Corrosion Failure of Post-Tensioned Tendons in Presence of Deficient Grout

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INTRODUCTION: Post-Tensioned Strand Corrosion

- Several documented cases of corrosion-related failures of post-tensioned (PT) strand in FL.

- Corrosion identified in early 2000’s attributed to grout void formation due to bleed water formation and chloride presence.

- Subsequent specifications in FL include low bleed grout requirements.

- However, corrosion problems persist.

✓ Investigation of recent PT corrosion and repair issues are on-going. This presentation overviews findings from field and laboratory explorations of deficient grout in tendons.
BACKGROUND:
PT Bridge in Florida built in 2002

• PT segmental bridge with int. and ext. tendons.
• Among first FL bridges to use low bleed grouts.
• Ext. tendons placed to reduce tensile stresses in web. Anchor caps at low elevation.
• Severe corrosion in multiple ext. tendons. Failure occurred after ~8 years service.
• Severe corrosion accompanied by wet plastic grout.
SEGREGATED GROUT

- Grout segregation characterized as:
  - A. Wet plastic
  - B. Sedimented Silica
  - C. White chalky

✓ Corrosion attributed to wet plastic grout but not necessarily to void presence.
✓ Grout segregation created environment with dissimilar pore water chemistry and physical properties.
Segregated Grout Properties: Moisture Content

- High moisture content associated with segregated grout.
- ~50% moisture in white chalky grout; ~70% moisture in wet plastic grout
Segregated Grout Properties: Pore Water pH

- Pore water of segregated grout typically retains high pH.
  - No indication of processes to decrease pH such as carbonation.
  - Regions with accumulation of corrosion products may contain localized low pH environments.

† Prepared by Ex-situ Leaching Method
Segregated Grout Properties: Chloride Content

- Assuming threshold ratio \([\text{Cl}^-]/[\text{OH}^-] = 0.3\), and an upper measured free Cl concentration \(~50\) to \(100\) ppm, threshold pore water pH \(<11.5-12\) \(<\) observed pH values (typ. \(>12\)).

- Assuming 67% cement content in grout, upper range 0.3mg/g would correspond to 0.05% cement which is \(<<C_T\).

✓ Low chloride content in grout. Below conventional chloride corrosion threshold concentrations.

- Apparent accumulated chloride content in moist grout may be due to ionic transport.
- However, total chloride test preparation methods may over-sample size of segregated grout thus higher reported chloride concentrations.
• Apparent enhanced presence of sulfurous compounds in segregated grout.
• Gypsum and ettringite identified as sulfur bearing crystalline compounds.
• Ettringite-filled voids visually predominant in segregated grout; however, identified in vicinity of segregated grout as well.

☑ Possible indicator of enhanced sulfate presence segregated grout free water.
Sulfate concentrations as high as 9700 ppm measured in pore water.
Corrosion at Low Elevation Anchor Caps

- Corrosion and similar deficient grout characteristics observed at low elevations, too.

- Chloride content and pH levels vary across different moisture conditions and sulfate concentrations:
  - 0.47 mgCl/g dry, pH 9.8, 7800 ppm SO$_4^{2-}$
  - 0.25 mgCl/g dry, pH 11.9, 7100 ppm SO$_4^{2-}$
  - 0.14 mgCl/g dry, pH 12.7, 55% moisture, 4300 ppm SO$_4^{2-}$
  - 0.18 mgCl/g dry, pH 12.7, 44% moisture, 1900 ppm SO$_4^{2-}$
  - 0.09 mgCl/g dry, pH 12.7, 14% moisture, 310 ppm SO$_4^{2-}$

- Visual inspection shows corrosion patterns correlating with environmental conditions.
At least five other bridges contained grout with some form of deficiency.
Extent of grout deficiencies vary greatly by bridge.
Grout leachate remains alkaline.
High chlorides found in some bridges (but thought to be unrelated to segregation).
Deficient grout shows higher moisture and free sulfate concentrations.
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• Deficient grout shows higher moisture and free sulfate concentrations.
**PRELIMINARY CORROSION TESTING**

- Variation in open-circuit potential characterizing local anodes in wet plastic grout and passive steel elsewhere.
- Differences in OCP develop macrocell corrosion.
Polarization Resistance

