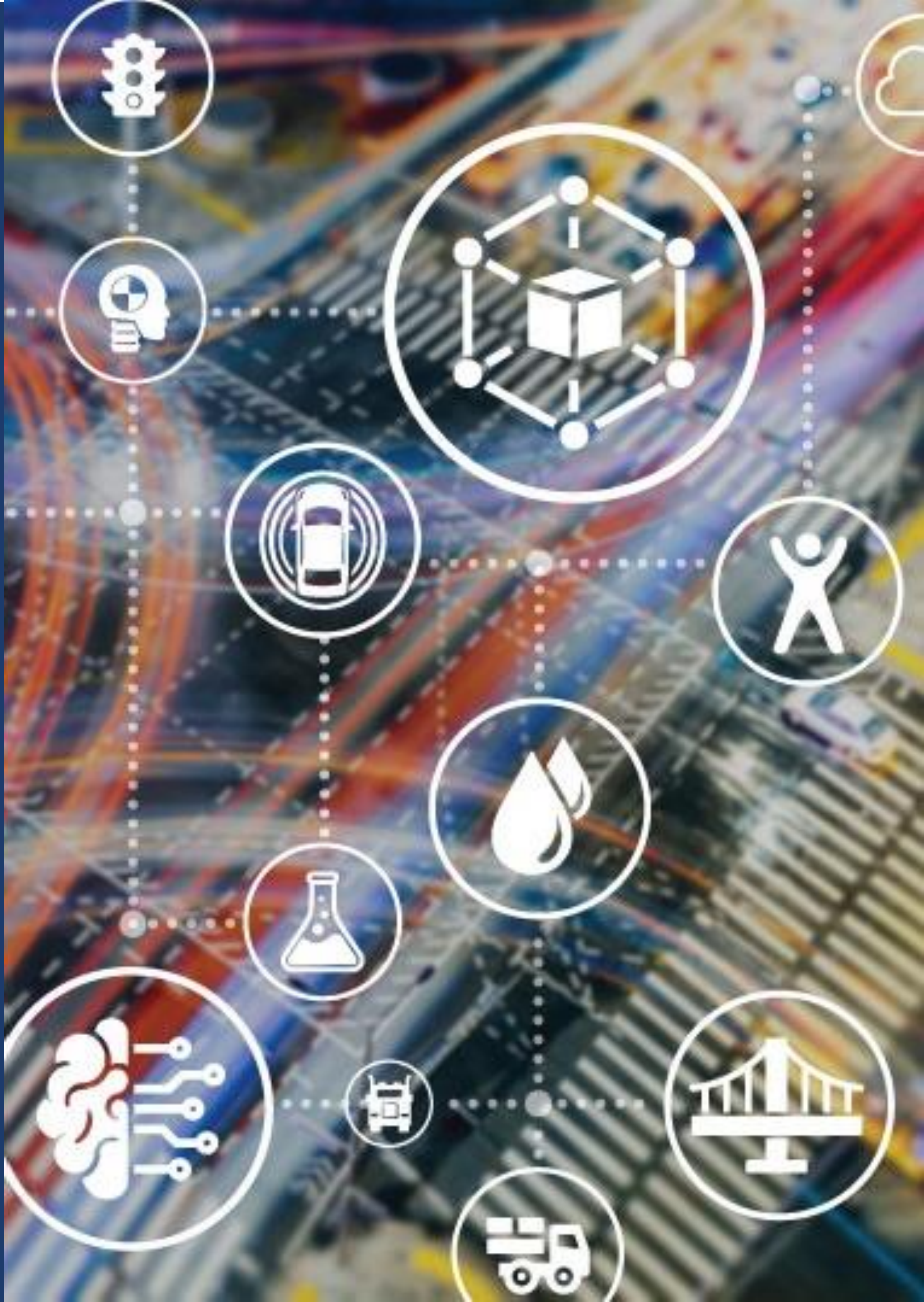
U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank
Highway Research Center

Federal Highway Administration (FHWA) Coatings and Corrosion Laboratory (CCL):
Ongoing Research on Tendon Corrosion

Office of Infrastructure Research and Development
FHWA CCL
October 2023

Frank Jalinoos
Coatings and corrosion lab manager
Long-Term Infrastructure Performance Team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Outline

- CCL expertise, mission, and research disciplines.
- CCL's past tendon corrosion laboratory studies.
- CCL's recently completed tendon corrosion laboratory studies.
- Planned tendon corrosion laboratory studies.

Turner-Fairbank Highway Research Center Expertise

- Structural design and performance.
- Pavement design and evaluation.
- Safety design and operations.
- Human factors analytics.
- Connected vehicle technologies.
- Intelligent transportation systems.

Source: FHWA.

Laboratories

Infrastructure

- Aggregate and Petrography Laboratory
- Asphalt Binder and Mixture Laboratory
- Chemistry Laboratory
- Coatings and Corrosion Laboratory
- Concrete Laboratory
- Geotechnical Laboratory
- J. Sterling Jones Hydraulics Research Laboratory
- Nondestructive Evaluation (NDE) Laboratory
- Pavement Testing Facility
- Structures Laboratory

Safety

- Federal Outdoor Impact Laboratory (FOIL)
- Geometric Design Laboratory
- Human Factors Laboratory
- Safety Training Analysis Center (STAC)

Operations

- Saxton Transportation Operations Laboratory (STOL)

Source: FHWA.

CCL Goals

1. Conduct research to discover innovative solutions for the most critical materials-related problems that affect durability and serviceability of transportation infrastructure.

2. Focus on research that can yield field-applicable results.

3. Make the Nation's infrastructure safer and last longer by providing useful research products to stakeholders (e.g., State and local highway agencies, industries, and academia).

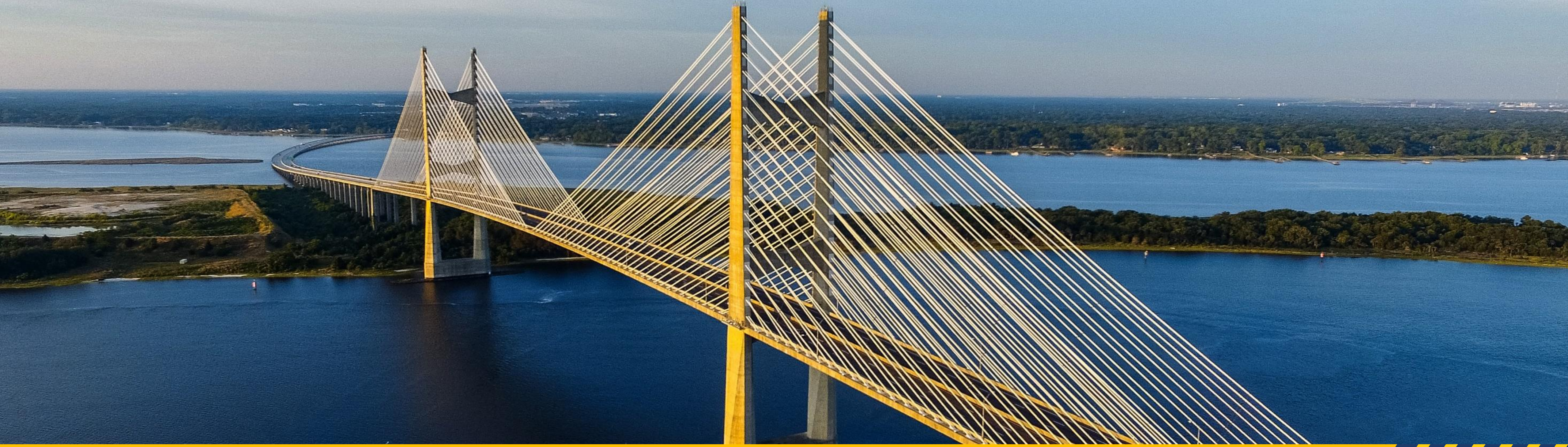
Corrosion Modeling and Simulation

Data sources:

- Construction documents.
- Field assessment.
- Laboratory testing.

Modeling corrosion:

- Chloride ingress.
- Corrosion initiation and propagation.
- Corrosion damage to steel and concrete.



Source: FHWA.

