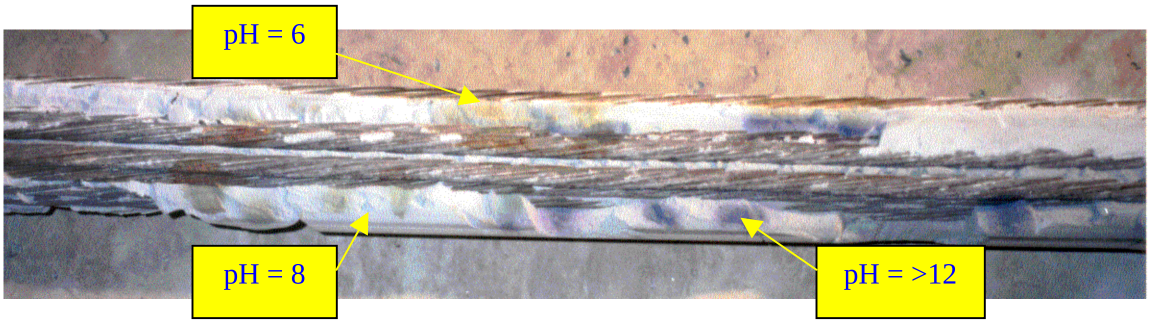

Figure 9. Variation of pH of the grout along Tendon #2 of Span 40-A as revealed by application of a visual indicator.

For Span 37-C, the pH measurements upon the grout of Tendons 5 and 6 indicate no loss of alkalinity except for a relatively thin layer about 1/64” deep at the upper surface. However, the grout around Tendon 4 was carbonated to a depth of about ¼”. Figure 10 schematically illustrates the general overall alkalinity profile.

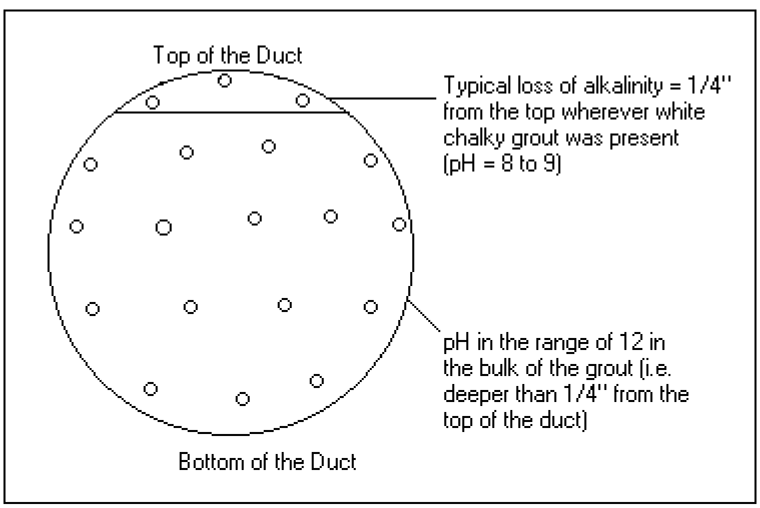

Figure 10: General distribution of grout pH as measured in the field. (Note: Cable end positions are not exact.)

Samples Acquired in the Field

General. Grout samples of varying size were obtained for chloride and petrographic analyses from Tendons 1-3 of Span 40-A and Tendons 4-6 of Span 37-C. The samples were stored in sealed zip lock bags to prevent contamination and further exposure to the atmosphere.

Chloride Analyses. The maximum allowable chloride concentration for prestressed concrete structures is 0.08% (acid soluble) by mass of cement (ACI 222R-89, page 222R-13). The equivalent chloride concentration based on 2115 lbs of cement per cubic yard of grout is 1.7 pounds per cubic yard. However, while this value applies for fresh grout that is fully alkaline, the chloride threshold becomes progressively lower with decreasing pH (carbonated concrete). Once the grout pH drops to a value where the steel is no longer passive, then in the presence of oxygen and moisture active corrosion occurs irrespective of chloride concentration (3).

Select grout samples were sent to the FDOT Corrosion Laboratory in Gainesville for acid soluble chloride analysis. Table 4 presents the results of these. While the rate of corrosion is generally enhanced by the presence of chlorides, due to the tendency of this species to depassivate steel and their hygroscopic nature which lowers grout resistivity, the measured chloride concentrations are sufficiently low that this species is not thought to have played a significant role in the tendon deterioration.

Table 4. Listing of chloride analysis results for grout samples.

Sample Number	Span	Tendon Number	Location of Sample	Chloride* lb/yd^3
1	Span 40-A	1	top	0.192
2	Span 40-A	1	bottom	0.164
3	Span 40-A	2	top	0.259
4	Span 40-A	2	bottom	0.180
5	Span 40-A	3	top	0.194
6	Span 40-A	3	bottom	0.150
7	Span 37-C	1	top	0.202
8	Span 37-C	1	bottom	0.170
9	Span 37-C	2	top	0.158
10	Span 37-C	2	bottom	0.158
11	Span 37-C	3	top	0.151
12	Span 37-C	3	bottom	0.137

*Unit weight used = 2550 lb/yd^3

Petrographic Analyses. Grout samples were acquired from four different locations, as listed below, and sent to Lankard Materials Laboratory for petrographic evaluation:

1. Span 40-A, tendon #2, top,
2. Span 40-A, tendon #2, bottom,
3. Span 37-C, tendon #4, top, and
4 Span 37-C, tendon #6, top.

Such analysis provides information regarding 1) grout unit weight, 2) degree of cement hydration, 3) w/c ratio, 4) grout pH and the extent of carbonation, 5) void density, distribution, and interconnectivity, and 6) nature of the "white" versus "gray" grout. This, in turn, facilitated determination as to what role the grout played in the tendon corrosion and duct cracking. The complete petrographic report is attached as Appendix B. Specific findings are summarized below.

