미국연방도로청 PT 텐던 연구프로그램 - 12년의 과정과 결과 소개

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서울시설공단
2020년 6월 30일

발표 순서

- 연구 배경 소개
- 그라우트 임계염화물량(Cl^-) 연구
- 그라우트 재료분리 특성과 황산염(SO_4^{2-})의 부식성 연구
- 텐던 부식에 따른 파단 예측 모델 연구
- 비파괴검사 방법 개발
- 부식억제 방법 실증 연구 (시간이 허락하는 경우)

Background

- 텐던부식에 관한 연방정부 차원의 연구 필요성 인식
  - San Francisco-Oakland Bay Bridge 내부텐던 부식문제 발생 (2007)
  - Varina-Enon 외부텐던 파단문제 발생 (2007)
- 외부텐던용 새로운 비파괴검사방법 개발 시작 (2008)
- SikaGrout 300 PT Pre-Packaged Grout 관련 문제 발생
  - VDOT and TxDOT 프로젝트에서 재료분리로 인한 문제점 발견 (2010)
  - FDOT Ringling Causeway Bridge 외부텐던 파단문제 발생 (2011)
  - FDOT I-4 Connector 프로젝트 재료분리 문제점 발견 (2012)
  - 일부 시멘트에 과다한 염화물 포함 (2012)

Background

- 오염된 그라우트의 임계염화물량을 정확히 파악할 필요성 대두 (2012)
- 수용성 황산염의 부식성 연구 필요성 인식 (2013)
- 텐던 파단을 예측할 이론 모델 개발 (2015)
- 내부텐던용 새로운 비파괴검사방법 개발 시작 (2017)
- 지금까지 알려진 텐던부식 사례와 관련 연구결과를 취합하여 텐던의 내구성에 관련한 종합보고서(synthesis report) 작성 (2019)

  → 상업화된 차세대 강연선의 부식특성 연구 개시 (2020)

  → 선별된 부식억제방법 검증 개시 (2020)

그라우트 임계염화물량 연구 (2012 – 2014)

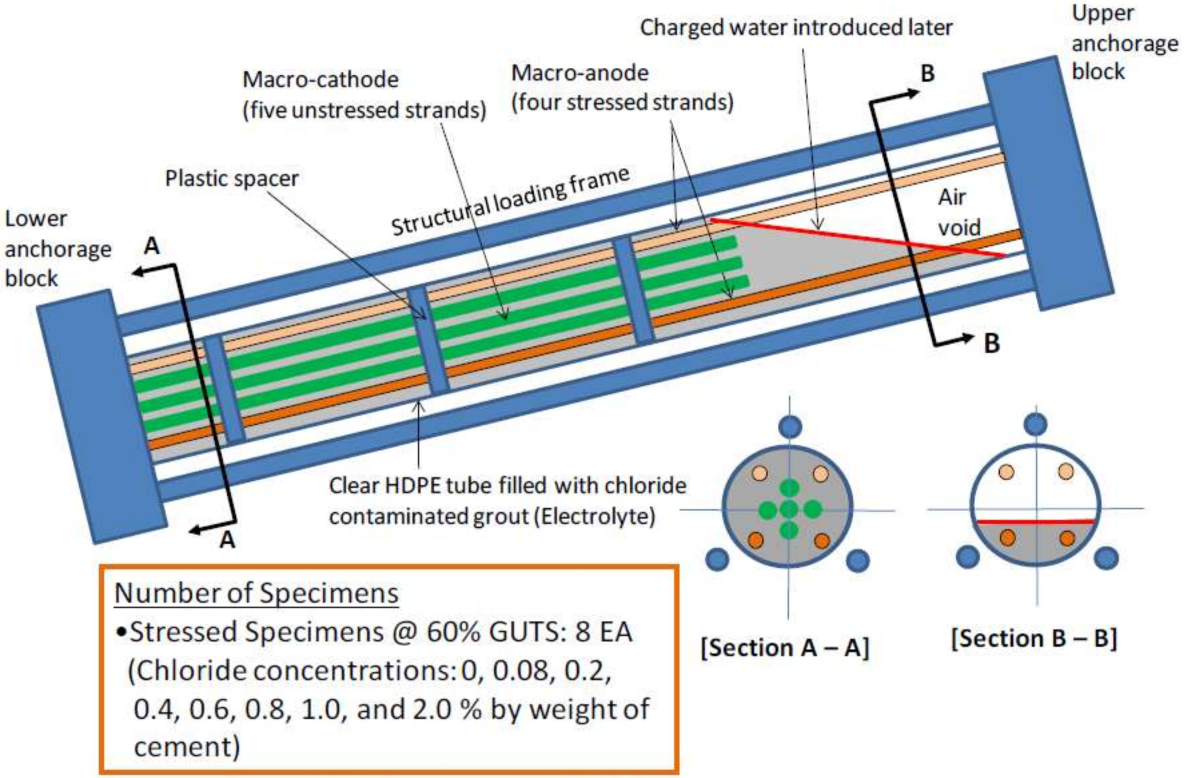
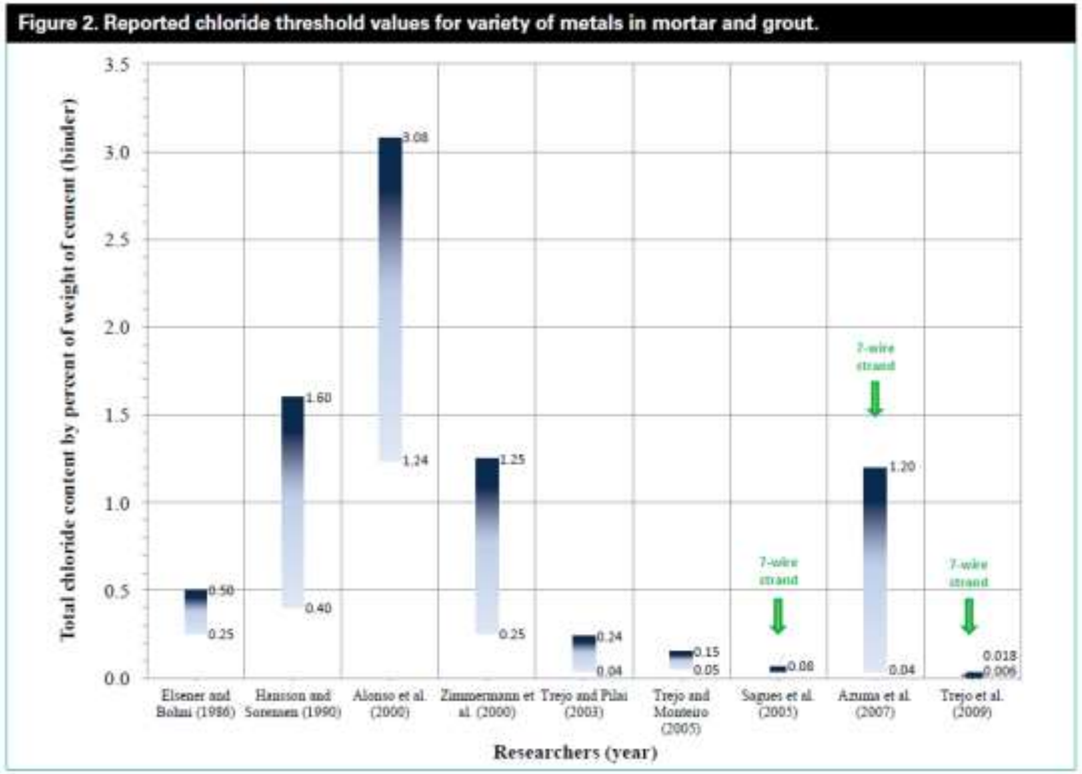
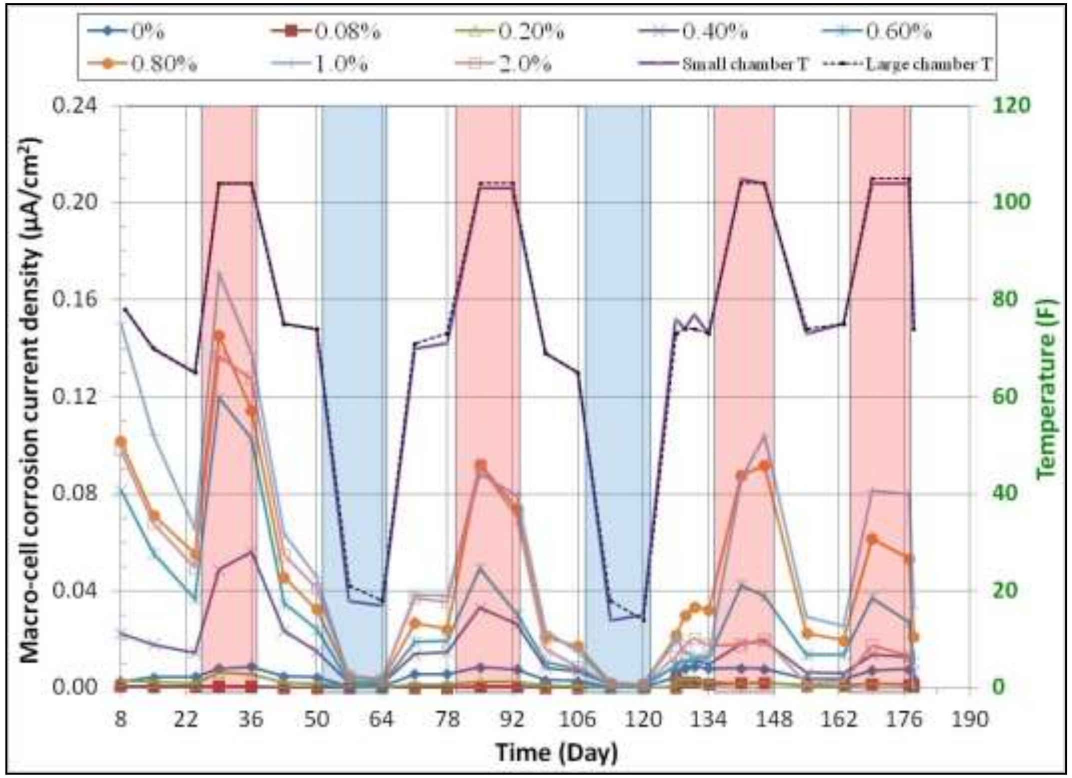


Figure 35. Illustration. Task 2.3 multi-strand specimens.