CCL’s Past Tendon Corrosion Laboratory Studies

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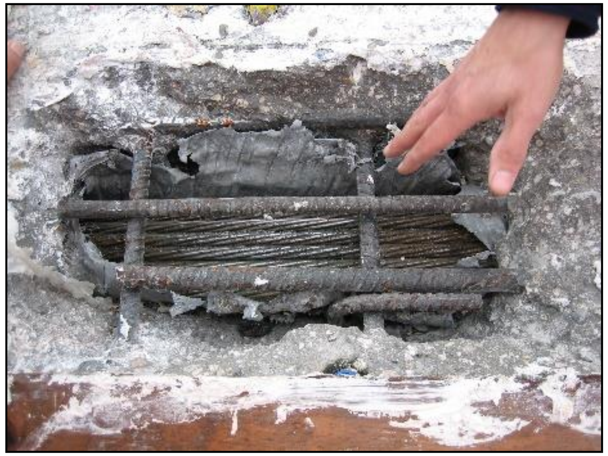
Technical Assistance:
San Francisco-Oakland Bay Bridge (2006)

All figures source: FHWA.



(Lee 2022)

(Lee 2022)

Background: Caltrans inspectors discovered many ungrouted internal tendons during the construction of the San Francisco-Oakland Bay Bridge Construction in 2006. At the request of the FHWA California division office, CCL participated in the corrosion investigative work.

Based on the analysis of water samples collected from the site and findings from the lab investigation, the study concluded that most seven-wire prestressing strands were not exposed to a very aggressive environment for pitting corrosion.

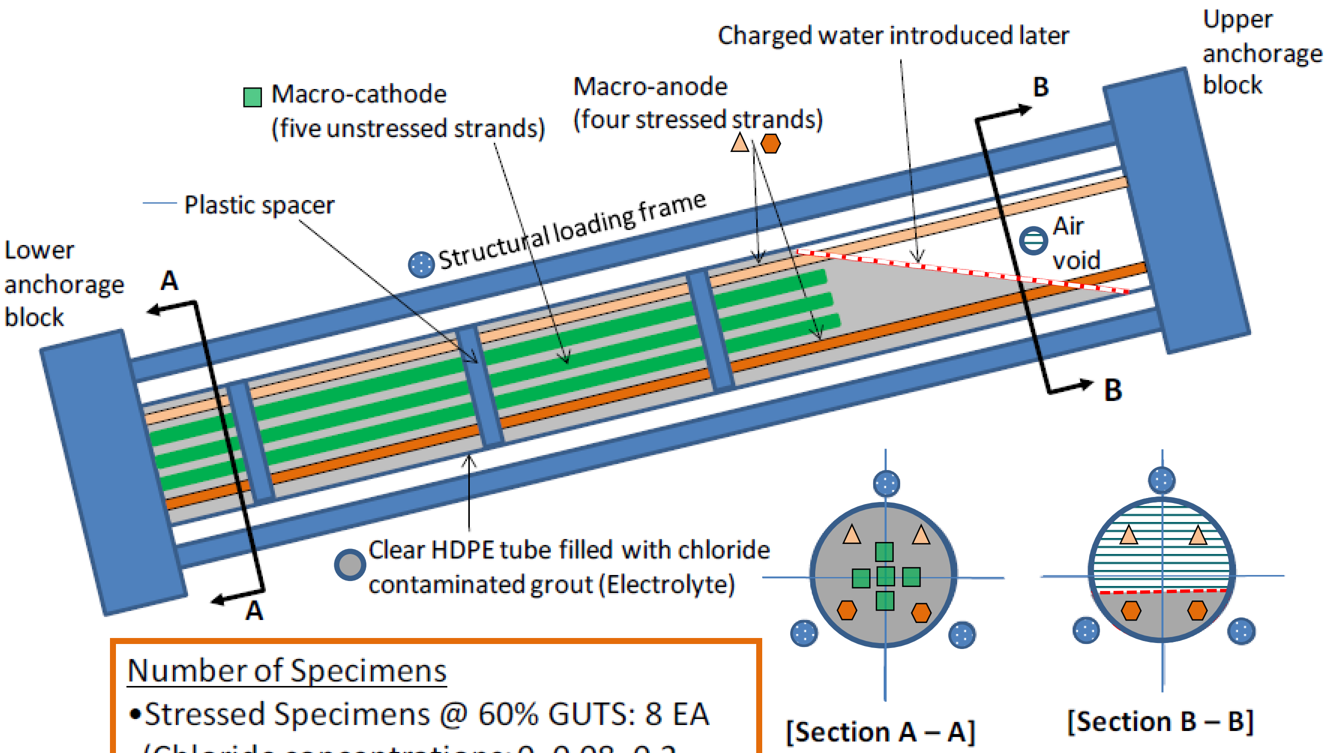
Determination of Chloride Thresholds for Tendon Corrosion (2012–2014) (1/5)

- Background: The discovery in 2010 of elevated chloride levels in a post-tensioning (PT) concrete bridge in Texas triggered a follow-up investigation by a grout manufacturer (Sika), which determined that grout produced had chloride levels exceeding the specified limit—well above the American Association of State Highway and Transportation Officials- (AASHTO) and Post-Tensioning Institute- (PTI) recognized limit of 0.08 percent chloride by weight of cementitious material (AASHTO 2010; PTI 2011). As a result, Sika and FHWA each initiated independent research programs to understand better the effects of chlorides at various levels on the long-term corrosion resistance of PT systems (Lee, S-K., and J. Zielske 2014).
- Relevant literature survey: A total of 35 reports and specifications were reviewed, and an FHWA summary report based on the literature survey was published (Lee 2012).

Determination of Chloride Thresholds for Tendon Corrosion (2012–2014) (2/5)

- Objectives:
  - Determine chloride threshold value(s) experimentally for PT strands in different conditions.
  - Perform an immediate corrosion risk assessment of the PT strands exposed to the chloride-contaminated Sika grout (Lee and Zielske 2014).
  - Evaluate the overall long-term safety of the affected bridge structures containing the unacceptable grout.
- Potential impacts: The study provided the basis for tolerable chloride concentrations (Lee and Zielske 2014).

Determination of Chloride Thresholds for Tendon Corrosion (2012–2014) (3/5)



Number of Specimens

- Stressed Specimens @ 60% GUTS: 8 EA (Chloride concentrations: 0, 0.08, 0.2, 0.4, 0.6, 0.8, 1.0, and 2.0 % by weight of cement)

All figures source: FHWA (Lee and Zielske 2014).

Determination of Chloride Thresholds for Tendon Corrosion (2012–2014) (4/5)