1. The color difference between the white and dark gray grout material was a consequence of a) variations in the w/c of the grout and b) the degree of hydration of the Portland cement. The associated stratification of the cement paste phase resulted from bleeding which was promoted by high w/c, prolonged initial set, and single-end injection resulting in long pumping lengths.

2. The w/c of the hardened grout (away from the duct surface) was in the range 0.42-0.50. The highest w/c was within a 1/8 inch layer at the outer grout surface and was estimated as 1.0 or greater. This material is highly porous, very soft, and weak (it should exhibit a low compressive strength, if this could be measured, due to relatively high porosity). Within 1/8" to 3/8" from the duct, the w/c was estimated as being between 0.6 and 0.7. Figure 11 summarized this schematically.

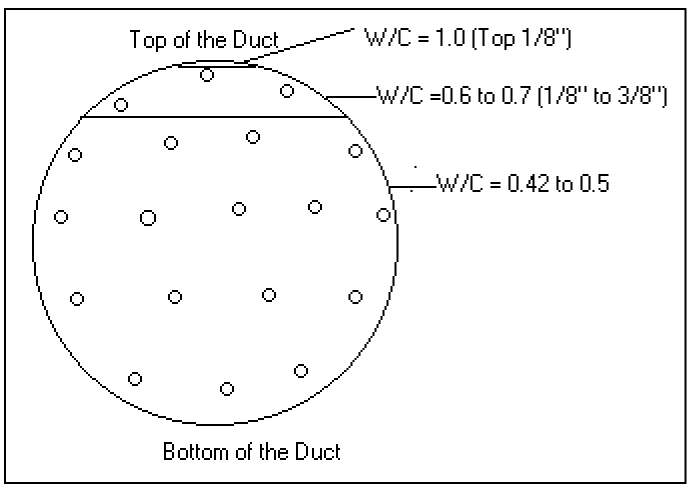

Figure 11: Schematic illustration of the w/c distribution based on petrographic analysis. (Note: Cable end positions are not exact.)

3. The average air void content of the grout is about ten percent. However, there are small regions without voids and others where voids are interconnected and have clustered to form a frothy condition where the total content may be 20 to 40 percent.

4. There is evidence that the grout mix design was such that its open time; that is, the time during which it remained fluid, was abnormally long. This resulted in 1) segregation/sedimentation of solid phases, 2) stratified zones, 3) large variations

in water-cement ratio, 4) non-uniform void distribution, and 5) void coalescence, each of which negatively impacted quality. . Depending upon the factors listed above, hydration reactions occurred at different rates in different portions of the grout.

CONFORMANCE WITH CONSTRUCTION SPECIFICATIONS

The construction specifications for the Mid Bay Bridge read as follows (4):

> "Grouting shall start at the lowest injection with all the vent holes open. The pumping pressure through the pipe shall be maintained until grout is continuously wasted at the next vent hole and until no visible slugs or other evidence of water or air are ejected and the grout being ejected has the same consistency as the grout being injected."

While the specification language is vague with regard to defining vent hole particulars (number, location, and size, for examples), clearly it was intended that, 1) the duct terminations (trumpet ports and pour backs) were not to serve as the sole vent ports and 2) the trumpet vent ports were not to serve as the pumping port since these are located at the highest point in the post-tensioning system. Also, the in-place condition of the grout is indicative of the open time of the grout having been abnormally long. This resulted in excessive bleeding, segregation/sedimentation of solid phases, stratified zones, large variations in water-cement ratio, non-uniform void distribution, and void coalescence. Corrosion of the cables resulted as a direct consequence of this.

PROPOSED TENDON CORROSION MECHANISM

Based upon the observations described above and results of the various measurements that were made, the following mechanism is considered to have caused the tendon corrosion and fracture. Susceptibility of a particular tendon to deterioration by this cause should vary depending upon the extent to which deleterious conditions are present.

1. Placement of the grout was such that for some tendons a void was present within the anchorage trumpet region. This void resulted from some combination of incomplete pumping, cavitation followed by subsidence, and excessive bleed water accumulation in this region (2). Each of these was a consequence of improper, out-of-specification grout placement procedures, as described above. Macroscopic voids were also present in the grout. These were most prevalent at the far duct end (the end toward which grout was pumped), and their density tended to decrease with increasing distance therefrom. The voids were often elongated along the duct length and were concentrated at the top region of the duct and also beneath multiple cables that were in contact with one another.

2. In spite of the fact that fresh bleed water typically has a pH in the range 12-13, such solutions have been shown to be corrosive to prestressing steel (1,5). This

has been reported to be particularly the case when Intraplast-N is employed as an expansive admixture (1). Apparently, the bleed water carbonates; and once this transpires, corrosion results. A mechanism has been proposed as a part of this study whereby the expansive reaction generated by Interplast-N could lead to reduced pH irrespective of carbonation. This is attached here as Appendix C. It is concluded that corrosion must be anticipated wherever bleed water has collected. Likely locations for this include 1) steel exposed within any grout anchorage cavity, 2) steel exposed at grout voids, and 3) cable wire intersticies into which bleed water has migrated (1).

3. Once the bleed water is reabsorbed into the grout and drying occurs, the corrosion rate was reduced to a relatively low value. However, there are two concerns here. First, condensation has probably occurred periodically and must be anticipated in the future whenever temperature drops below the dew point since corrosion should reinitiate during such times. Second, the observation of acidic corrosion products upon the exposed cables (see Figures 7 and 8) suggests that the bleed water residuals are hygroscopic and corrosive such that greater attack than what would otherwise be anticipated may occur during periods of wetness (moisture condensation).