그라우트 임계염화물량 연구 (2012 – 2014)





정상적인 그라우트에서 부식개시에 필요한 염화물 농도는 시멘트량을
기준으로 0.4%; 활발한 부식진행에 필요한 염화물 농도는 0.8%.

결함이 있는 그라우트에서는 결함의 특성과 정도에 따라 크게 낮아질 수 있음.

그라우트 임계염화물량 연구 (2012 – 2014)

Long-Term Bridge Performance Program

SUMMARY REPORT

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

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

FHWA Contacts: Paul Y. Virmani, HRDI-60, (202) 493-3052, paul.virmani@dot.gov; Hamid Ghasemi, HRDI-60, (202) 493-3042, hamid.ghasemi@dot.gov.

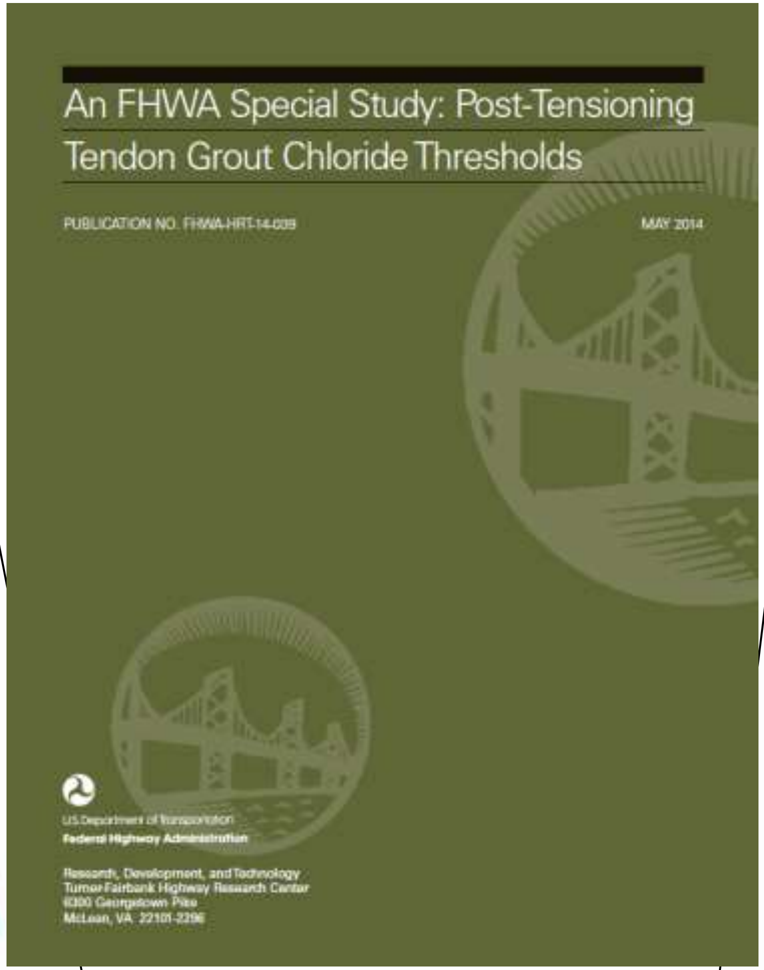
About LTBP

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.

Introduction

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)



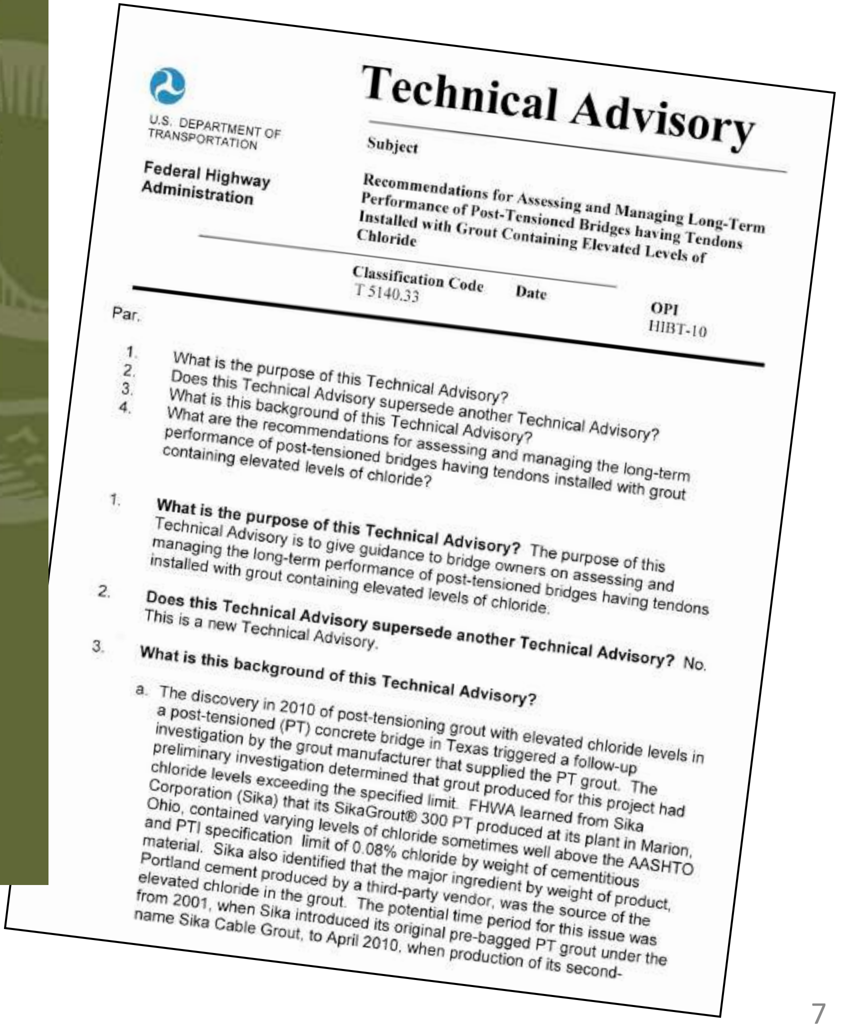
An FHWA Special Study: Post-Tensioning Tendon Grout Chloride Thresholds

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
McLean, VA 22101-2296



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.

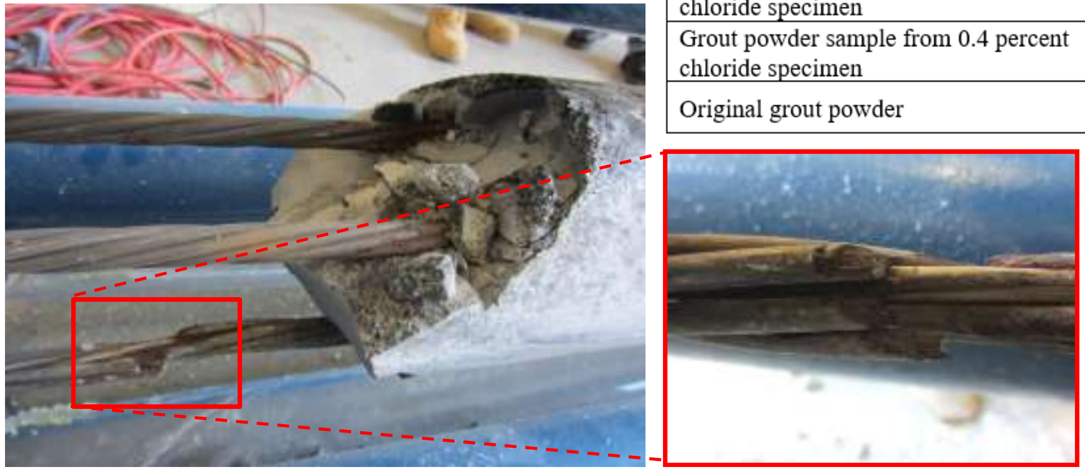
1. What is the purpose of this Technical Advisory?
2. Does this Technical Advisory supersede another Technical Advisory?
3. What is this background of this Technical Advisory?
4. What are the recommendations for assessing and managing the long-term performance of post-tensioned bridges having tendons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

그라우트 재료분리로 인한 황산염의 부식 유발

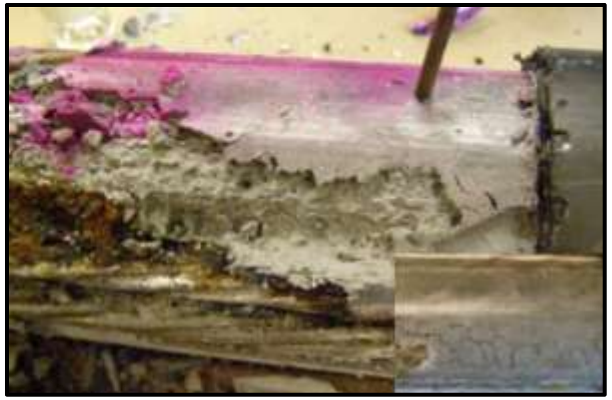
Free sulfate Analysis Results

Sample ID	Sample weight	Percent by grout weight
Black particles collected from void/grout interface of 0 percent chloride specimen	2 g	1.5
Top layer scraped from void/grout interface of 0 percent chloride specimen	5 g	1.5
Top layer scraped from void/grout interface of 0.2 percent chloride specimen	5 g	0.4
Top layer scraped from void/grout interface of 0.4 percent chloride specimen	5 g	0.1
Grout powder sample from 0 percent chloride specimen	2 g	0.0
Grout powder sample from 0.08 percent chloride specimen	2 g	0.1
Grout powder sample from 0.4 percent chloride specimen	2 g	0.0
Original grout powder	5 g	0.5

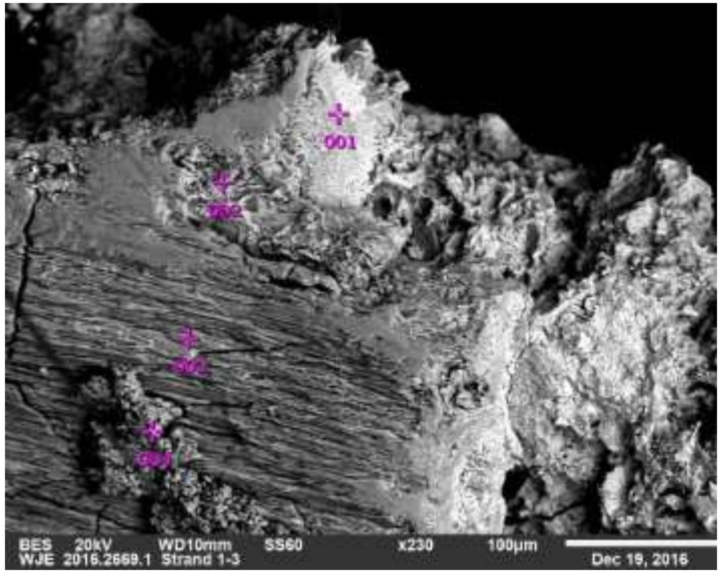


Source: Lee, S-K. and Zielske, J. (2014), "An FHWA Special Study: Post-Tensioning Tendon Grout Chloride Thresholds," Federal Highway Administration (FHWA-HRT-14-039).