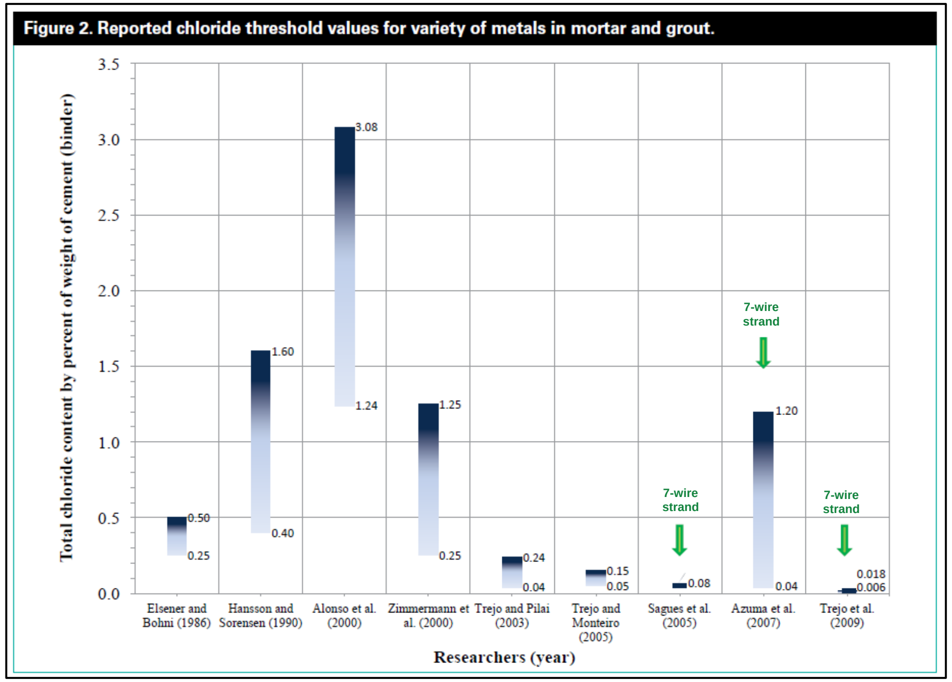
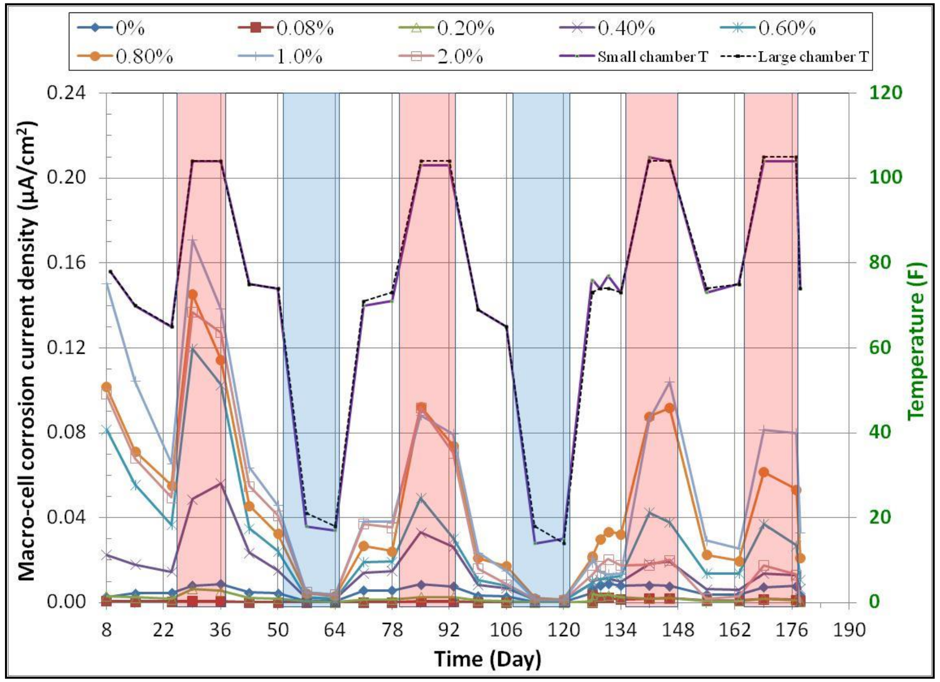


Figure 2. Reported chloride threshold values for variety of metals in mortar and grout.



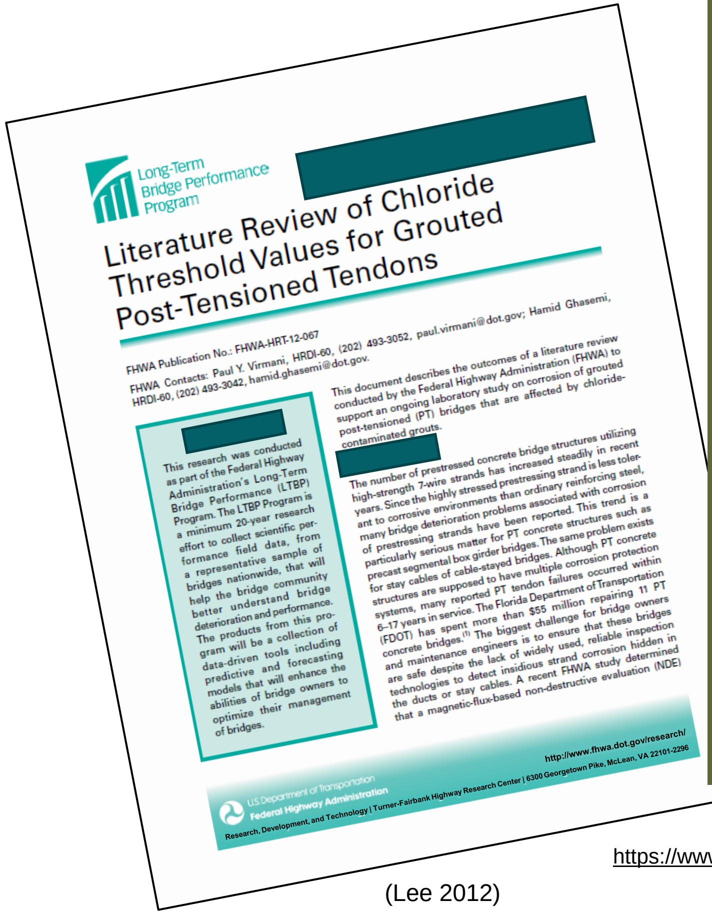
All figures source: FHWA (Lee and Zielske 2014).

All figures source: FHWA (Lee and Zielske 2014).

Major conclusions (Lee and Zielske 2014):

- Chloride threshold for corrosion initiation = 0.4 percent by weight of cement or 0.2 percent by weight of sample.
- Chloride threshold for corrosion propagation = 0.8 percent by weight of cement or 0.4 percent by weight of sample.
- These thresholds are for normally hardened grout. There are much lower thresholds for defective grout and other unfavorable conditions.

Determination of Chloride Thresholds for Tendon Corrosion (2012–2014) (5/5)



Long-Term Bridge Performance Program

Literature Review of Chloride Threshold Values for Grouted Post-Tensioned Tendons

FHWA Publication No.: FHWA-HRT-12-067

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This research was conducted as part of the Federal Highway Administration's Long-Term Bridge Performance (LTBP) Program. The LTBP Program is a minimum 20-year research effort to collect scientific performance field data, from a representative sample of bridges nationwide, that will help the bridge community better understand bridge deterioration and performance. The products from this program will be a collection of data-driven tools including predictive and forecasting models that will enhance the abilities of bridge owners to optimize their management of bridges.

This document describes the outcomes of a literature review conducted by the Federal Highway Administration (FHWA) to support an ongoing laboratory study on corrosion of grouted post-tensioned (PT) bridges that are affected by chloride-contaminated grouts.

The number of prestressed concrete bridge structures utilizing high-strength 7-wire strands has increased steadily in recent years. Since the highly stressed prestressing strand is less tolerant to corrosive environments than ordinary reinforcing steel, many bridge deterioration problems associated with corrosion of prestressing strands have been reported. This trend is a particularly serious matter for PT concrete structures such as precast segmental box girder bridges. The same problem exists for stay cables of cable-stayed bridges. Although PT concrete structures are supposed to have multiple corrosion protection systems, many reported PT tendon failures occurred within 6–17 years in service. The Florida Department of Transportation (FDOT) has spent more than \$55 million repairing 11 PT concrete bridges.[1] The biggest challenge for bridge owners and maintenance engineers is to ensure that these bridges are safe despite the lack of widely used, reliable inspection technologies to detect insidious strand corrosion hidden in the ducts or stay cables. A recent FHWA study determined that a magnetic-flux-based non-destructive evaluation (NDE)

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http://www.fhwa.dot.gov/research/
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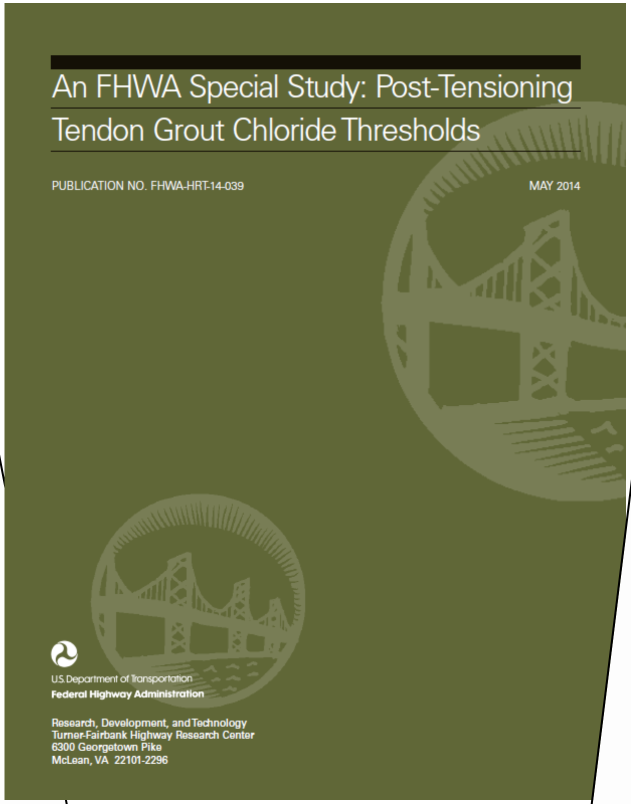
(Lee 2012)