4. While the duct cracking is not thought be of concern in the short term, it does facilitate direct oxygen, moisture, and chloride access to the grout and to exposed steel. Left unaddressed, these cracks will eventually lead to enhanced corrosion of the cables according to the mechanism discussed in2) and 3) above. (Note: It is understood that FDOT has taken steps in the past to reseal the PE ducts at cracked locationsand plans to reseal any new cracks that occur.)

CONCLUSIONS

The following conclusions were reached based upon the field inspection and evaluations and laboratory analyses of grout samples that were acquired.

1. The grout per se generally conformed to what was specified; however, grout placement did not. As a direct consequence of this, the grout in many regions within the tendon ducts exhibited 1) a cavity in the anchorage/trumpet area at the opposite end from pumping, 2) excessive bleeding during pumping and setting, and 3) segregation/sedimentation of solid phases, stratified zones, large variations in water-cement ratio, non-uniform void distribution, and void coalescence. In sound regions, the grout has retained its alkalinity; but in others carbonation has occurred and pH is 8±1.

2. At locations of cavities and grout voids, cables and wires thereof commonly exhibit corrosion, the magnitude of which varies from minimal to severe. Three instances of wire fracture were noted in the case of Tendon 2 of Span 40-A. Half-cell potential data indicated no ongoing active corrosion of grout embedded steel

at the time of the time of the inspection for locations where measurements were made. This was probably a consequence of the grout having then been dry. Corrosion of the steel that is exposed at cavities and grout voids and that is embedded in carbonated grout must be anticipated during periods when a) relative humidity is high and b) condensation occurs. The latter (condensation) is likely to arise during periods when temperature drops below the dew point.

3. Corrosion of prestressing steel has been shown to occur where bleed water accumulates. Research has shown that Intraplast-N, which was apparently employed as an expansive admixture in the grout, results in a particularly corrosive bleed water (1). A mechanism whereby this admixture can promote reduced bleed water pH beyond what occurs in conjunction with carbonation has been proposed (Appendix C).

4. End anchorages that were exposed by others by removal of the mastic and packing grout in October, 2000 exhibited pronounced ongoing corrosion as indicated by the presence of rust-colored hygroscopic acidic corrosion products. In numerous instances, these products were emanating from the strand intersticies. Similar dried corrosion products were found within the tendons at locations where corrosion had occurred. This suggests that the bleed water residuals are hygroscopic and acidification of condensed moisture, both on the exterior surface of cable wires and within the intersticies. Exposure of the cables by removal of duct sections and, in some cases, underlying grout has not, however, significantly affected their corrosion state.

5. Cracking of the polyethylene ducts is extensive. This is apparently a consequence of hydrostatic tensile stresses that develop as the duct thermally contracts about the grout fill during times of cold weather and, in many cases, of bending stresses that develop in the duct at locations of voids. A mechanism for this has been proposed (Appendix A). The duct cracking has not been a primary cause of tendon corrosion problems; however, it does serve as a corrosion promoter by providing greater moisture, oxygen, and chloride access to the steel. Left unrepaired, the cracks will contribute in the long-term to further tendon corrosion.

RECOMMENDATIONS

The following recommendations are made for the purpose of 1) insuring safety of this and other comparably constructed bridges, and 2) further verifying and understanding the mechanisms whereby post-tension tendons have deteriorated and failed.

1. A series of experiments should be performed upon simulated post-tension tendons in an attempt to a) reproduce the deterioration that has transpired and b) confirm the proposed deterioration mechanisms.

2. Research efforts should continue with the objective of developing improved methods for disclosing post-tension tendon corrosion.

3. Experiments should be initiated within the bridge box girders whereby steel specimens with various surface preparations are exposed. The purpose of these would be to confirm corrosiveness of bleed water residuals that are thought to be present upon the cables and anchorage ends.

4. The next deteriorated post-tension tendon that is identified on either the Mid Bay or another bridge should be "surgically" autopsied under controlled conditions in the presence of corrosion professionals.

5. Construction standards and inspection methods relevant to post-tension tendons should be revised based upon the experience gained at the Mid Bay and other bridges.

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APPENDIX A

Proposed Duct Cracking Mechanism

PROPOSED MECHANISM OF HDPE CRACKING

Observations

Duct cracking has occurred predominantly between the 10 and 2 o'clock orientations, considering that 12 o'clock is the vertical. Also, the cracks are mostly confined to the inclined cable sections as opposed to the horizontal runs. Lastly, the cracks predominantly occur at the location of an elongated grout void or channel in the underlying mortar. As an example of this, Figure A1 shows a photograph that was taken looking down upon cable 2 of section 40-A from above. Here, the HDPE duct has been cut away on the right side of the cable, thereby revealing the grout and a void channel at the 12 o'clock orientation (the void is difficult to discern in the photograph but its side edges are indicated). Also apparent is that the top of a tendon is exposed near the base of the void. A duct crack that is aligned with the void is seen at the left of the photograph.