- Surface rust was apparent on samples with deficient grout.
- Rewetting of interstitial spaces may worsen condition; Possible concern for regrouting repair procedures.
- Differentiation from passive corrosion conditions was apparent for samples with wet/plastic grout, generally indicating corrosivity of that grout condition.
Anodic polarization of active steel due to coupling with passive steel enhances corrosion rates.
Evaluation of Corrosion Behavior in Enhanced Sulfates Conditions

Tendon Mockup

- 15 ft tendon mockup cast with varying sulfates and chlorides addition to the mix water.
  - 0 %, ~0.09%, ~0.9%, ~5.5% sulfates by cement weight.
  - 0.08%, 0.2% chlorides by cement weight.
  - (Grout was past expiration and mix had excess water).
  - Crevice and Non crevice steel probes were embedded in the grout.
  - The tendons were inclined at 30°.

Studied parameters: corrosion potential (OCP), polarization resistance and anodic characterization
The test results indicate the top part of the tendons tend to have higher levels of sulfate concentrations.

In comparison to the resolved sulfate content measured in grout from Bridge I and II, it is seen that separation of grout material can allow for accumulation of sulfate ions without external sulfate sources.
Corrosion Behavior In Mock-up Tendons

- Corrosion potentials and current density indicative of active corrosion in top portion of tendon (enhanced sulfates).
- Similar corrosion activity with intentional crevice condition.
Solution Resistance of Grout in Mock-up Tendons

- Grout at high elevations have lower solution resistance.
- Grout deficiency appears more severe at high elevation.
• Indication of passive film development in all conditions.
• Larger passive currents in deficient grout in top portion than bottom portion of tendons.
• Abrupt increase in anodic current at lower potentials indicative of breakdown of passive-like conditions in high admixed sulfate conditions.

![Graphs showing anodic characterization of steel in mock-up tendons.]

![Graphs showing anodic characterization of steel in mock-up tendons.]

• Indication of possible role of sulfates in steel corrosion initiation.

Sulfates were thought to be related to localized corrosion process by reaction i.e.

\[
\text{Fe}^{2+} + 2\text{H}_2\text{O} + \text{SO}_4^{2-} \rightarrow \text{Fe(OH)}_2 + \text{H}_2\text{SO}_4
\]  

(Jones.1992)
Electrochemical Tests of Steel in Sulfate Solutions

Small cells filled with alkaline solution 1 and 2 (pH ~12.5 and ~13.3)
- Steel test samples: 1.5 inch long, 1/4 inch diameter steel wire
- Ref. and Ctr. Electrodes: Activated titanium rods
- Testing conducted in pre-mixed alkaline solutions with containing 0 ppm, 2,000 ppm or 20,000 ppm sodium sulfate.
- Some samples subjected to incremental additions of sodium sulfate (5,000 ppm weekly for a month (up to 65,000 ppm))
- Other conditions: crevice and elevated temperature

First Set of Testing
- Maintained at steady-state open circuit potential condition.
- Corrosion potentials with a saturated calomel reference electrode (SCE).
- Linear polarization resistance measurements.
- Pre-mixed or incremental admixed sulfate solutions.

Second Set of Testing
- Anodic Polarization Measurements starts from $-1V_{SCE}$ to $+500mV_{SCE}$ with scan rate 0.05mV/s.
- Pre-conditioned at open-circuit potential or at $-1V_{SCE}$ for 1 day were made
- Conditioned at $-1V_{SCE}$ for at least 30 minutes prior to testing
Sulfates in pH 13.3 showed no effect on initiating or enhancing corrosion in any of the test conditions at OCP.

The corrosion potential for the elevated temperature condition was more negative.

Stable passive film can develop for steel immersed in pH 13.3 solution with little adverse effect from sulfate ion presence. Sulfate ions cannot destabilize already developed passive film.
Anodic polarization curves were not well differentiated by sulfate ion presence.

Indication of passive-like behavior for all test scenarios.

Sulfate ions have shown minor indication to increase the anodic current exchange density. Crevice and enhanced temperature did not seem to aggravate corrosion conditions.
No corrosion was observed for the sulfate-free and 2,000ppm sodium sulfate solution and also when incremental sulfates (up to 65,000 ppm sodium sulfate) were added.

In pH 12.5 solutions, sulfates may not be able to depassivate steel, but the early presence of sulfates may destabilize passive film growth.
1-dy OCP Pre-Conditioning

- Differentiation in anodic behavior was observed with the presence of sulfate ions.
- With the admixed presence of 2,000 ppm sodium sulfate, the passive current density showed an approximate threelfold increase.
- The polarization graphs show transition from passive to active corrosion behavior of steel in solution with the admixed presence of 20,000 ppm sodium sulfate.