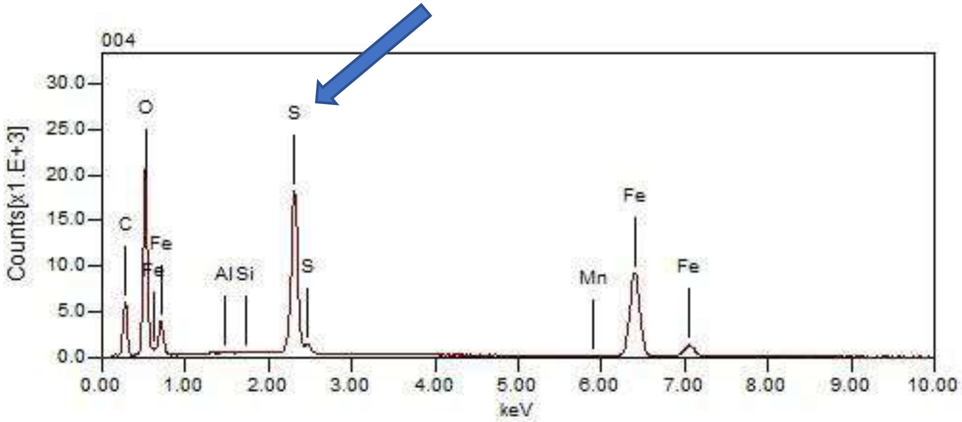
그라우트 재료분리로 인한 황산염의 부식 유발



[Ringling Bridge]

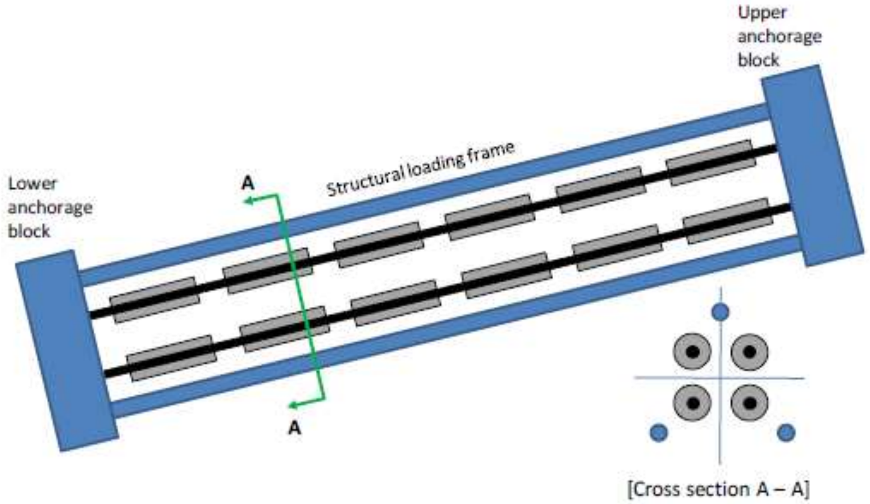


[서호교]



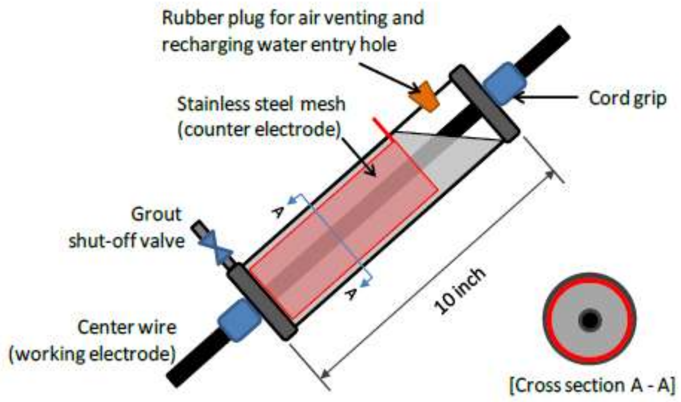
그라우트 재료분리 특성과 황산염의 부식성 연구
(2014 – 2019)

그라우트 재료분리 특성과 황산염의 부식성 연구 (2014 – 2019)



Source: FHWA.

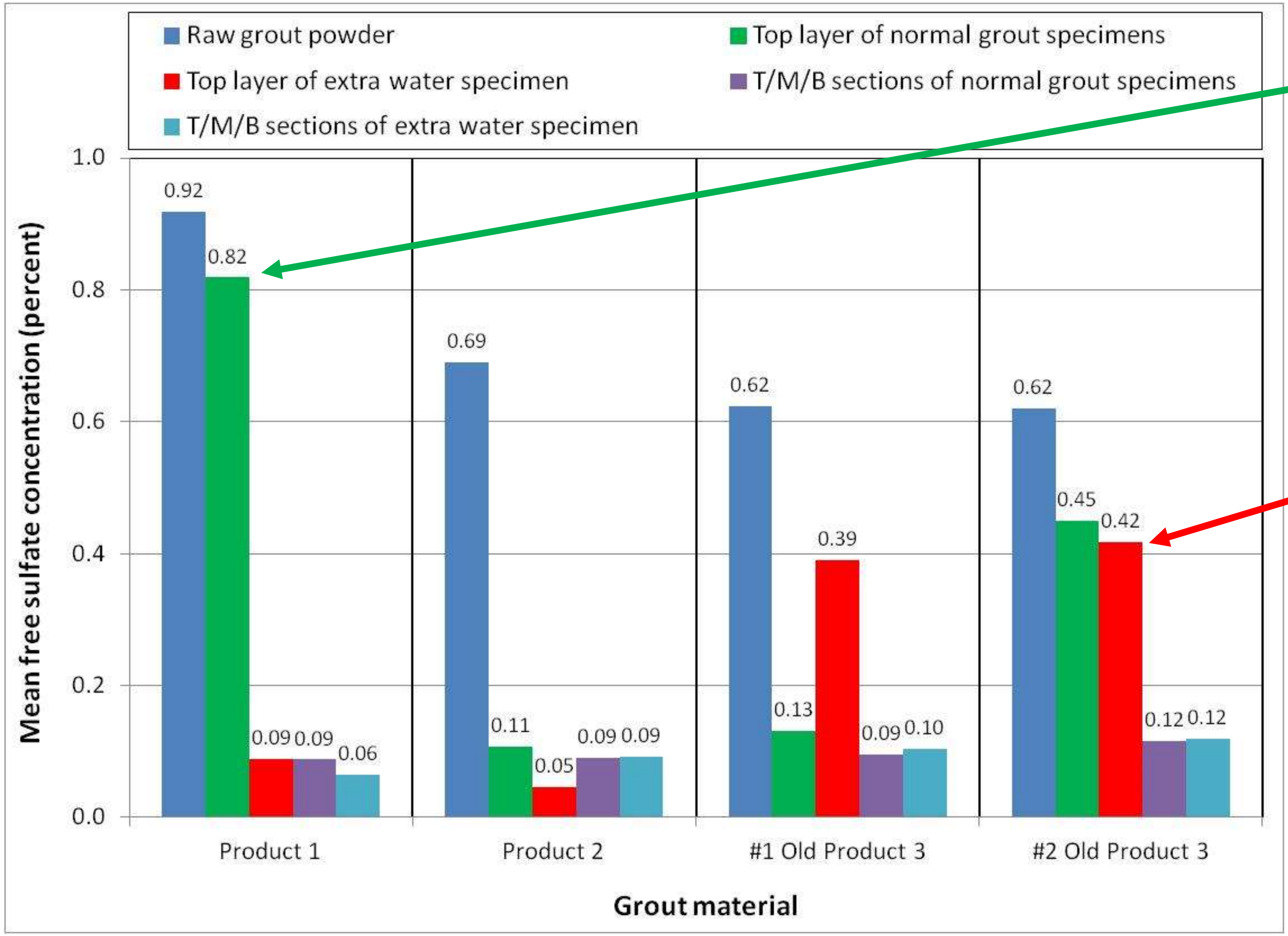
Figure 12. Illustration. Specimen arrangement in the large loading frame.



Source: FHWA.

Figure 10. Illustration. Schematic of test specimen containing an artificial void.