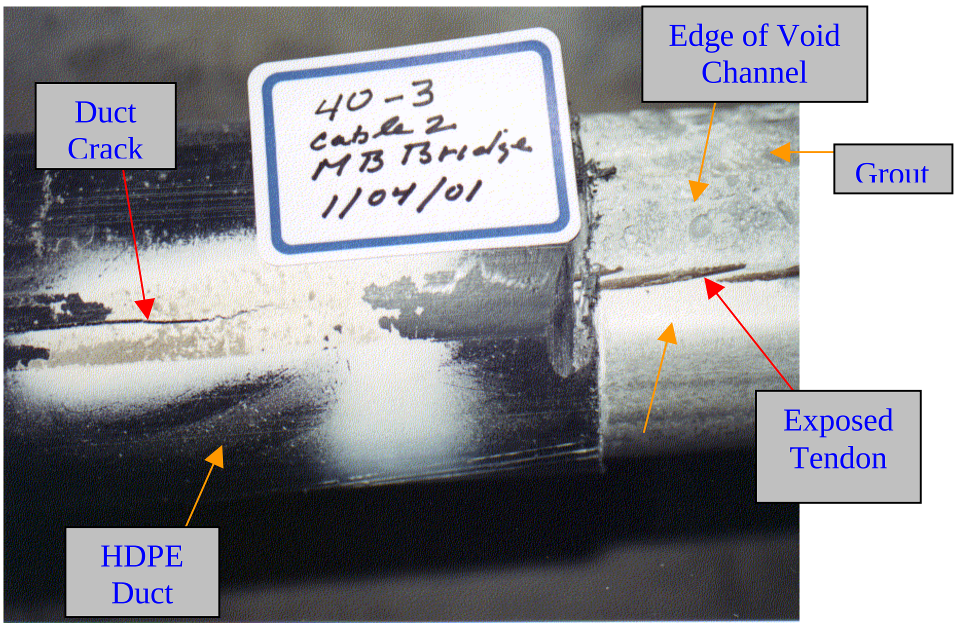

Figure A1: Photograph of duct crack and exposed grout with void channel.

Discussion

HDPE pipe is typically fabricated by extrusion such that properties are expected to be circumferentially, if not longitudinally, homogeneous. The above observations indicate, however, that the cracking is spatially inhomogeneous. On this basis, it is concluded that the duct cracking is related to aspects of the cable system rather than solely due to properties of the HDPE.

Because the coefficient of thermal expansion for HDPE exceeds that of grout, contraction of the former about the latter during periods of a temperature drop should be resisted by the latter such that a tensile hydrostatic stress state results in the duct. Presence of a void channel is expected to complicate the otherwise simplistic hydrostatic stress state and to introduce both transverse tensile and bending stresses within the portion of the duct adjacent to the void channel. Figure A2 illustrates this situation schematically. Thus, as a consequence of the hydrostatic stress, Points A and B become displaced radially outward and away from one another. This results in the bending stresses as schematically shown with maximum stress occurring on the

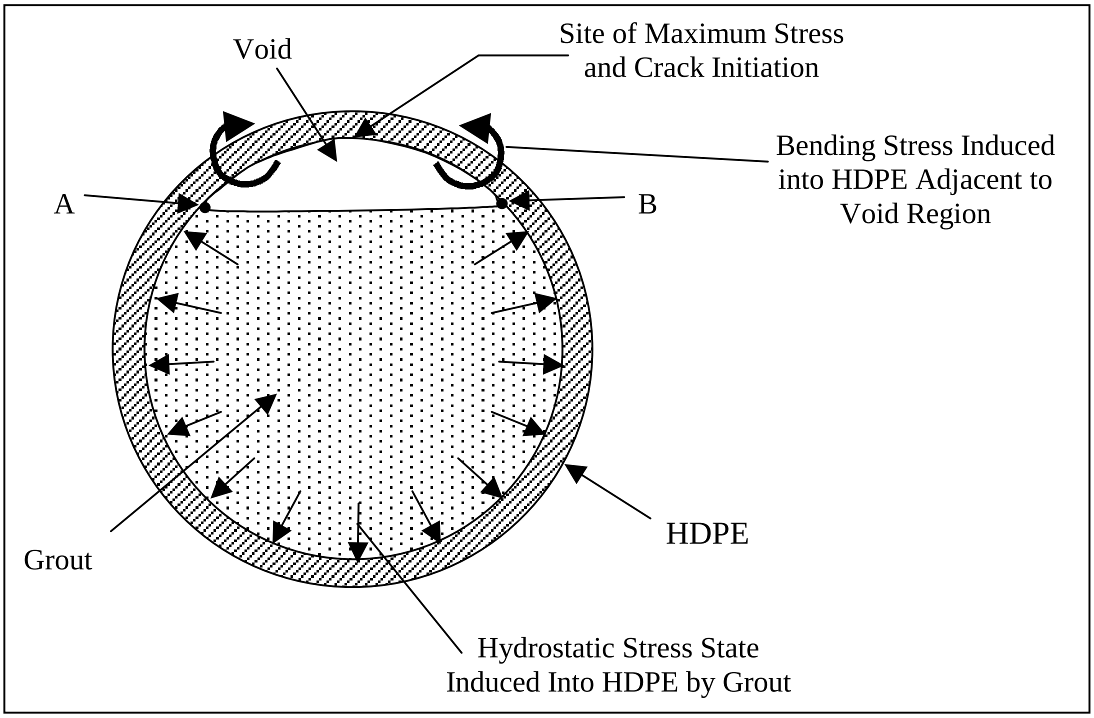

Figure A2: Schematic illustration of the proposed HDPE duct cracking mechanism.

interior surface midway between Points A and B. If this stress is sufficiently elevated, as is relatively easy to achieve in bending, then a crack initiates on the interior surface and propagates outward.

Two rectangular sections of HDPE duct, each of which contain a crack several inches long, were cut from cable 40–2-C. These measured approximately 2x7 inches and were located several feet apart. The cracks were in the 12 o'clock orientation, and a grout void channel extended along the cable directly beneath the cracks. In both cases, the crack opening was greater on the interior surface than the exterior. Figure A3 shows this for one of the two samples. Also, the crack was longer on the interior surface. These findings (greater crack width and length on the interior surface) are consistent with the crack having initiated on the inside of the HDPE and, as such, support the proposed cracking mechanism. This does not preclude the possibility that the duct may have been out of specification or have been improperly specified.

(a)

(b)

Figure A3: Photograph of crack on duct sample 1 acquired from cable 2 of section 40-C:
(a) external surface and (b) internal surface.