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/12067/12067.pdf



An FHWA Special Study: Post-Tensioning Tendon Grout Chloride Thresholds

PUBLICATION NO. FHWA-HRT-14-039

MAY 2014

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
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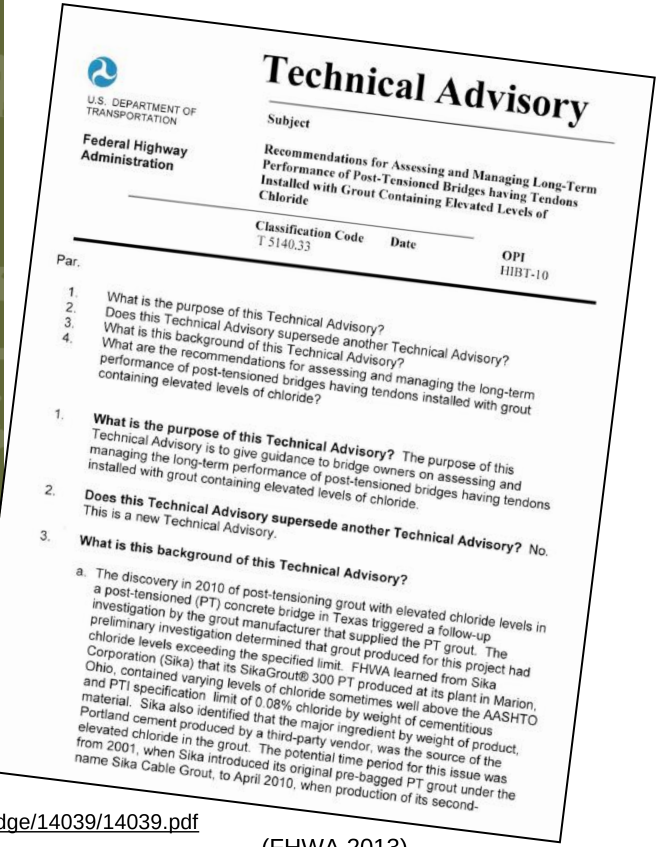
(Lee and Zielske 2014)

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/14039/14039.pdf



U.S. DEPARTMENT OF TRANSPORTATION

Federal Highway Administration

Technical Advisory

Subject

Recommendations for Assessing and Managing Long-Term Performance of Post-Tensioned Bridges having Tendons Installed with Grout Containing Elevated Levels of Chloride

Classification Code T 5140.33

Date

OPI HIBT-10

Par.

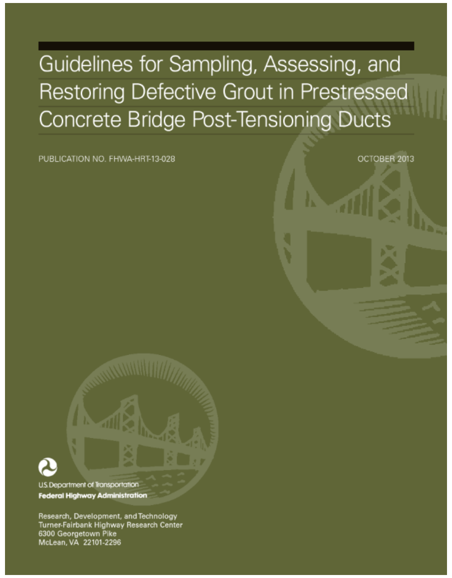
1. What is the purpose of this Technical Advisory?
2. Does this Technical Advisory supersede another Technical Advisory?
3. What is this background of this Technical Advisory?
4. What are the recommendations for assessing and managing the long-term performance of post-tensioned bridges having tendons installed with grout containing elevated levels of chloride?

1. **What is the purpose of this Technical Advisory?** The purpose of this Technical Advisory is to give guidance to bridge owners on assessing and managing the long-term performance of post-tensioned bridges having tendons installed with grout containing elevated levels of chloride.
2. **Does this Technical Advisory supersede another Technical Advisory?** No. This is a new Technical Advisory.
3. **What is this background of this Technical Advisory?**
   a. The discovery in 2010 of post-tensioning grout with elevated chloride levels in a post-tensioned (PT) concrete bridge in Texas triggered a follow-up investigation by the grout manufacturer that supplied the PT grout. The preliminary investigation determined that grout produced for this project had chloride levels exceeding the specified limit. FHWA learned from Sika Corporation (Sika) that its SikaGrout® 300 PT produced at its plant in Marion, Ohio, contained varying levels of chloride sometimes well above the AASHTO and PTI specification limit of 0.08% chloride by weight of cementitious material. Sika also identified that the major ingredient by weight of product, Portland cement produced by a third-party vendor, was the source of the elevated chloride in the grout. The potential time period for this issue was from 2001, when Sika introduced its original pre-bagged PT grout under the name Sika Cable Grout, to April 2010, when production of its second-

(FHWA 2013)

https://www.fhwa.dot.gov/bridge/t514033.pdf

Supplementary Report Related to PT Tendons



Guidelines for Sampling, Assessing, and Restoring Defective Grout in Prestressed Concrete Bridge Post-Tensioning Ducts

PUBLICATION NO. FHWA-HRT-13-028

OCTOBER 2013

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

(Theryo, Hartt, and Paczkowski 2013)

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/13028/index.cfm

All figures source: FHWA.

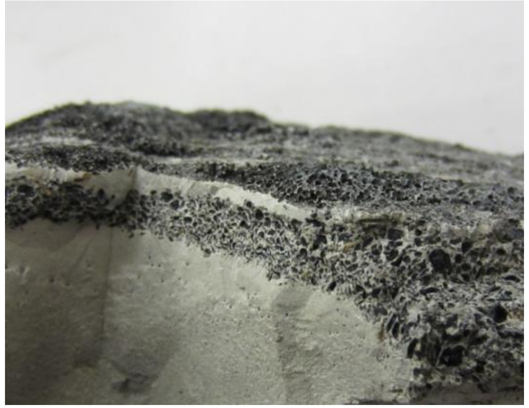
Grout Segregation and Sulfate Corrosivity Study (2014–2019) (1/8)

- Background: The first corrosion problem associated with segregated grout was reported in the United States in 2011 when two ruptured PT tendons were discovered in the Ringling Causeway Bridge in Sarasota, FL, after 7 years of service. The segregated grout was made with a prepackaged, commercial product. Since then, similar instances have been reported in the US, including in FHWA lab studies and other countries. In many cases, the segregated grout contained elevated levels of water-soluble sulfate which was responsible for rapid tendon corrosion and occasional complete failure.
- Relevant literature survey: 18 reports, including investigative Florida Department of Transportation (FDOT) reports, were reviewed to develop a research plan.

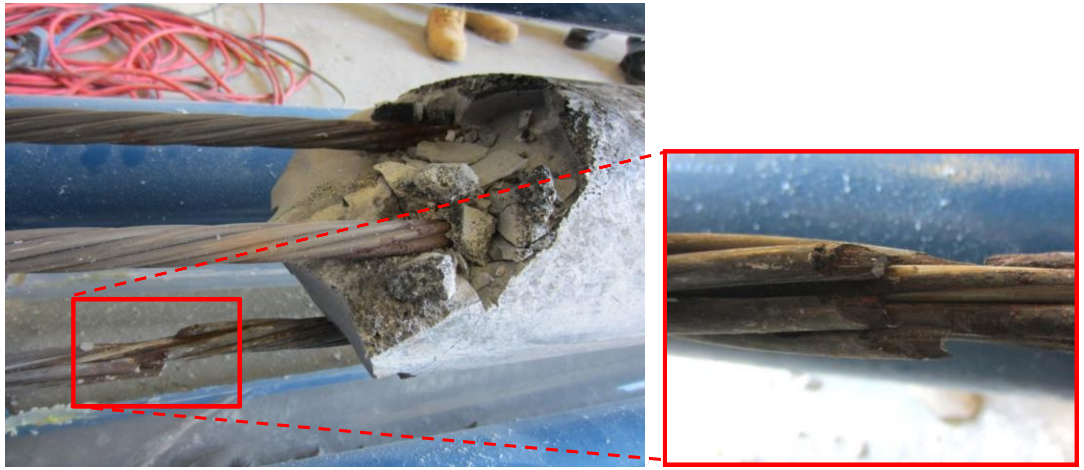
Grout Segregation and Sulfate Corrosivity Study (2014–2019) (2/8)

- Objectives: This study had three objectives:
  - Investigate the corrosion behaviors of center wires exposed to sulfate and chloride ions in high and low-pH aqueous solutions.
  - Characterize the physical characteristics of various types of grout samples.
  - Determine the total amounts of water-soluble sulfate ions in raw grout powder ingredients and hydrated grout samples.
- Potential impacts: Better understanding of grout segregation phenomena and a corrosion relationship between pH and sulfate concentration.