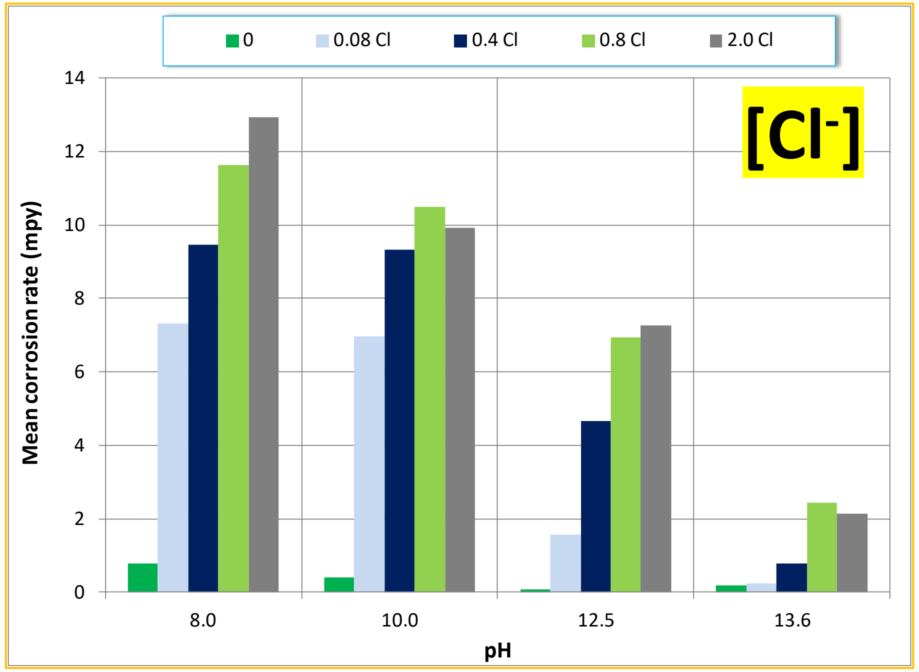
그라우트 타입과 위치별 수용성 황산염의 농도

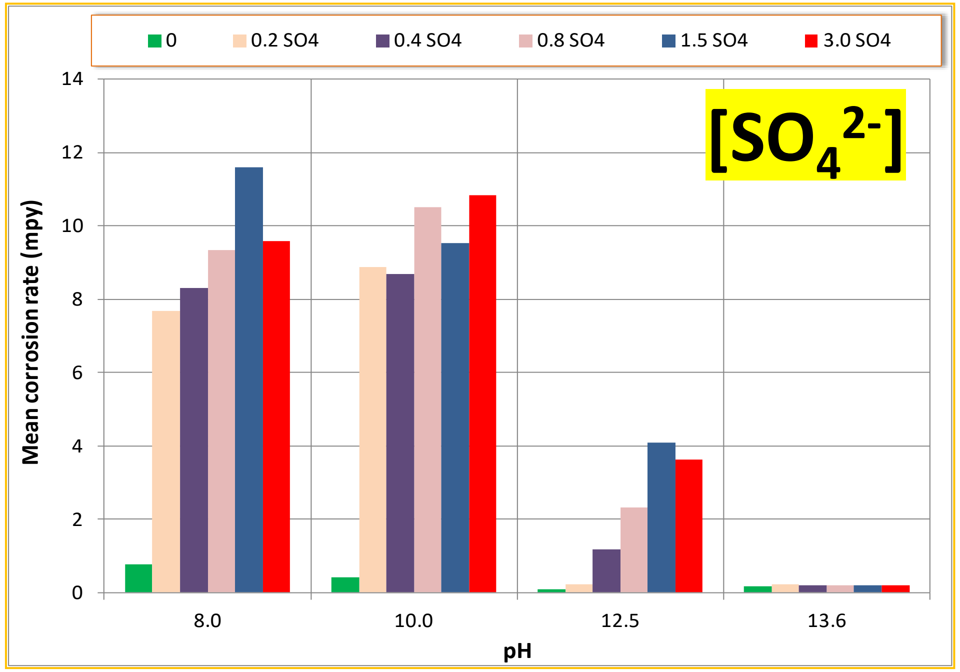


[Product 1
- normal]

[#2 Old Product 3
- Extra water]

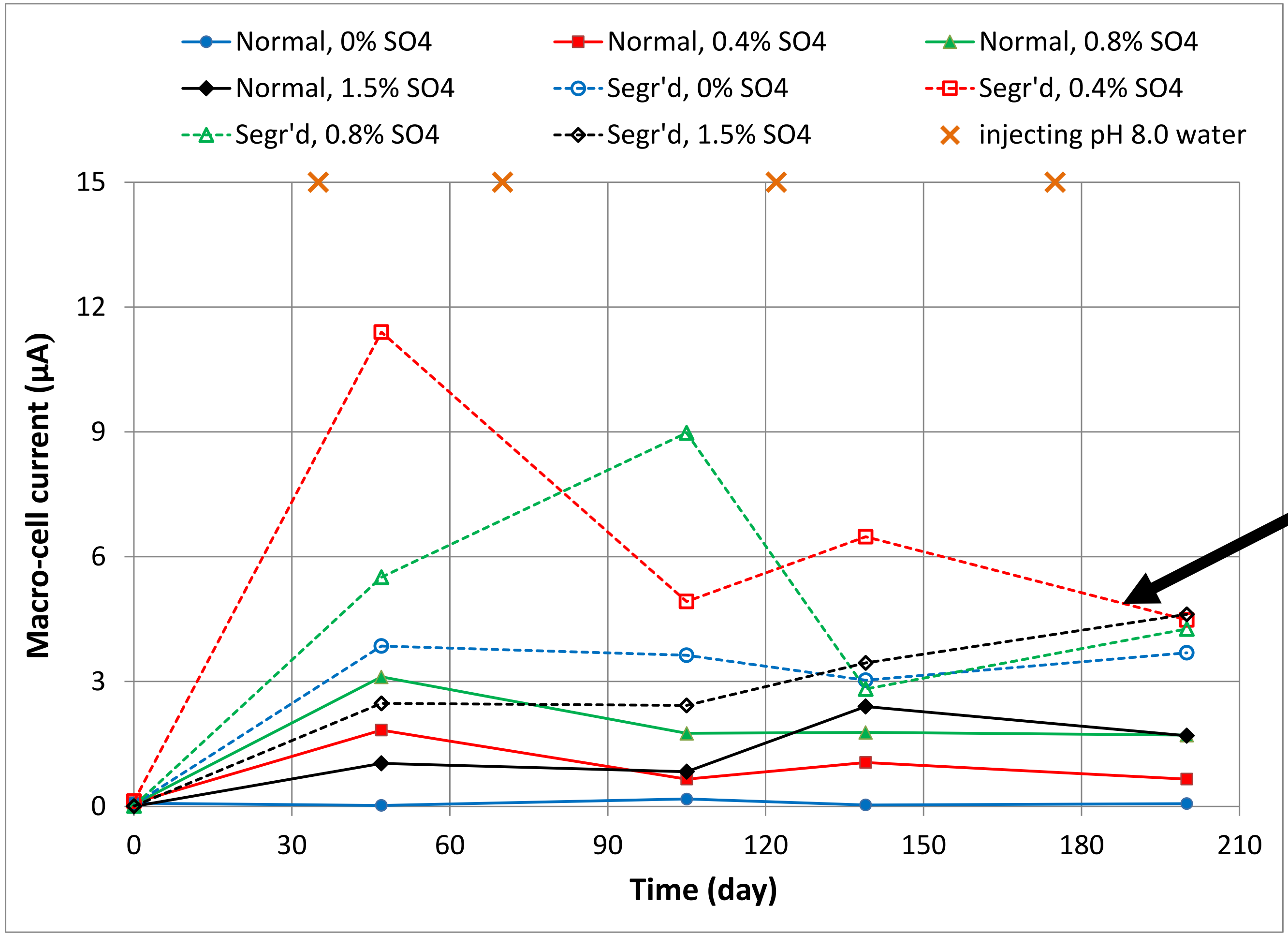
Chloride versus Sulfate

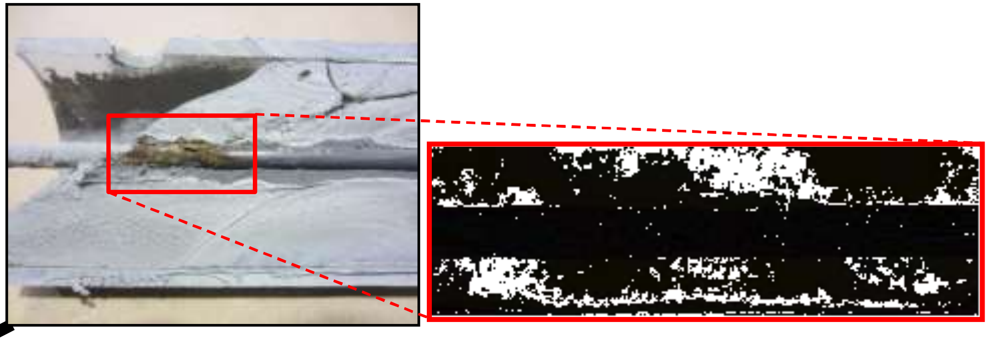




- pH 8.0 및 10.0 용액 속의 황산염 및 염화물은 유사한 이온농도에서 비슷한 평균 부식 속도 보임.
- 황산염에 의한 부식 속도는 pH가 12.5, 13.6으로 증가함에 따라 실질적으로 감소 → 농도에 관계없이 pH 13.6 용액에서 0에 근접.
- 염소 이온은 pH 12.5, 13.6 용액에서도 황산염에 비해 높은 부식속도를 유발.