APPENDIX B

Grout Petrographic Report
(Lankard Materials Laboratory)

REPORT NO. 5289

ON

PETROGRAPHIC EXAMINATION OF PORTLAND CEMENT GROUT SAMPLES FROM THE MID BAY BRIDGE DESTIN, FLORIDA

TO

SCS, INCORPORATED
LANSDOWNE, PENNSYLVANIA

FEBRUARY 27, 2001

LANKARD MATERIALS LABORATORY, INC.
COLUMBUS, OHIO

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INTRODUCTION

Four small grout samples were received from SCS, Inc. (Siva Venugopalan), on January 18, 2001. The samples were taken from ducts housing steel tendons in the Mid Bay Bridge in Destin, Florida.

This is a segmental box girder bridge (post-tensioned) that went into service in 1993. During the summer of 2000, problems were identified in this bridge in the form of (1) cracked polyethylene ducts, and (2) corrosion of steel tendons.

As part of a larger investigation into the cause of these problems, Lankard Materials Laboratory was requested by SCS to perform petrographic examinations of the grout samples. Specific information was requested on (1) grout unit weight, (2) degree of cement hydration, (3) water-cement ratio, (4) carbonation and pH, (5) characterization of air void distribution, and (6) assessment of air void communication (interconnectedness).

Information was also requested on an assessment of the differences between what was described by SCS as "white" and "dark gray" grout material.

The broad objective of the petrographic examination is to assess the role of the grout, if any, in the duct cracking and steel corrosion problems.

BACKGROUND INFORMATION

This is a segmental box girder bridge. The box girders are held together by six, post-tensioning cables that span eight to nine boxes and terminate at a metal trumpet type anchorage assembly which is cast into the bulkhead at each end. There are three cables on each side of the bridge. Each cable is comprised of 19 spirally wound 7-strand tendons within a grouted polyethylene duct. The duct has a 4-inch inside diameter and a wall thickness of 1/8-inch.

All of the prestressing tendons are of the draped variety beginning with a level run of about 6-feet, followed by an incline of about 50-feet, followed by a horizontal run of 36-feet, and then back up to the 6-foot level run over a 50-foot inclined section.

The approved grout mixture used on the project is Holnam Type I portland cement at a water-cement ratio (w/c) of 0.44 (5 gallons of water to 94-pounds of cement). An expansive admixture identified as Sika Chemical Corporation "Intraplast-N" was specified at the rate of 0.5-pounds per 94-pounds of cement.

The project specifications called for a minimum flow cone efflux time of 11-seconds, and a minimum initial set time of 90-minutes. The 28-day compressive strength specification is 3000 psi.

SCS attempted to learn if any field data were available for the grouting operation used on this project. This exercise was not fruitful as it appears that no field data are available.

The cracks that were observed in the polyethylene ducts pass through the full thickness of the duct wall and are oriented parallel to the long dimension of the ducts. Relative to the circular cross section of the duct, the cracks are most prevalent at the ten o'clock and two o'clock positions. The duct cracking is more prevalent in the incline sections relative to the horizontal sections.

Associated with the duct cracks in many cases is a void in the grout at these locations. These voids represent a physical separation of the grout from the inside surface of the duct and typically occur in the top half of the duct (top being the "up" location in service). The grout was described as being "white and powdery" along many of the void channels ("the larger the void channel, the larger is the white powdery deposit").

At the time of the field inspection, it was observed that "there are circumferential cracks in the grout all along the cable ("even in good areas").

DESCRIPTION OF SAMPLES

Four grout samples were provided as broken pieces extracted from the ducts. They are identified below:

Sample I.D. Number	Span Number	Cable Number	Location In Duct
37-3-4T	37-3	4	Top
37-3-6T	37-3	6	Top
40-A-2B	40-A	2	Bottom
40-A-2T	40-A	2	Top

All of the samples came from inclined sections of the ducts. The location of the samples in the duct (top/bottom) refers to the top and bottom of the duct as positioned in service.

The majority of work in the present investigation was conducted on Samples 37-3-4T and 40-A-2T, as instructed by SCS. All of the samples were taken on January 5, 2001, and immediately put into zip lock plastic bags. They were received in this condition at LML on January 18, 2001. Photographs of Samples 37-3-4T and 40-A-2T as-received are shown in Figure 1 and 2. These samples, as well as the other two samples, contain a surface that had been in contact with the polyethylene duct surface and a surface that had been in contact with the steel tendons. The other surfaces of the samples are fracture surfaces.

SAMPLE EXAMINATION PROCEDURES

The samples were given a detailed preliminary visual and stereomicroscopic examination. Photographic documentation of the samples was obtained at this time and their dimensions measured. Information/observations made included: (1) the existence and location of cracks, (2) color differences, (3) cement paste hardness, (4) condition of the steel strand imprints on the cement paste, (5) evidence of, and nature of, steel corrosion products, (6) nature and distribution of air voids, and (7) diagnostic microstructural features (bleed channels, secondary deposits).

During the preliminary examination, small samples were excavated from the bulk sample for use in a scanning electron microscopy (SEM) examination. The samples were taken at this time to avoid any contamination that might occur during subsequent treatments of the samples for other types of examination. The SEM work was conducted using an AMR-1000 scanning electron microscope. Elemental species present in the samples were identified using energy dispersive x-ray spectroscopy (EDS) techniques in conjunction with the SEM examination. The elemental chemistry is converted to oxide chemistry assuming stoichiometric proportions of cations and oxygen.

Portions of the bulk samples were then separated and prepared for use in a petrographic examination following the guidelines outlined in ASTM C 856-95, "The Standard Practice for Petrographic Examination of Hardened Concrete" (Optical Microscopy Procedures). Samples of 37-3-4T and 40-A-2T were prepared for both transmitted light optical microscopy examination (using thin sections of approximately 30-μm) and for reflected light optical microscopy examination on lapped surfaces.

