NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Resistivity and Concrete Durability

October 11, 2022

12:30 – 2:00 PM

NOVEMBER 2022 UPDATE

PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Beth Ewoldsen at TRBwebinar@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

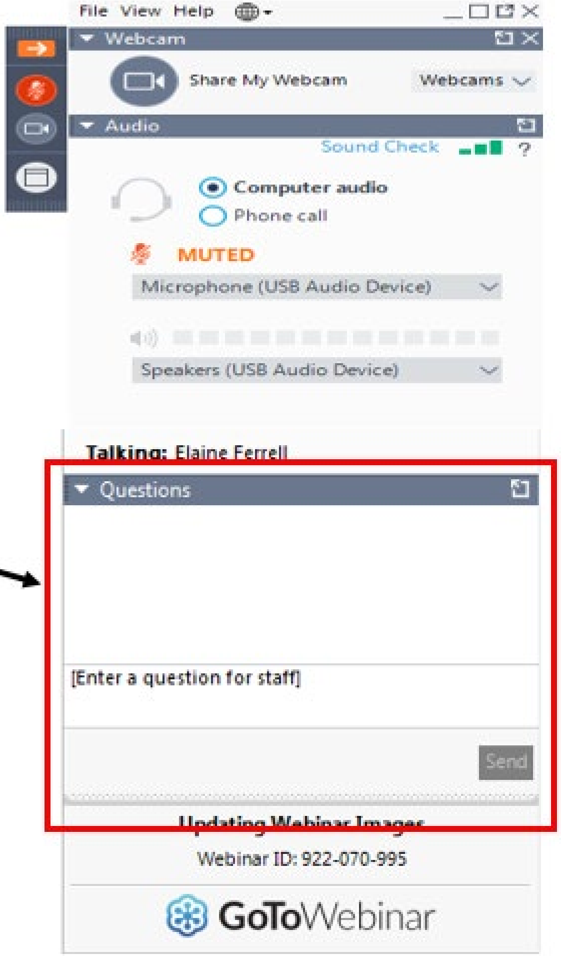
RCEP
REGISTERED CONTINUING EDUCATION PROGRAM

Learning Objectives

- Provide a foundational understating of concrete resistivity and its impact on durability.
- Learn about how this is being implemented in practice and new research developments.

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's presenters

Michael Praul
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NATIONAL ACADEMIES *Sciences Engineering Medicine*

Resistivity: What is it and how can it help make durable concrete?

TRB Webinar Series

October 11, 2022

Robert Spragg, Ph.D.
Concrete Materials Engineer, Pavement Materials Team
Office of Infrastructure
Federal Highway Administration

Disclaimers

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
EDC	Every Day Counts
EPDs	Environmental Product Declarations
FHWA	Federal Highway Administration
P&R	Preservation and Repair
PEM	Performance Engineered Mixtures
QC	Quality Control
SCMs	Supplementary Cementitious Materials
TFHRC	Turner-Fairbank Highway Research Center
UHPC	Ultra-High Performance Concrete

Bottom Line Up Front:

Resistivity is an economical, practical, and scientifically-based technique to assess the durability of concrete. It is implementation-ready in both agency QA programs and contractor quality control operations.

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Similar Terminology

Resistivity /riˌzisˈtivədē/

- A measure of how a material resists the flow of electric current.
- Independent of size and shape.
- Units of ohmmeter (Ω·m)
- Analogous to stress (psi).