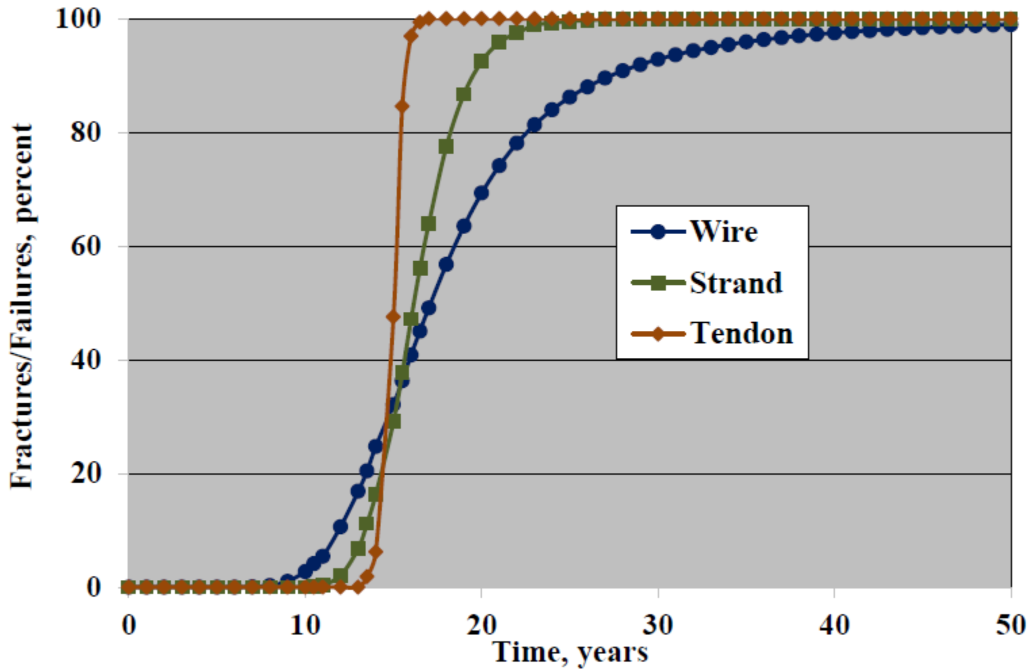
그라우트 재료분리+황산염 → 심각한 부식 손상





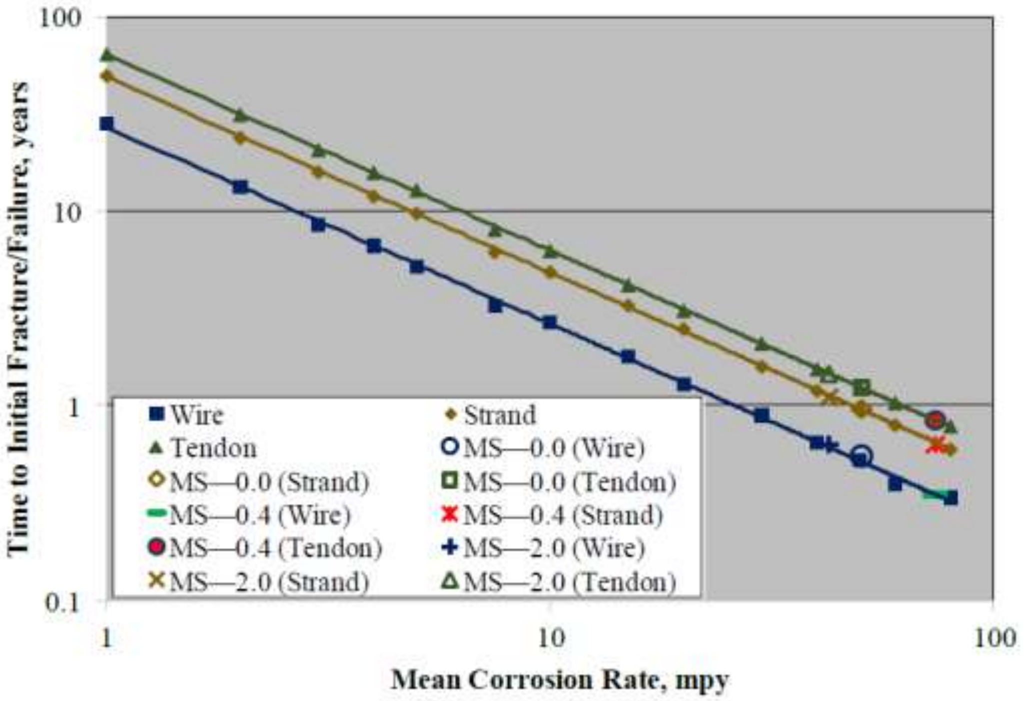
Source: Hartt, W. H. and Lee, S-K. (2018). “Corrosion Forecasting and Failure Projection of Post-Tensioned Tendons in Deficient Cementitious Grout,” Federal Highway Administration (FHWA-HRT-17-074).

텐던 부식에 따른 파단 예측 모델 연구 (2015 – 2017)



Source: FHWA.

Figure 55. Graph. Plot of the percentage of wire and strand fractures and tendon failures as a function of time based on phase 1 corrosion data for Specimen Number 1.0%–V–S (grout with 1.0 wt% chloride and an air void).(1)



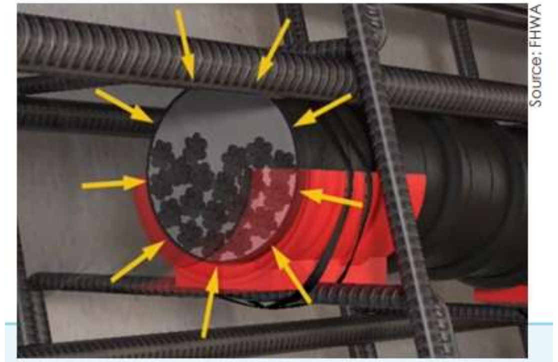
Source: FHWA.

Figure 83. Graph. Plot of T_f for wires, strands, and tendons as a function of corrosion rate as determined from the results in tables 14, 17, 18, and 20–33.

Source: Hartt, W. H. and Lee, S-K. (2018). "Corrosion Forecasting and Failure Projection of Post-Tensioned Tendons in Deficient Cementitious Grout," Federal Highway Administration (FHWA-HRT-17-074).

Electrically Isolated Tendons

The main advantage of EIT systems is the ability to non-destructively monitor tendon encapsulation over time. In the photo above, initial construction reading is collected.



The plastic ducts used in EIT systems provide a shield from corrosive substances and stray currents.

By measuring the AC impedance between the tendon and the reinforcing steel, bridge owners can assess the quality of the EIT encapsulation.

The EIT system has no macro-cell interaction with the reinforcing steel.

Source: Accelerating Market Readiness (2018). "Electrically Isolated Post-Tensioning Tendons for More Durable Bridges," Federal Highway Administration, https://www.fhwa.dot.gov/bridge/concrete/amr_eit.pdf.

PSC 거더 비파괴검사방법 평가 (2012 – 2019)

[December 2005]

[Impact Echo]

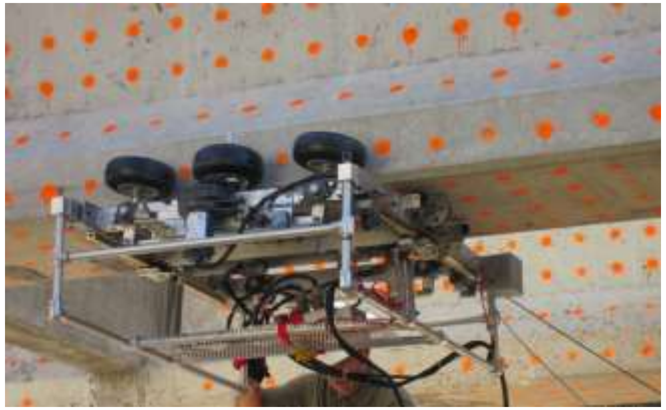
[Ultrasonic Surface Wave]

[Ultra Pulse Echo]

[GPR]

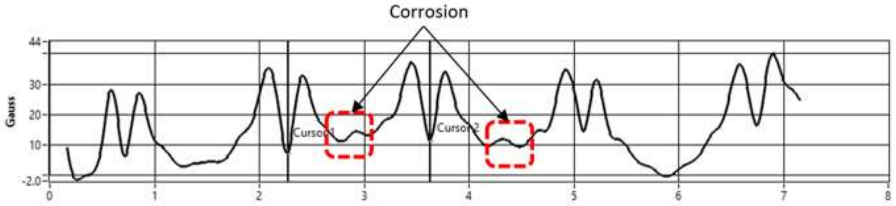
[Corrosion Testing]

PSC 거더 비파괴검사방법 평가 (2012 – 2019)

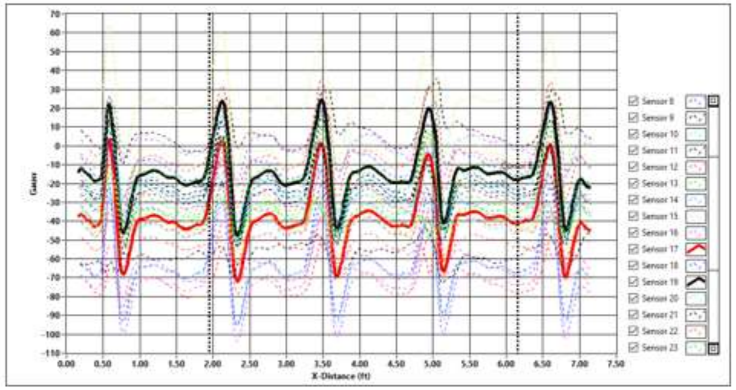


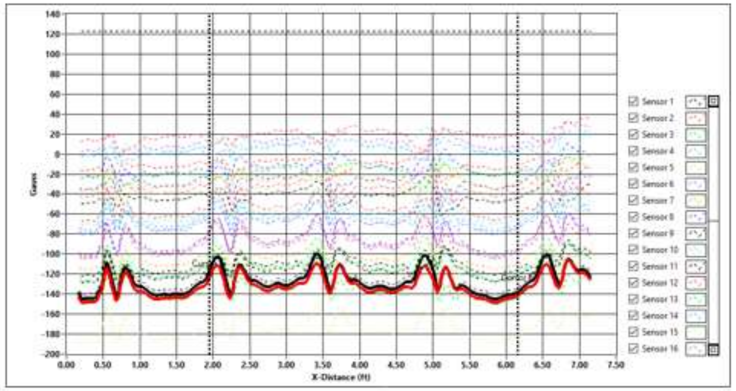
MFL System - 2012
(University of Wisconsin-Milwaukee)

Remnant Magnetism System - 2013
(Ingenieure Für Das Bauwesen)



Data interpretation of the representative sensors





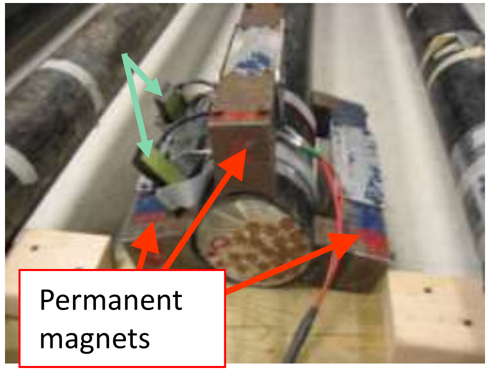
64 sensor data in axial and normal directions

Robotic MFL System - 2019
(University of Wisconsin-Milwaukee)

외부텐던용 비파괴검사방법 개발 (2008 – 2018)

[Ultrasonic]

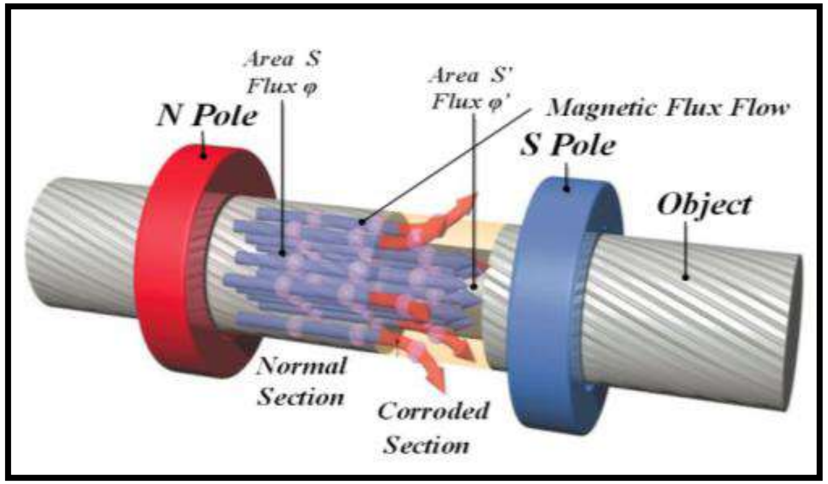
[Sonic Echo/Impulse Response]