Portions of the bulk samples not used in the petrographic examination were used for a measurement of density following a 48-hour soaking period in lime-saturated water. This measurement was made following the guidelines outlined in ASTM C 642-90, "The Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete".

Measurements of the depth of carbonation of the grout were made by applying an indicating solution (phenolphthalein) to fresh sawcut surfaces. Measurements of pH were made in the same way using a universal indicating solution (Rainbow Indicator, Germann Instruments, Inc.). In view of the limited amount of grout sample provided for this examination, and its condition (small broken pieces), the observations and findings of the examination will be presented from the point of view of the features observed and measured in the samples that relate to (1) the overall quality of the grout, (2) the conditions experienced by the grout during placement, and (3) the condition of the grout at the time it was removed from the duct. Drawing upon this information, a discussion is given as to the role that the grout has played in the observed problems of duct cracking and corrosion of the prestressing steel.

RESULTS OF THE EXAMINATION/TESTING

The grout used on this project was specified as a Type I portland cement having a water-cement ratio (w/c) of 0.44. It reportedly contained an admixture identified as Sika Chemical Corporation "Intraplast-N". This is a dry powder admixture containing an expansive ingredient as well as "fluidifying and water-reducing agents". The expansive ingredient in the admixture (aluminum powder) is intended to produce a controlled expansion in the grout prior to hardening to assure that the space into which the grout has been placed is filled fully by the grout once hardening does occur.

The in-place grout produced from such a system should be simply a cement paste (hydrated cement and water) containing air voids created by the expansive ingredient.

Features of the in-place grout that are discussed in the remainder of this report include:

1. Characterization of cracking in the grout
2. Characterization of voids formed in the grout
3. Characterization of the cement paste phase
4. Characterization of the air voids
5. Characterization of steel corrosion products
6. Density measurements

Cracking In The Grout Samples

All of the grout samples provided here have one large surface that is the contact between the grout and the polyethylene duct. There is also a surface representing the point of contact of the grout with the steel strands. The remaining surfaces on the grout samples are fracture surfaces. Most of these surfaces are relatively fresh in appearance indicating that they were formed at the time the samples were taken from the duct. This does not rule out the possibility that some of these fractures were preexisting, but tight.

A common form of cracking in the grout samples is radial cracks oriented perpendicular to the long dimension of the grout plug. An example of this type of cracking is shown in Figure 1 for Sample 37-3-4T. In this samples, one of the cracks had resulted in a separation of the grout sample into two pieces. There are at least three other tight radial cracks in this 3½-inch long sample, one of which can be seen in Figure 1. The other cracks can only be observed under microscopic examination. The spacing between these cracks varies from less than ½-inch to about 1-inch. The tightest of these cracks do not pass through the complete section of the grout sample (they are confined to the perimeter area). Cracks similar to these were seen in grout Samples 40-A-2T and 40-A-2B. Sample 37-3-6T, which is 5-inches long, did not show any of these fractures over the 5-inch length (although the end surfaces of this sample represent this type of fracture).

Tight cracks running the length of the strand imprint on these samples are also common. The appearance of these fractures indicates that they were formed during the sample retrieval operation.

There are other separations or tears in these grout samples that are discussed in the section on air void characterization.

Voids In The Grout Samples

It is obvious that a void has formed between the duct-side surface of the hardened grout and the inside surface of the polyethylene duct. The presence of this void is indicated by a deviation from complete sphericity of the surface of the grout in contact with the duct. In the samples examined here, this "gap" is estimated at $^{1}/_{16}$-inch to $^{3}/_{16}$-inch (1.5-mm to 4.5-mm). This condition was observed in the three samples examined here that were located in the "top" portion of the duct. The grout at these locations, characterized here as "voids", is (in these three samples) the "white material" identified previously by SCS.

It is difficult to estimate the area covered by these voids. In one of the samples examined here (37-3-4T), at least a 2-inch length of the perimeter of the grout plug (as viewed in a section perpendicular to the long dimension of the plug) represents a portion of the void area. The extent of the void area along the length of the grout plug is not known, although evidence on Sample 37-3-6T indicates that it is at least 5-inches.

Characterization Of The Cement Paste Phase

Information gained during the present investigation shows that despite large and obvious color differences both within and between the grout samples, they are all comprised only of hydrated portland cement. The color difference reflects a difference in both the water-cement ratio of the paste and the degree of hydration of the portland cement. This stratification of the cement paste phase is due to a phenomenon known commonly as "bleeding". The term bleeding refers to an event that occurs in the freshly placed material after it has reached its final point of deposition and agitation has ceased. Under these conditions, solid particles in the grout, including unhydrated portland cement particles (UPC's) and cement hydrate clusters can settle out under the force of gravity. The extent of bleeding is aggravated by a high w/c, a prolonged open time prior to initial set, and an increased depth of the cast. In the present case, the settling of the solid particles in the grout, has in some areas been accompanied by a movement of air bubbles within the still fluid grout (which is discussed in detail in a subsequent section of this report).

Water-Cement Ratio

In the three samples examined here from the top portion of the duct, there is an increase in w/c in going from the point at which the grout is in contact with the tendons to where it is in contact with, or adjacent to, the inside duct surface. Over the majority of this distance (up to 1½-inches in the samples examined here), the w/c is in the range of 0.42 to 0.50. Within 1/8-inch to 3/8-inch distance from the duct side surface of the grout, the w/c increases fairly abruptly to values ranging from 0.6 to over 0.7. The highest w/c material is the outside surface of the grout in contact with, or adjacent to, the duct surface (estimated at 1.0 or greater). This material is highly porous and is very soft and weak. The higher w/c layer (0.6 to 1.0) varies in thickness in these samples from 3-mm to 10-mm.