Grout Segregation and Sulfate Corrosivity Study (2014–2019) (3/8)



Free sulfate contractions ranged from 0 to 1.5 percent by weight of grout samples.

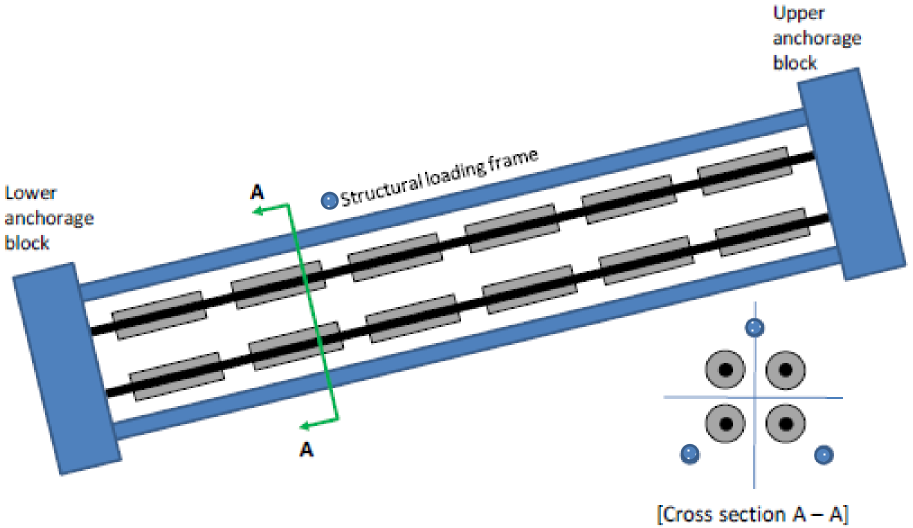


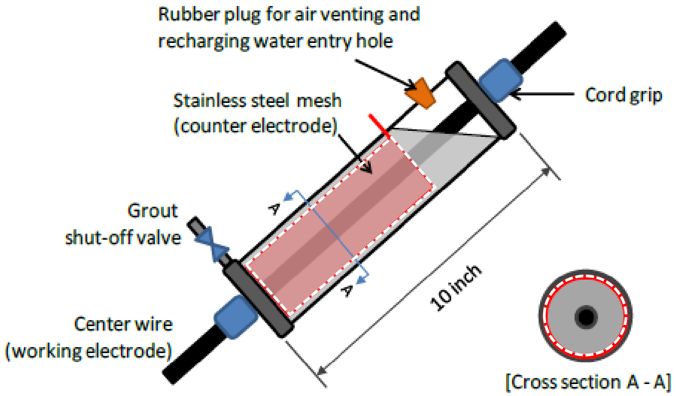
All figures source: FHWA (Lee and Zielske 2014).

Grout Segregation and Sulfate Corrosivity Study (2014–2019) (4/8)

All figures source: FHWA (Lee 2021).

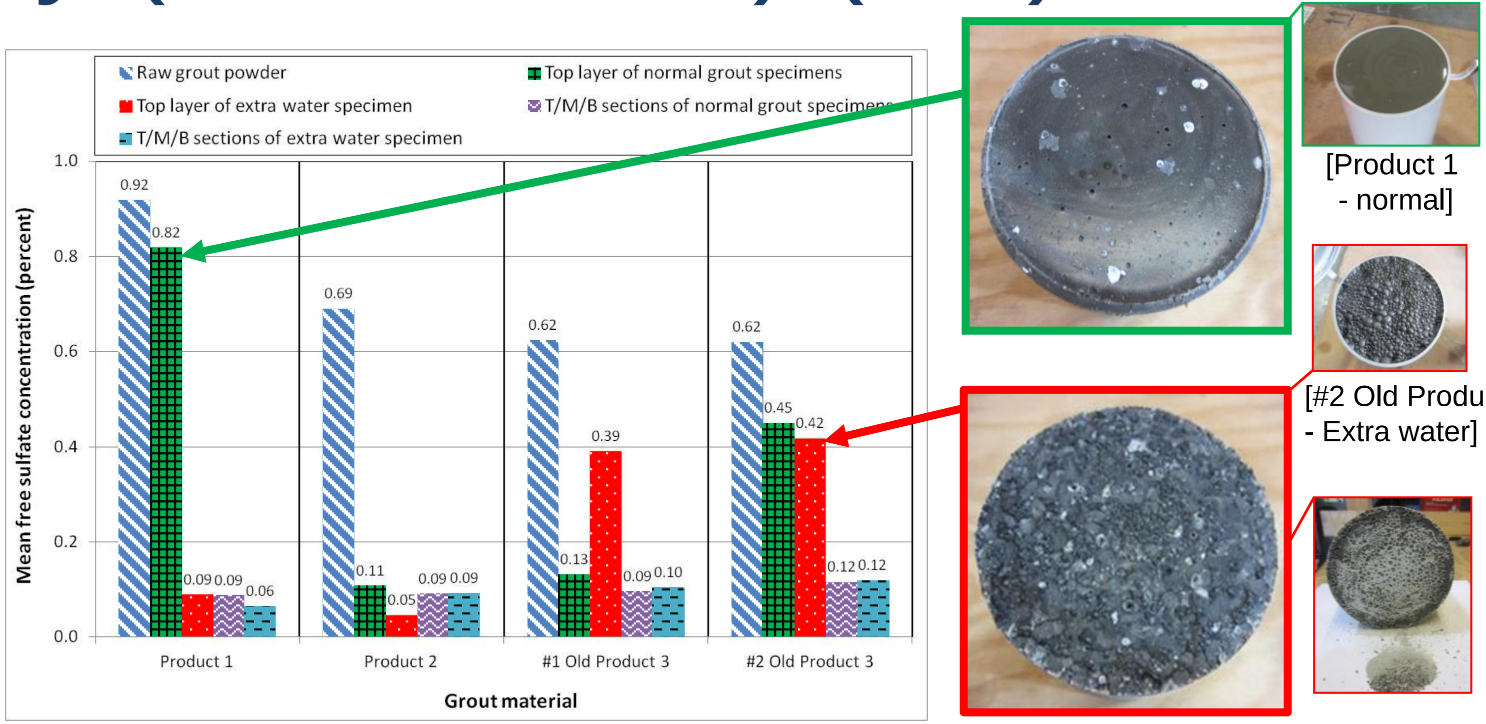
Grout Segregation and Sulfate Corrosivity Study (2014–2019) (5/8)





All figures source: FHWA (Hartt and Lee 2018).

Grout Segregation and Sulfate Corrosivity Study (2014–2019) (6/8)



[Product 1 - normal]

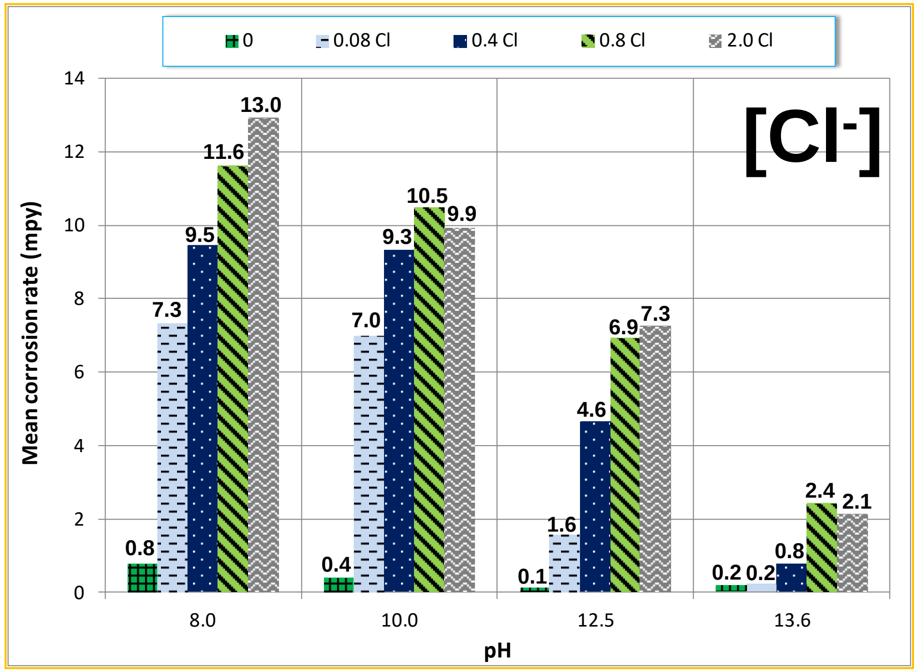
[#2 Old Product 3 - Extra water]