[Magnetostrictive Sensor]

[Remnant Magnetic]

[Microwave Thermoreflectometry]

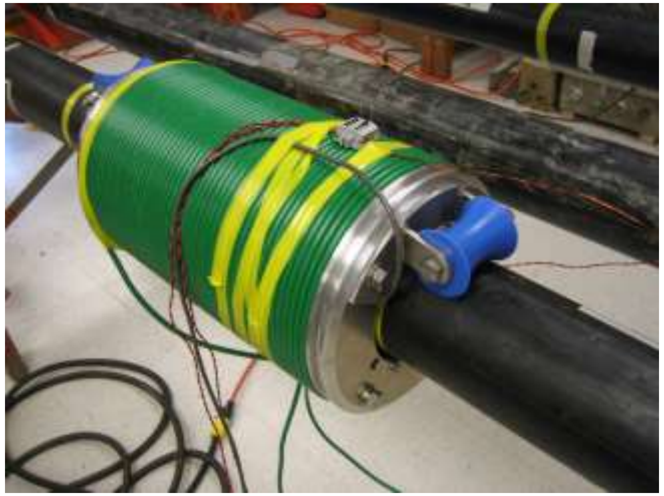


[Magnetic Main Flux Method]

최종 선정된
비파괴검사방법

외부텐던용 비파괴검사방법 개발 (2008 – 2018)

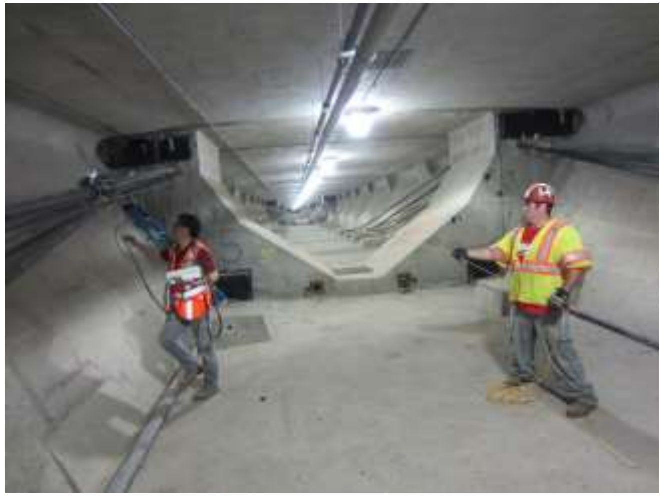
[Tokyo Rope Solenoid Type 1세대]



[Tokyo Rope Solenoid Type 2세대]

[Varina-Enon Bridge Field Trial]

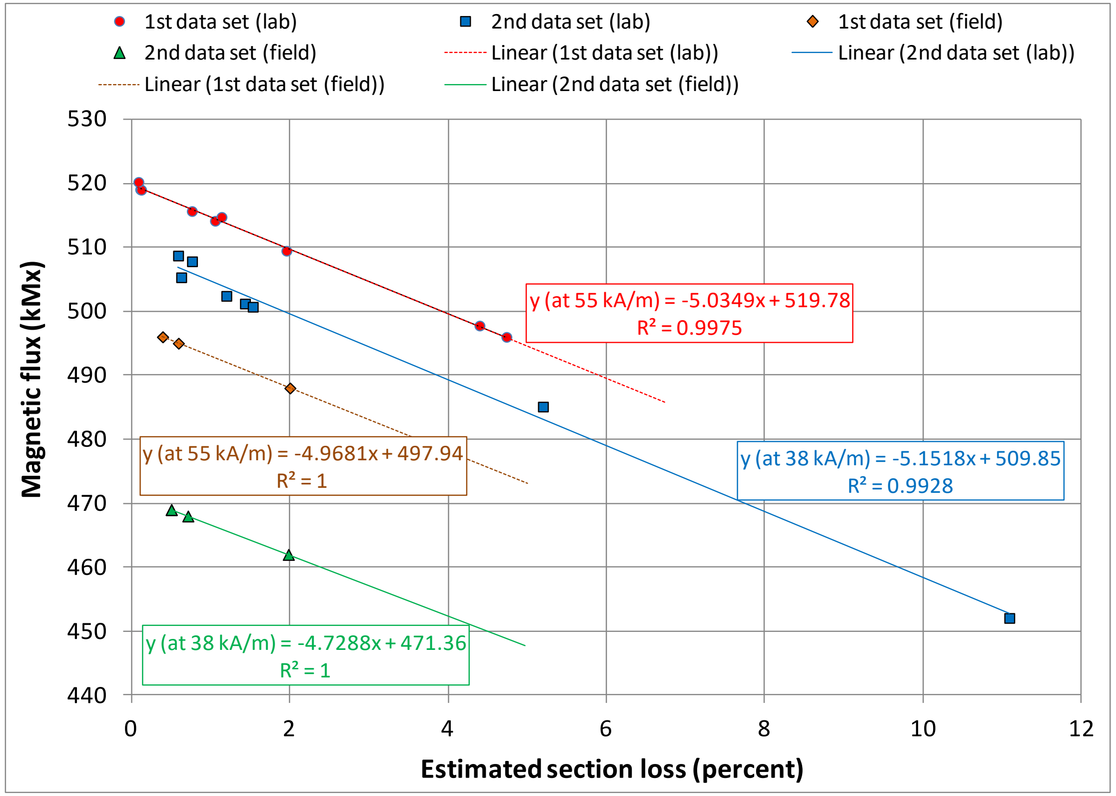
[Tokyo Rope Permanent Magnet Type]



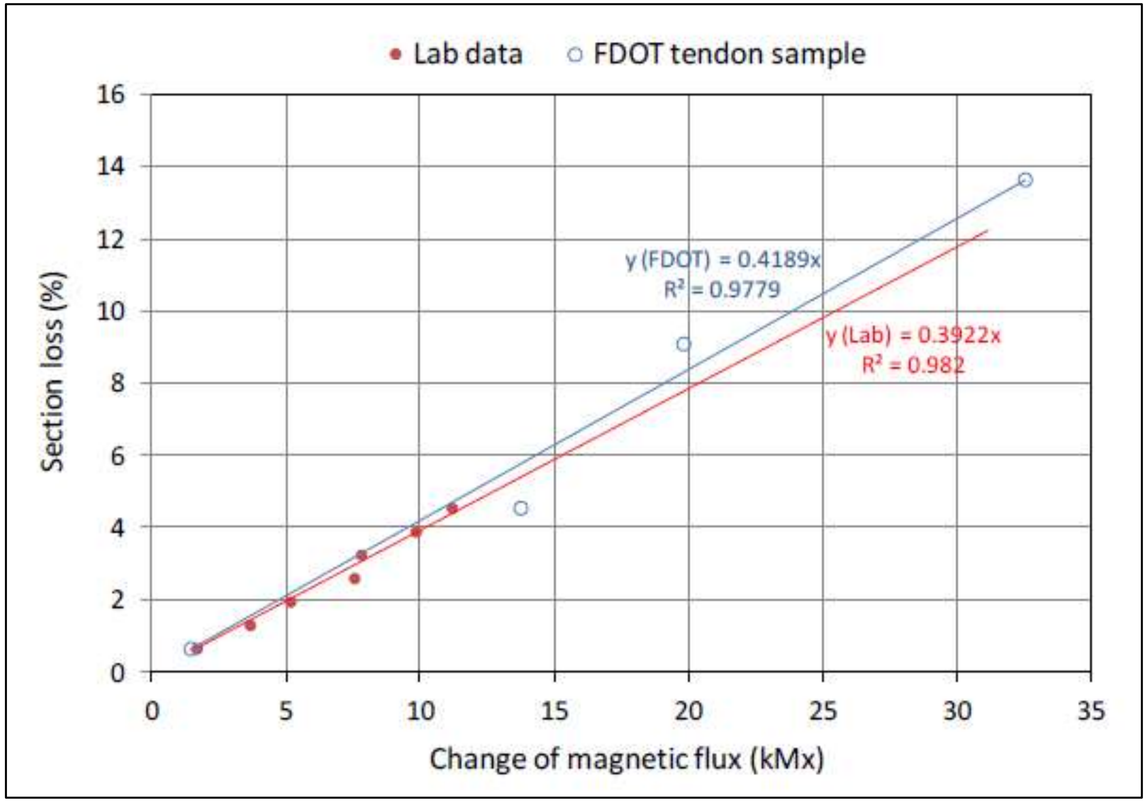
[Varina-Enon Bridge Field Trial]

[FDOT Ringling Bridge Evaluation Project]