Cement Hydration

The hydration of the portland cement is a function of the water-cement ratio of the paste as just described. Where the w/c exceeds 0.6, there are relatively few unhydrated portland cement clinker particles (UPC's). Those that are present are mainly the ferrite phase. The UPC's increase in the interior of the samples in a matrix of calcium silicate hydrate (CSH) and calcium hydroxide (CH). There is a correlation between the cement paste color and the amount of UPC's with an increase in the latter resulting in a darker colored paste.

Overall, the present degree of hydration in the samples is estimated at greater than 90%. Considering the age of the grout and the variations in water-cement ratio, the hydration of the cement used in the preparation of this grout is judged to be normal.

Carbonation/pH

In the samples examined here, there is a correlation between the depth of carbonation and the w/c of the grout. Carbonation depth was measured by applying indicating solutions to fresh sawcut surfaces taken through uncracked portions of the samples. The sawcut surfaces are perpendicular to the long axis of the grout plug.

In sample 37-3-4T, the maximum thickness of the grout layer (from the steel strand to the duct surface is about 1½-inches (38-mm). Only the top 0 to 6-mm thickness of the high w/c paste is carbonated. The pH of the exposed 1-mm thickness of the grout on the duct side has been reduced to 7. From the 1-mm to the 6-mm depth (as measured from the duct surface) the pH is in the range of 9 to 10. At depths below 6-mm from the duct surface, the grout is not carbonated showing a pH in the expected normal range of 12 to 13.

The cement paste defining the surface in contact with the steel strands is lightly carbonated (pH 9 to 10), but it is judged that this occurred after removal of the grout sample from the duct.

The surfaces of a number of the air voids examined in the sawcut sections also showed light carbonation (pH 9 to 10) suggesting that these air voids may have had access to CO_2-containing air in service.

With regard to depth of carbonation and pH, a similar condition was found in Sample 40-A-2T. The high w/c cement paste defining the duct side surface of the grout is fully carbonated (pH 7) to a depth of 1-mm or so, followed by a 1-mm to 3-mm thickness of lightly carbonated paste (pH 10 to 11) in this 15-mm thickness of grout. At depths below about 5-mm to the point of contact with the steel strands, the grout is not carbonated showing a pH of 12 to 13. Again, paste defining the contact surface of the grout with the steel strand is lightly carbonated indicating that what carbonation is there likely occurred after removing the grout from the duct.

Overall, it is indicated that sound portions of the grout do not show extensive carbonation. Full carbonation, where the pH is reduced to a value of 7, occurs only in the exposed 1-mm or so thickness of grout on the duct side. There is then a thin region of lightly carbonated paste which shows a pH in the range of 9 to 10. This occurs typically in the higher w/c (greater than 0.6) portions of the grout. In the interior of the grout samples, down to the point of contact with the steel strands (15-mm to 30-mm), the grout is not carbonated and shows a pH in the range of 12 to 13.

Cement Paste Chemistry

The chemistry of the cement paste phases in this grout was analyzed using the EDS procedure on material taken from fresh fracture surfaces. Four sites within the dark gray paste, and four sites within the white paste were analyzed in Samples 40-A-2T and 37-3-4T. Representative EDS spectra for these two materials are shown in Figure 3. The averaged results (n = 8) are summarized in Table 1. The oxide constituents in the two materials are the same and represent the expected constituents for portland cement. In the white paste (relative to the dark gray paste), there are higher levels of oxide phases based on aluminum (Al), iron (Fe), potassium (K), and sulfur (S).

Also shown in Table 1 is the oxide chemistry of the cement paste in contact with the duct surface. At these locations, the CaO content of the paste is significantly higher relative to both the dark gray and the white paste in the bulk sample. This is a reflection of the fact that there has been significant deposition of calcium hydroxide [$Ca(OH)_2$] at this site. The EDS spectrum for the paste in contact with the duct is shown in Figure 4.

There is widespread evidence of the deposition of secondary deposits on the surfaces of voids in the grout and within the larger pores of the higher w/c cement paste. Examples of these are shown in Figure 5. The top photograph in Figure 5 shows an existing large void surface in Grout Sample 40-A-2T. At this site, there is an accumulation of calcium hydroxide platelets. The bottom photograph in Figure 5 shows the deposition of calcium hydroxide platelets and fibrous ettringite crystals (a calcium sulfoaluminate hydrate) on free surfaces in the higher w/c paste in Grout Sample 40-A-2T. Accumulations of calcium hydroxide platelets are also common on the grout surface in contact with the duct in both grout samples.

Air Void Size And Distribution

The grout used on this project contained an additive (Intraplast-N) that has, as one of its ingredients, a gas-forming agent (reportedly aluminum powder) which is intended to provide a controlled expansion of the grout prior to hardening to assure intimate contact with all of the grouting cavity surfaces. The aluminum powder reacts with calcium hydroxide and water forming hydrogen gas and a calcium aluminate hydrate phase. The gas evolution forms spherical voids within the fluid grout which are subsequently filled with air. They are referred to in subsequent text as air voids. Photographs of these voids in the bulk grout samples are shown in Figure 6. The characteristics of these air voids are as follows:

1. They are spherical in shape.
2. They range in size from 0.1-mm to 1.0-mm.
3. The distribution of the air voids is not uniform.
4. In some areas of the grout, the air voids are connected.
5. The average size of the air voids in the region of the steel tendons is considerably greater than that of the air voids in the bulk grout.
6. A clustering of air voids has occurred in some of the grout samples.