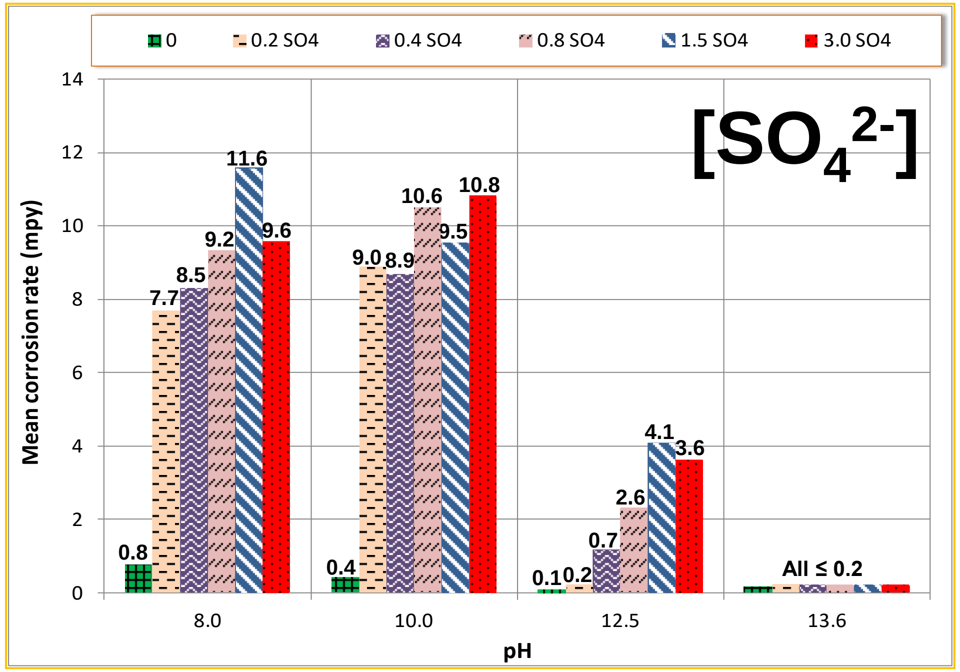
All figures source: FHWA (Lee 2021).

Major conclusions (Lee 2021):

- Water-soluble sulfate concentration in the raw grout powders was 0.35 ~ 1.01 percent by sample weight.
- Product 1 contained the highest mean concentration (0.92 percent); product 2 and product 3 had similar mean concentrations of 0.69 and 0.62 percent, respectively.

Grout Segregation and Sulfate Corrosivity Study (2014–2019) (7/8)





All figures source: FHWA (Lee 2021).

Major conclusions (Lee 2021):

- Chloride and sulfate ions exhibited similar mean corrosion rates in pH 8.0 and 10.0 aqueous solutions.
- Corrosion rate by sulfate ions decreased as pH increased to 12.5 and 13.6 → virtually zero in pH 13.6.
- Chloride ions exhibited higher corrosion rates than sulfate ions as pH increased to 12.5 and 13.6.

Grout Segregation and Sulfate Corrosivity Study (2014–2019) (8/8)

$[Cl^-]$

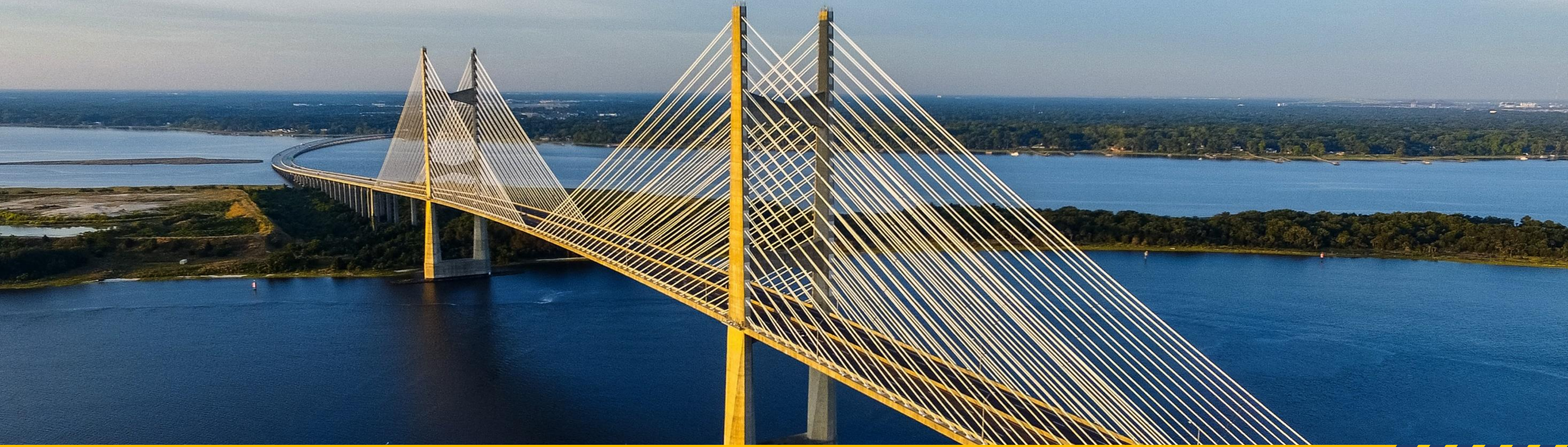
Chloride ions produced relatively high mean corrosion rates (from 7 to 13 mils per year) in the 2 lower pH solutions of 8 and 10. In the higher pH solutions of 12.5 and 13.6, chloride ions yielded lower mean corrosion rates (from 0.03 to 7 mils per year) compared to those observed in the pH 8 and 10 solutions.

$[SO_4^{2-}]$

Sulfate ions in the pH 8.0 and 10.0 solutions produced relatively high mean corrosion rates (from 7 to 13 mils per year). In an intermediate pH of 12.5, the mean corrosion rate was substantially reduced compared to those obtained in the lower pH solutions. In the highest pH of 13.6, the corrosion rate dropped noticeably.

Major conclusions (Lee 2021):

- Chloride and sulfate ions exhibited similar mean corrosion rates in pH 8.0 and 10.0 aqueous solutions.
- Corrosion rate by sulfate ions decreased as pH increased to 12.5 and 13.6 → virtually zero in pH 13.6.
- Chloride ions exhibited higher corrosion rates than sulfate ions, as pH increased to 12.5 and 13.6.



Source: FHWA.

Recently Completed Tendon Corrosion Laboratory Study

U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank
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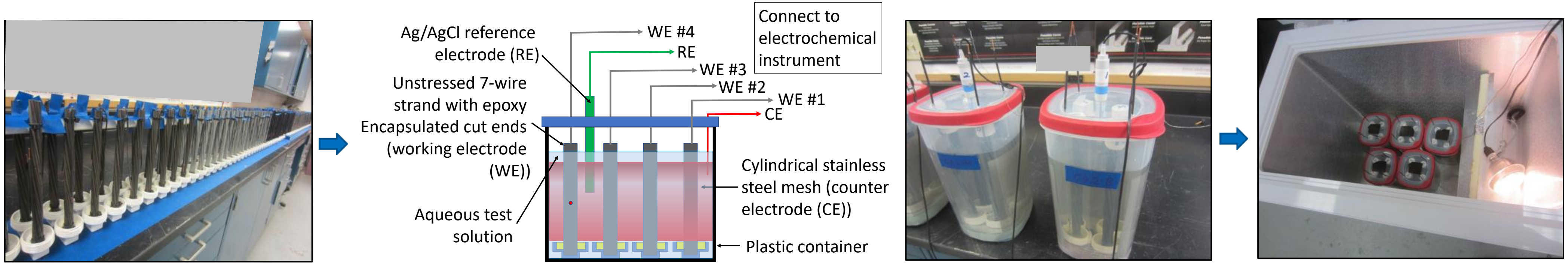
Corrosion Resistance of Alternative Metallic Strands (2020–2022) (1/4)

- Background: The tendons are always buried in grout/ducts (grouted external tendons) or in grout/ducts/concrete (grouted internal tendons), thus corrosion damage cannot be detected before it is too late. Therefore, more corrosion-resistant materials are needed for new construction and effective corrosion control methods are desirable for existing tendons.
- Relevant literature survey: More than 10 reports and company brochures were reviewed to develop a research plan.