단면손실 감지 능력



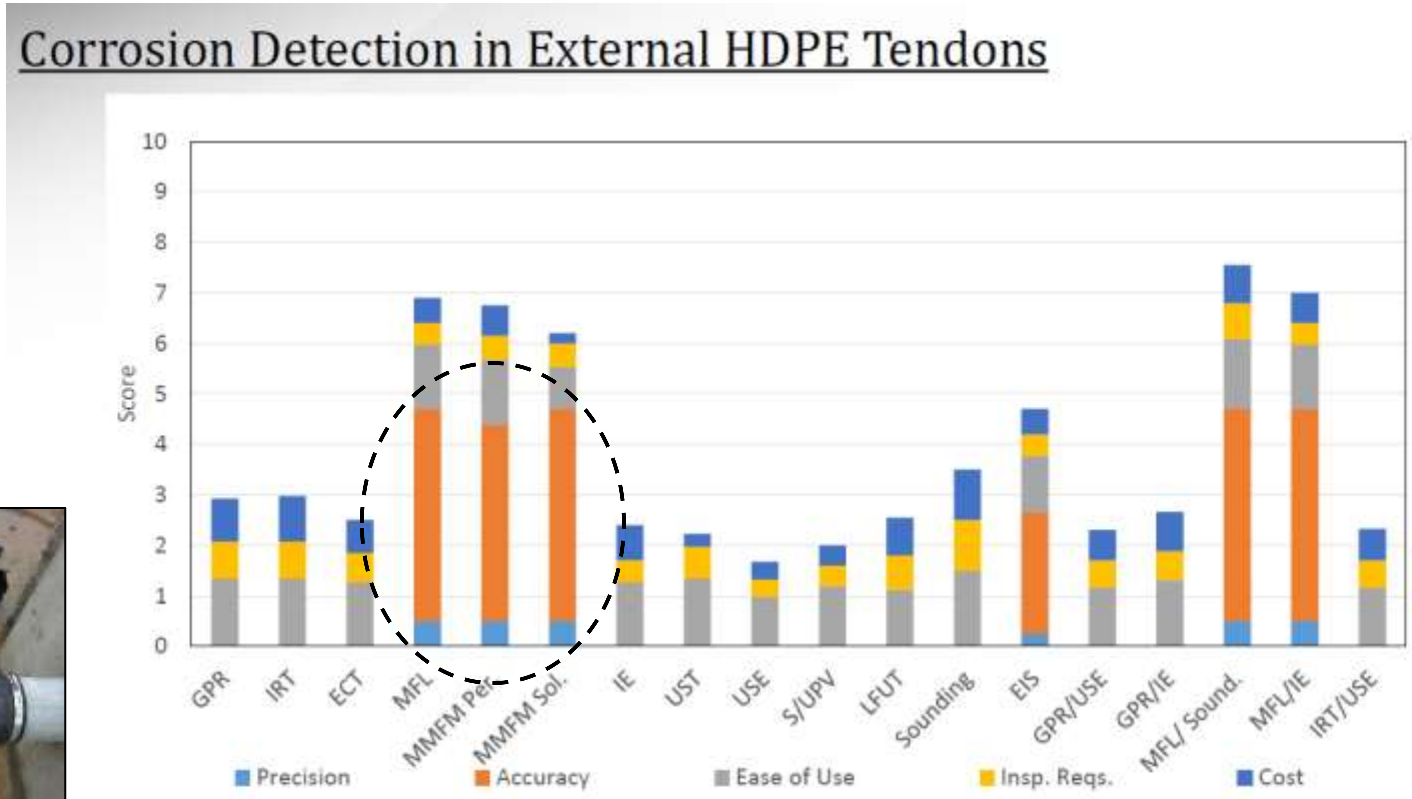
[Solenoid Type Data – FHWA Lab & Varina-Enon Bridge]



[Permanent Magnet Type Data – Ringling Bridge]

- Solenoid Type: 0.4% (point measurement) and 1.0% section loss (scan measurement)
- Permanent Magnet Type: 3.0% (scan measurement).

외부텐던용 비파괴검사방법 외부 평가 결과



Sources: Hurlebaus, S. et. al, "Condition Assessment of Bridge Post-Tensioning and Stay Cable Systems Using NDE Methods," NCHRP full report (Project No. 14-28), TRB, September 2016; TRB Webinar, October 2017.

외부텐던용 비파괴검사방법 외부 평가 결과

비파괴탐사의 Blind Test(Tokyo Rope)

2차 블라인드테스트 결과(부식 단면결손)

업체	탐사법	인위손상 (N)	탐사개수(M)		유효율 G/M (%)	위치정확률 G/N (%)	RMS	현장적용성
			G	PG				
B	MMFM	24	27(23)*		81.4 (95.7)*	91.7	1.78	◎
			22	0				

1차 블라인드테스트 결과(부식 단면결손)

업체	탐사법	인위손상 (N)	탐사개수(M)		유효율 G/M (%)	위치정확률 G/N (%)	RMS	현장적용성
			G	PG				
B	MMFM	24	26(22)*		61.5 (72.7)*	66.7	3.25	◎
			16	0				

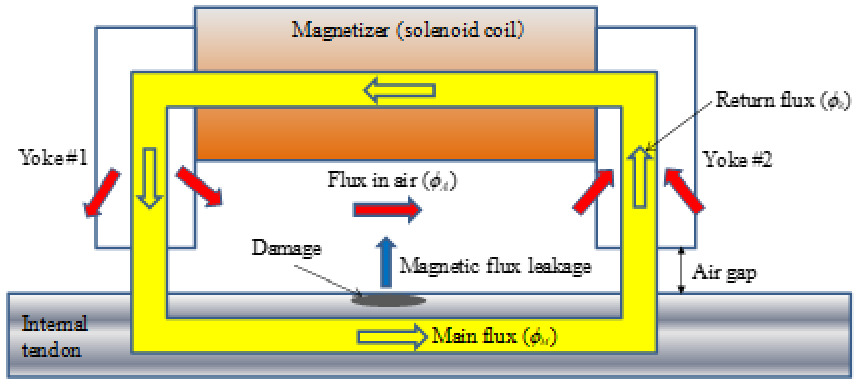
( )* : 찾아낸 탐사개수에서 중앙부 Tag 용접부 제외할 경우, ※ 현장적용성 : × < Δ < ○ < ◎

KICT 한국건설기술연구원 KIBSE 서울시설공단 서울특별시 13


[1차 테스트, 2016년 8월]

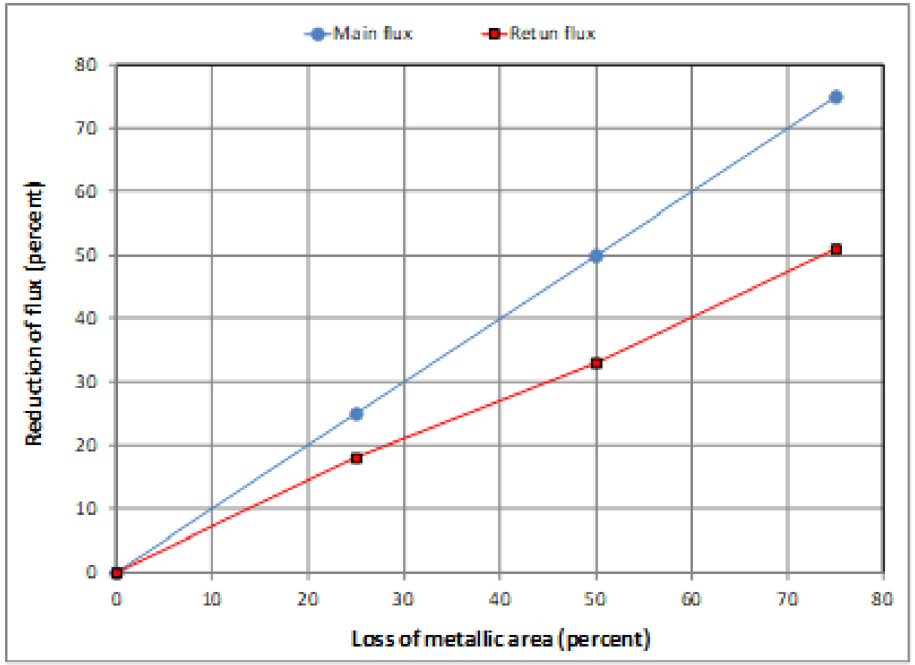

[2차 테스트, 2017년 7월]

내부텐던용 비파괴검사방법 개발 (2017 – ????)



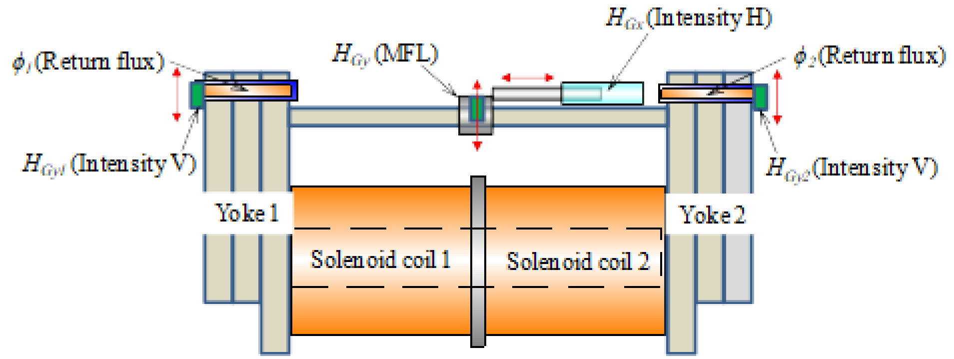
Source: FHWA

Figure 40. Illustration. Principle of Return Flux Method (RFM).



Source: FHWA

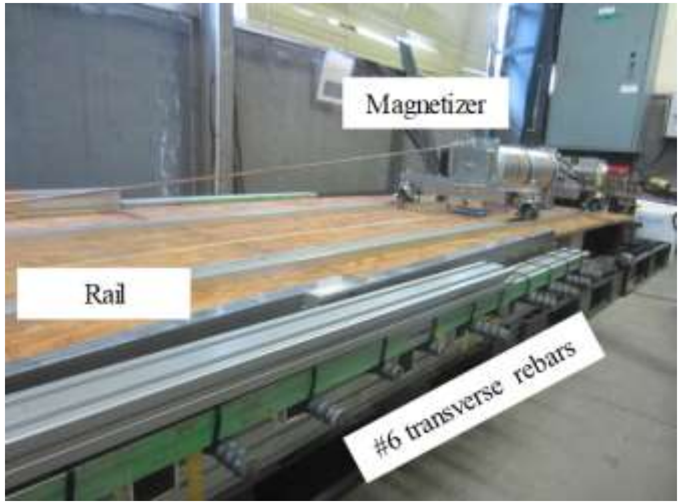
Figure 41. Graph. Relationship between magnetic flux and cross-sectional area.