1-dy Cathodic Pre-Conditioning

- Pitting corrosion occurred for samples exposed with 20,000 ppm sodium sulfate in samples subjected to extended cathodic pre-conditioning.
Corrosion Behavior In Sulfate Solution

- Enhanced corrosion activity with cathodic pre-conditioning (early passive film instab).
- Generally larger corrosion currents in sulfate solutions with localized corrosion.
- Lower corrosion current density calculated for sample with pitting corrosion due to small pit areas.
Sulfate Levels for Corrosion Development

- Important role of:
  - Solution pH,
  - Early presence of sulfate ions,
  - Level of sulfate presence,
  - and Cement content.
Conclusions

• Segregated deficient grout typically contains high moisture content that maintains high pH and low chloride levels.
• Enhanced sulfate concentrations in segregated deficient grout coincident with severe corrosion development.
• High sulfates levels can occur even without external sulfate source.
• Segregated grout material provided poor corrosion protection for embedded strand that did not attain uniform stable passivity.
• Stable passive film apparent for steel immersed in pH 13.3 solution with little adverse effect from sulfate ion presence. Sulfate ions not readily able to destabilize already developed passive film.
• In pH 12.5 solutions, sulfates may not be able to depassivate steel, but the early presence of sulfates may destabilize passive film growth.
• Pitting corrosion conditions apparent in initial stage of degradation due to destabilization of passive film. Active corrosion afterwards.
• Accelerated corrosion likely enhanced by macrocell coupling of local anodes in the strand embedded in segregated grout and extended cathode throughout the tendon.
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ANY HINTS FROM GROUTING RECORDS?

Records from one construction project.
Initial material deficiencies identified and greater awareness made early.
- Apparent Batch Time: Cumulative Time of Mixing Grout Batches/Total # of Bags.
- Elapsed Pumping Time: Cumulative Pumping Time of a Series of Tendons.

- 132 tendons reviewed.
- 42% used Grout A, 58% used other approved grouts.
- Soft grout observed on 14% of 132 tendons (84% of Grout A).
PROPOSED CORROSION MECHANISM

- High water content was present in the grout.
- High water content carried higher concentrations of ionic species including sulfates ions. High concentrations of sulfurous compounds (sulfates in solution) were present in the grout.
- Segregated grout material provided poor corrosion protection for embedded strand that did not attain uniform stable passivity.
- Differential aeration condition present due to easy access to oxygen, vastly different moisture contents in localized regions, and strand interstitial spaces creating crevices.
- Accelerated corrosion was caused by macrocell coupling of local anodes in the strand embedded in segregated grout and extended cathode throughout the tendon.
Two distinct impedance loops was observed for all test samples
High frequency limit impedance corresponds to solution resistance, Rs.
Intermediate frequency limit impedance , Rc, related to moisture content and permeability of existing grout (including interstitial spaces)
CPE at intermediate frequencies representative of dielectric properties of grout.
Low frequency limit impedance, Rp, corresponds to polarization resistance
CPE behavior at low frequencies representative of steel interfacial capacitance.
Impedance equivalent circuit analog considered as a first approach to interpret impedance behavior.
Solution Resistance

- High frequency limit impedance corresponded to solution resistance, Rs.
- Rs trend with time representative of cement hydration of the introduced paste.
- Intermediate frequency limit impedance, Rc, showed distinction between hardened grout with low moisture content and segregated grout with high moisture content.
Sulfate ion Analysis

- Enhanced sulfate($\text{SO}_4^{2-}$) content was found in deficient grout.
- Rapid change of moisture content due to environmental exposure and time of exposure.

*Test methodology for uniform testing of discrepant grout sample conditioning.*

**Method 1**
- Crushed to pass a No. 100 sieve
- Dry the powder samples at 55°C for 24 hours
- 1:10 leaching volume
- Place on Hotplate with 66°C for 15-18 hours
- Filter, and Dilute leachate into 100mL solution

**Method 2**
- Crushed to pass a No. 100 sieve
- 1:10 leaching volume
- Stay at room temperature for 1 week
- Filter, and Dilute leachate into 100mL solution

**Method 3**
- Crushed to pass a No. 100 sieve
- 1:1 leaching volume
- Stay at room temperature for 1 week
- Collecting the leachate solution