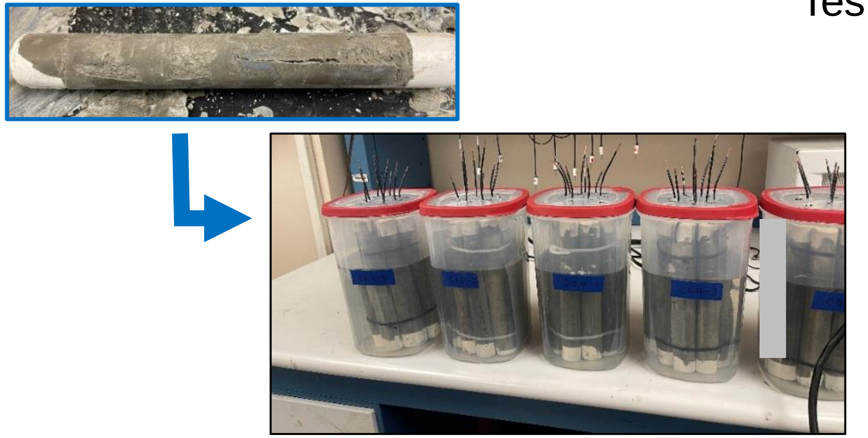
Corrosion Resistance of Alternative Metallic Strands (2020–2022) (2/4)

- Objectives: Conduct accelerated corrosion testing to quantify corrosion resistance of various metallic strand materials—bare strand, hot-dip galvanized strand, 95-percent zinc/5-percent aluminum coating strand, ECS (flow-filled type, no grit), and 2205 duplex SS strand—exposed to different concentrations of chloride (0.08, 0.2, 0.4, 0.8, 2.0 percent) and sulfate ions (0, 0.1, 0.2, 0.4, 0.8, 1.5, 3.0 percent).
- Potential impacts: Identify highly corrosion-resistant and economical “next-generation” strand material(s) for new construction PT bridges in the United States.

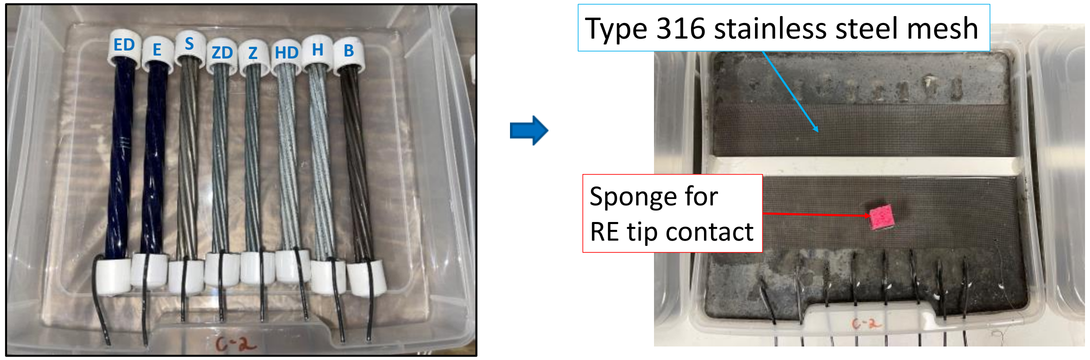
Corrosion Resistance of Alternative Metallic Strands (2020–2022) (3/4)



Testing in aqueous solutions.



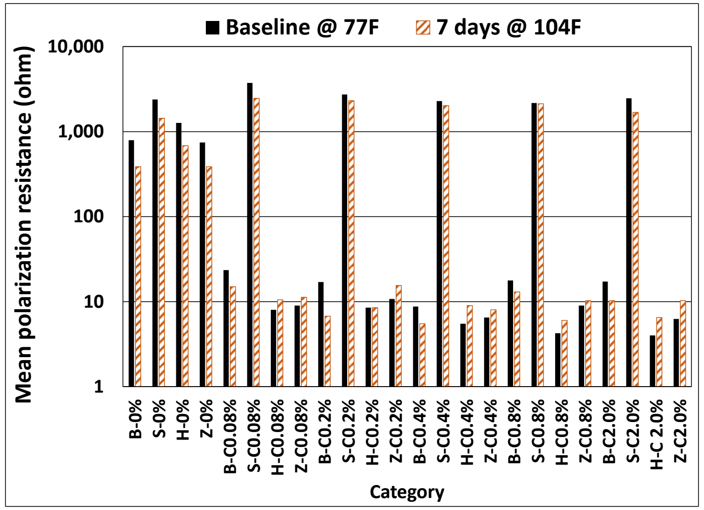
Testing in poor-quality grout.



Testing in good-quality grout.

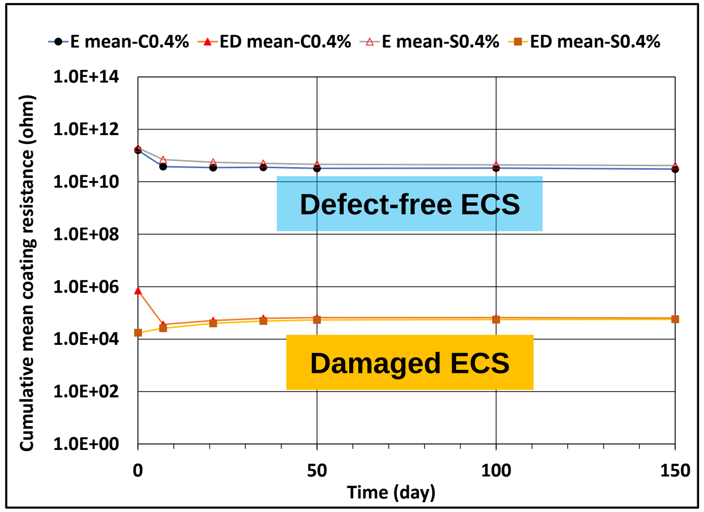
All figures source: FHWA (Lee Forthcoming b).

Corrosion Resistance of Alternative Metallic Strands (2020–2022) (4/4)



All figures source: FHWA (Lee Forthcoming b).

Mean polarization resistance data.

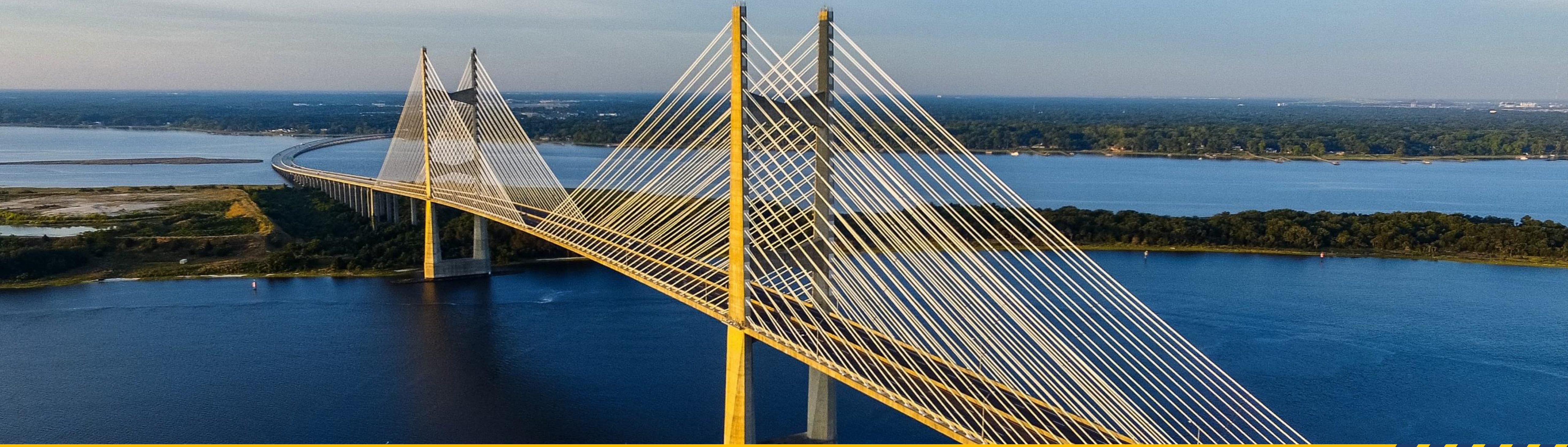


Cumulative mean coating resistance data.