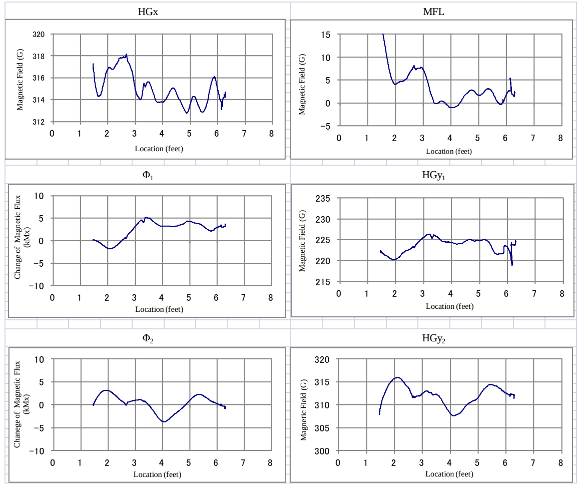
Source: FHWA

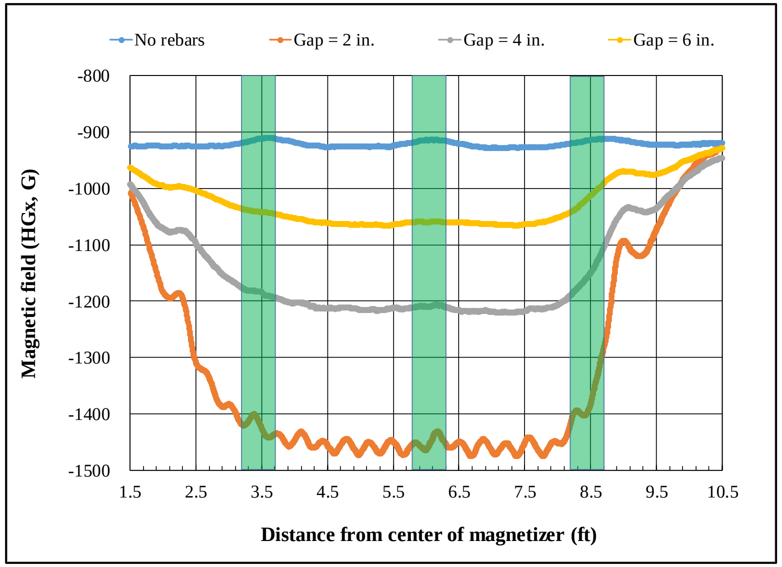
Figure 44. Illustration. Functionality of fourth prototype components.

내부텐던용 비파괴검사방법 개발 (2017 – ????)



내부텐던용 비파괴검사방법 개발 (2017 – ????)





Number of strands	Gap (in.)	Section loss (%)				
		6.7	10.0	13.3	20.0	40.0
5	No transverse rebars				Detected	Detected
	2				Detected	Detected
	4				Detected	Detected
	6				Detected	Detected
10	No transverse rebars		Detected		Detected	
	2		Missed		Detected	
	4		Missed		Detected	
	6		Missed		Detected	
15	No transverse rebars	Detected		Detected		
	2	Missed		Detected		
	4	Missed		Detected		
	6	Missed		Detected		

감사합니다.

차세대 강연선 내식성 평가 (2020 – 2022)

[Aqueous Solution Testing]

[Salt Spray Testing]

[In-Grout Testing]

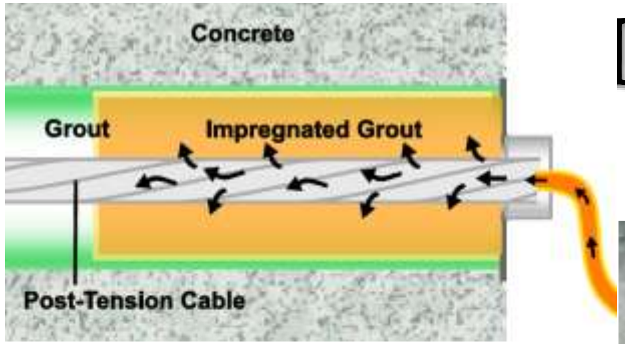
강연선 시편 종류

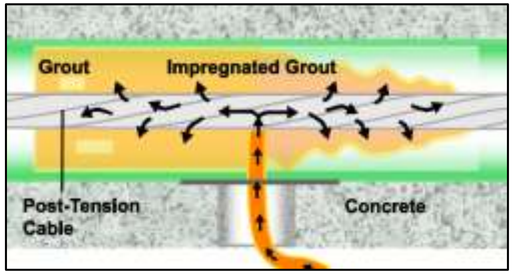
1. ASTM A416 Bare Strand
2. Hot Dip Galvanized Strand
3. Zinc Alloy Coating Strand
4. Flow-Filled Epoxy Coated Strand
5. 2205 Duplex Stainless Steel Strand

연구목적

1. 신설 PT 교량에 그라우트나 왁스없이 사용 가능?
2. 신설 PT 교량에 그라우트와 함께 사용할 경우 부식 억제 성능?

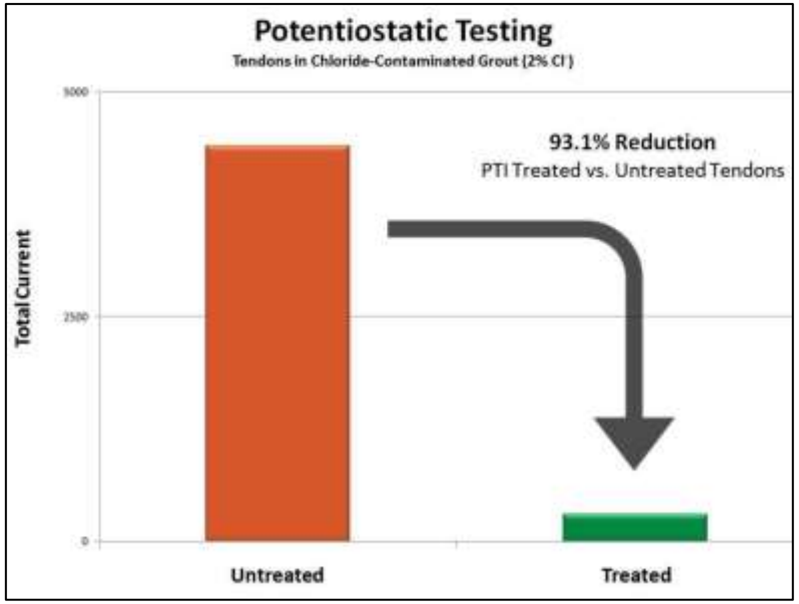
Impregnation Method (FDOT, VDOT)

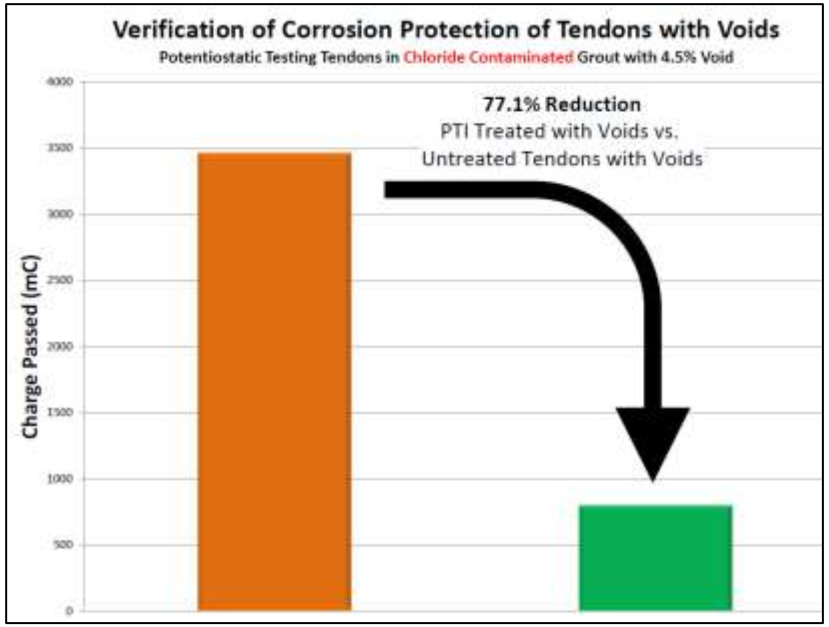




VDOT data (July 2015): $12,222 per tendon (mobilization for $3,947 and injection for $8,275)

Impregnation Method (Vendor Data)





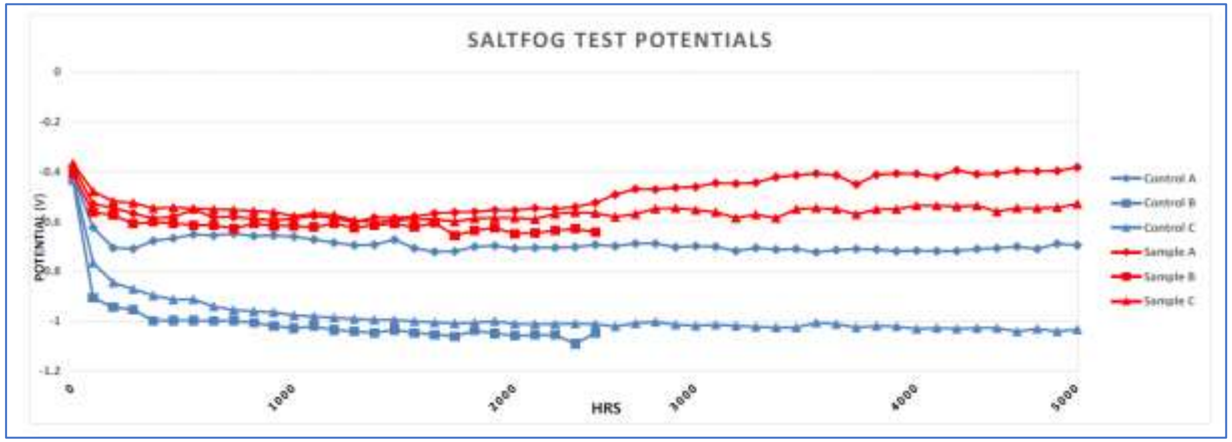
"Prior to completing impregnation, the moisture content of the strands was tested to ensure the strands, voids and grout was not saturated with water. As a result, drying of the strands and surrounding grout was not required prior to impregnation."

Sources: 2015 TRB Presentation Material; Whitmore, D. and Lasa, I., (2014). "Cable Impregnation for Post-Tension Grouting Problems."

Impregnation Method (FDOT Lab Data)

[Salt Fog Testing]

[Salt Water Ponding Testing]



[Fog Specimen-Control]

[Fog Specimen-Treated]

[Ponding Specimen-Treated]

Source: "Evaluation of a Silicon Based Polymer Corrosion Inhibitor for Post-Tensioned Tendons," Interim Unofficial Report, FDOT.

Impregnation Method 실험실 평가 (2020 – 2023)