In all four of the grout samples, non-uniform distribution of the air voids is a common microstructural feature. Overall, the average total air void content of the grout is estimated at 10%. However, there are small regions in the samples (1-cm^2 to 2-cm^2 when viewed in two dimensions) that are devoid of any air voids. There are also regions of a similar size where air voids have accumulated and clustered to form a frothy condition in which the total air void content within that clustered region may be 20% to 40%. This has led in these instances to a physical discontinuity in the grouts which is best characterized as a separation or tear between adjacent air voids in these clustered regions. Examples are shown in Figures 6 and 7. The presence of these tears may be related to differing rates of stiffening/hardening in these stratified grouts (as influenced by local water-cement ratio). In regions where the grout remained open, air voids have migrated to a point where hardening had already begun and collected there. This is shown in the top photograph of Figure 7 (Grout Sample 40-A-2B).

In the grout that is present in the interstices of the steel tendons, the air voids in several samples have coalesced to form voids that are in the range of 1-mm to 3-mm in diameter, and they are heavily clustered in this region as well. Examples of this condition are shown in Figure 8 for Grout Sample 40-A-2T. The breakdown of the wall between adjacent air voids is a common occurrence. This feature is readily observable in the photographs shown in Figure 8. In Grout Sample 40-A-2B, the collapse of these large interstitial air voids has advanced to the point that voids up to at least 2-inches long and ¼-inch wide have formed. Features such as those just described and shown in Figure 8 are observed primarily in Grout Samples 40-A-2T and 40-A-2B examined here. Less extensive clustering of these large air voids in the strand interstitial regions was also seen in Grout Sample 37-3-6T.

Steel Corrosion

No examples of extensive corrosion of the prestressing steel was observed in the grout samples examined here. All of samples showed very small iron oxide "spots" on grout surfaces in contact with steel prestressing strands (shown previously in Figure 1). Enlarged views of these features are shown in Figure 9 (for Grout Sample 37-3-4T). The iron corrosion products are typically rust-red in color and have formed within small void regions in the grout at its point of contact with the steel strand. The steel corrosion exhibited in Grout Sample 37-3-4T represents a worst-case situation with regard to the samples examined here.

Grout Density And Porosity

At a w/c of 0.444, the theoretical unit weight of the grout is 118 lb/ft^3. At an air content of 5%, the theoretical unit weight is 112 lb/ft^3; 106 lb/ft^3 at 10% air; and 101 lb/ft^3 at 15% air.

In the grout samples examined here, the saturated density ranges from 104.8 lb/ft^3 in Grout Sample 40-A-2T to 110 lb/ft3 in Grout Sample 37-3-6T. The permeable void volumes range from 41.3% to 45.4%.

DISCUSSION AND CONCLUSIONS

Four grout samples taken from the Mid Bay Bridge (Destin, Florida) were examined petrographically. The examination was prompted by problems in the form of (1) cracking in some of the polyethylene ducts, and (2) corrosion of prestressing steel in this 8-year old, post-tensioned, box girder bridge. The primary objective of the present investigation is to define the role (if any) of the grout in these problems.

The project specifications called for a Type I portland cement/water grout with a water-cement ratio (w/c) of 0.44. The grout contained a fluidifying admixture (Intraplast-N) that contained aluminum powder as an expansive agent.

The significant observations and conclusions discussed here are based principally upon the examination in the present investigation of the aforementioned four grout samples.

Compliance Of The In-Place Grout To The Project Specifications

It is judged that the grout, as placed in the polyethylene ducts on this project, is in reasonable compliance to the project specifications. This conclusion is based on:

1. Estimates of average w/c for the grout
2. Measurements of grout density
3. Confirmation that the grout is composed solely of hydrated portland cement

4. Confirmation of the presence of air voids generated from the reaction of the expanding agent

Despite this compliance, the in-place grout exhibits a number of features that may have played a role in one of the problems on this project.

The Role Of The Grout In The Polyethylene Duct Cracking Problem

It is judged that the grout has had no direct influence on the cracking of the polyethylene ducts. The gas formation resulting from the reactions of the expanding agent is only active during the period of time in which the grout is fluid. The pressures that form here are very low and are not expected to result in stresses that would exceed the tensile strength of the polyethylene duct.

Chemical analyses and microstructural features of the grouts show that no expansive reactions occurred in the grout in the hardened state that could have resulted in the cracking of the ducts.

The Role Of The Grout In Corrosion Of The Steel

There is a strong possibility that the grout did play a role in the corrosion of the prestressing steel. Numerous features were observed in the present investigation which indicate that the grout, despite material and proportioning compliance, was unstable. There is evidence showing that the open time of the grout was abnormally long, resulting in stratified zones within the grout characterized by large variations in w/c and non-uniform distribution of air voids. These features resulted from a segregation/sedimentation of solid phases in the grout and migration and coalescing of the air voids; both of which occurred during the time in which the grout was fluid, with hydration reactions occurring at different rates in different portions of the grout.

A common microstructural feature of the in-place grouts is a clustering of air voids within the body of the grout sample and in the grout positioned between adjacent prestressing strands. A full or partial rupture of the common void walls in adjacent voids (in the clustered regions) has resulted in extensive connected porosity regions within the grout.

There is evidence that following fracture of the polyethylene ducts, there was movement of pore water through the grout from regions of lower w/c to higher w/c. In the fractured ducts, this water was free to evaporate through the duct fractures. This drying, along with self-desiccation, has resulted in additional cracking in the grout plugs in the form of radial cracks (perpendicular to the long axis of the grout plugs). An extensive network of interconnected porosity (shrinkage cracks, high w/c cement paste, and communication between air voids) provides ample access for ambient air to reach the prestressing steel. The combination of moisture and oxygen at these sites would be sufficient to initiate and sustain steel corrosion.

Extensive carbonation of the cement paste contacting the prestressing steel would obviously exaggerate the steel corrosion at these sites. This may have occurred in portions of the ducts which show the most severe corrosion. In the grout samples examined here, this was not the case.

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