ECS = epoxy-coated strand.

Major preliminary findings (Lee Forthcoming b):

- The conventional bare strand (B) exhibited the lowest corrosion resistance.
- Duplex 2205 SS strand (S) performed very well with the most positive corrosion potential and the highest polarization resistance (PR), and the lowest macrocell corrosion current (Imacro).
- The hot-dip galvanized (H) and 95-percent zinc/5-percent aluminum coated strands (Z) were the most active materials with very negative corrosion potential, the lowest PR, and the largest Imacro.
- The flow-filled epoxy strand (E) showed encouraging performance due to its high-quality electrical insulation barrier; when artificial coating defects were introduced (ED), the mean coating resistance was reduced significantly.



Source: FHWA.

Planned Tendon Corrosion Laboratory Studies

U.S. Department of Transportation
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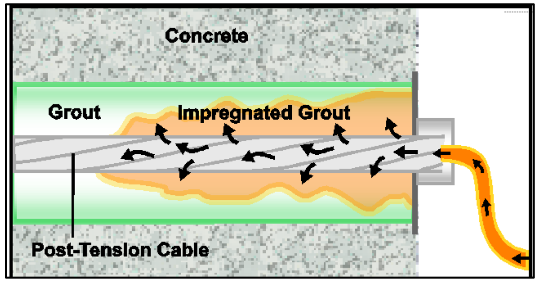
Effectiveness of Silicon-Based Polymer Corrosion Inhibitor by Impregnation Method

Research objective: to collect quantitative scientific data from the grouted specimens experiencing different levels of corrosion under an accelerated corrosion testing setup.



© 2014 Vector Corrosion Technologies (Lee 2022).

Injection of corrosion inhibitor.

Source: FHWA.

Field trial in Varina-Enon Bridge.

208 days in 5% NaCl fog chamber

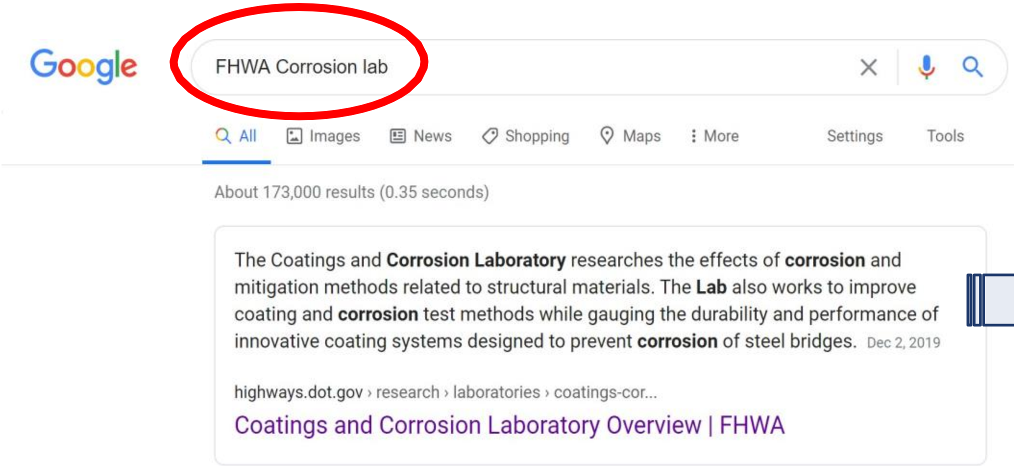
© 2017 FDOT (Lee 2022; Lee Forthcoming a).

Laboratory evaluation at the FDOT.

CCL Web Page

https://highways.dot.gov/research/laboratories/coatings-corrosion-laboratory/publications (FHWA n.d.)

Google® search: “FHWA Corrosion Lab”



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The Coatings and **Corrosion Laboratory** researches the effects of **corrosion** and mitigation methods related to structural materials. The **Lab** also works to improve coating and **corrosion** test methods while gauging the durability and performance of innovative coating systems designed to prevent **corrosion** of steel bridges. Dec 2, 2019

highways.dot.gov › research › laboratories › coatings-cor...

Coatings and Corrosion Laboratory Overview | FHWA

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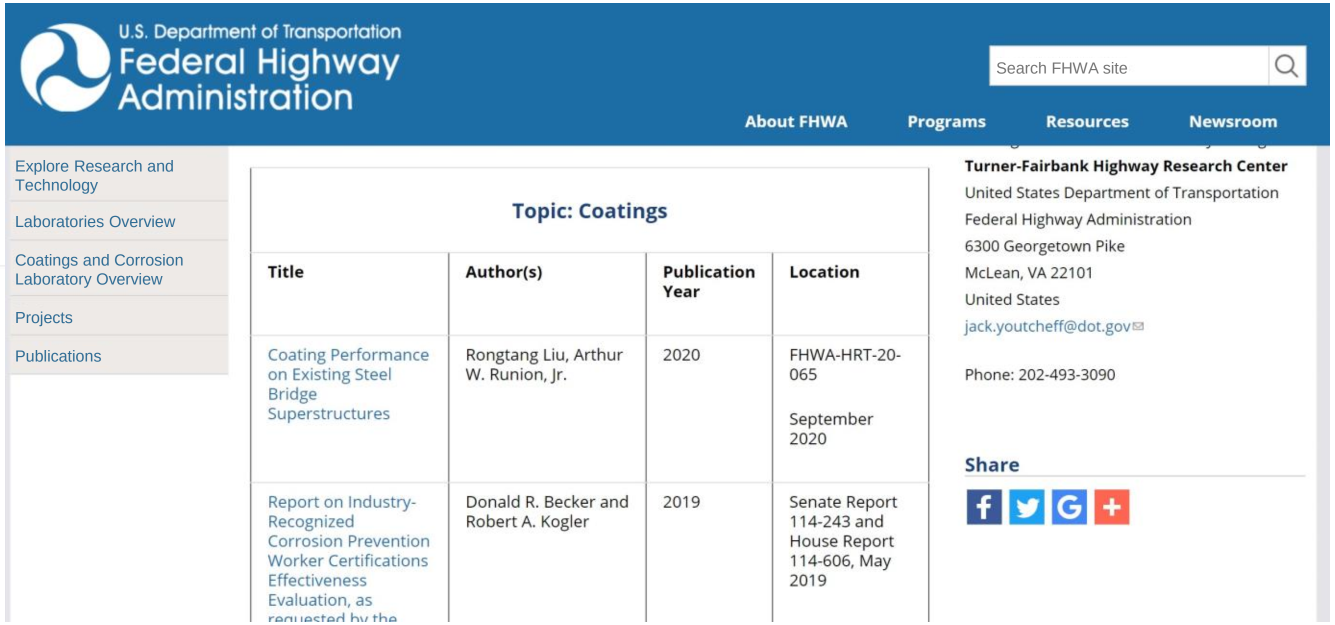

Topic: Coatings

Title	Author(s)	Publication Year	Location
Coating Performance on Existing Steel Bridge Superstructures	Rongtang Liu, Arthur W. Runion, Jr.	2020	FHWA-HRT-20-065 September 2020
Report on Industry-Recognized Corrosion Prevention Worker Certifications Effectiveness Evaluation, as requested by the	Donald R. Becker and Robert A. Kogler	2019	Senate Report 114-243 and House Report 114-606, May 2019

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Source: FHWA (FHWA n.d.).

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PTI. 2011. *Specifications for Grouting of Post-Tensioned Structures.* PTI M55.01-03. Farmington Hills, MI: PTI.

Lee, S.-K.. 2012. *Literature Review of Chloride Threshold Values for Grouted Post-Tensioned Tendons*. Report No. FHWA-HRT-12-067. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/12067/12067.pdf, last accessed May 19, 2023.

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