Resistance /rəˈzistəns/

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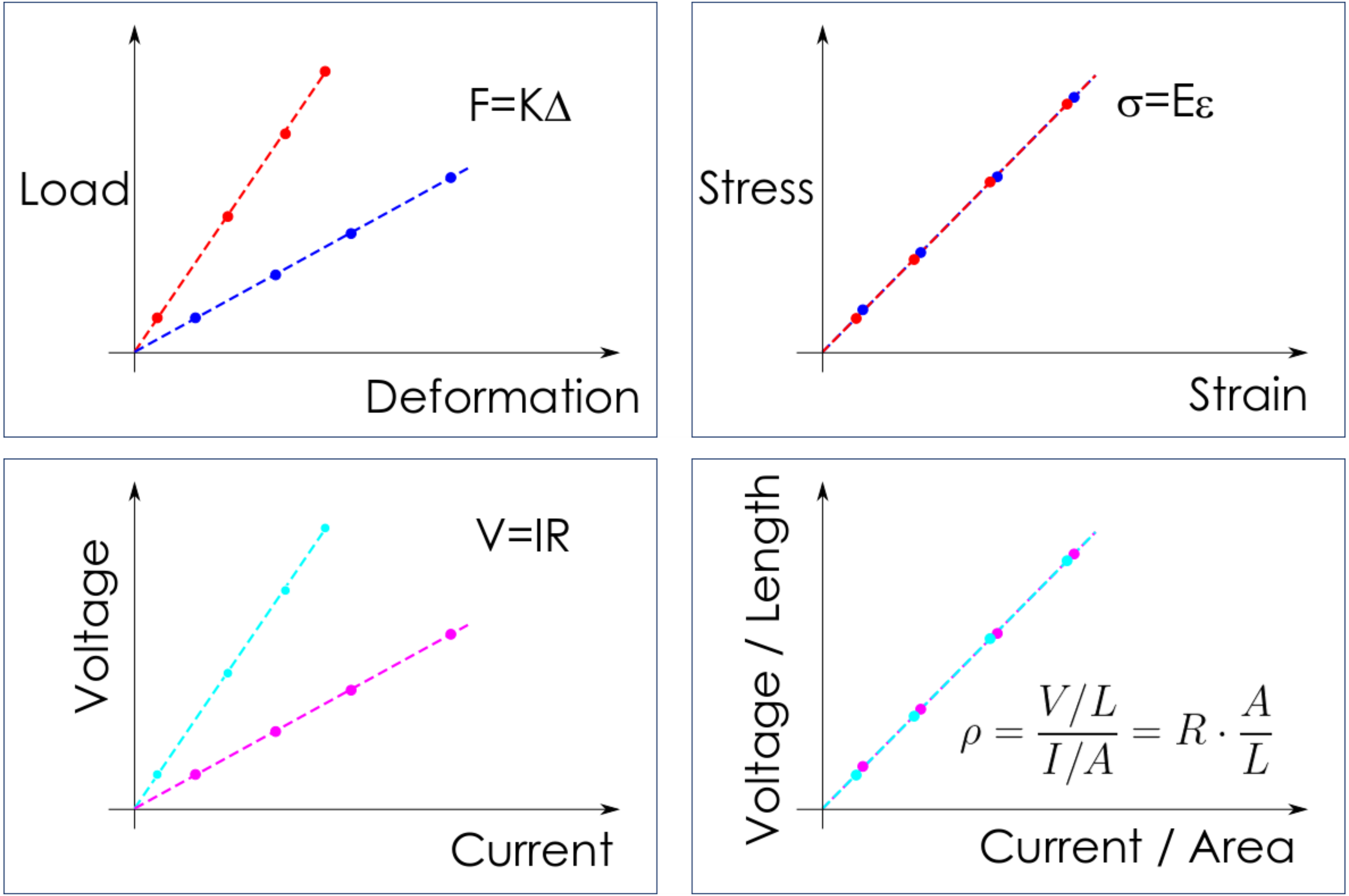
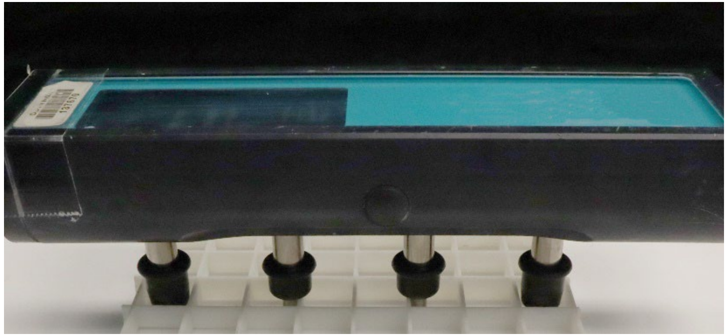

F=KΔ
Load
Deformation
σ=Eε
Stress
Strain
V=IR
Voltage
Current
Voltage / Length
Current / Area
$\rho = \frac{V/L}{I/A} = R \cdot \frac{A}{L}$

Bottom Line Up Front:

Resistivity is an **economical**, **practical**, **and scientifically-based** technique to assess the durability of concrete. It is implementation-ready in both agency QA programs and contractor quality control operations.



$ 20,000

per year per (bridge) project

BAU	**Resistivity**
Equipment: 18k	Equipment: 3k
Time: 8 h	Time: 0.33 h

Rupnow and Icenogle, 2012.
"Evaluation of Surface Resistivity Measurements as an Alternative to the Rapid Chloride Permeability Test for Quality Assurance and Acceptance – Implementation Report". FHWA/LA.13/496.

Practical

Performance Engineered Mixtures

AASHTO R 101 presents a framework for using resistivity measurements.

AASHTO Test Methods are valid, updated, and ready for implementation.

Agencies and Contractors

Both agencies and members of the contracting community have found benefits from using resistivity in their operations.

FHWA's Mobile Concrete Technology Center

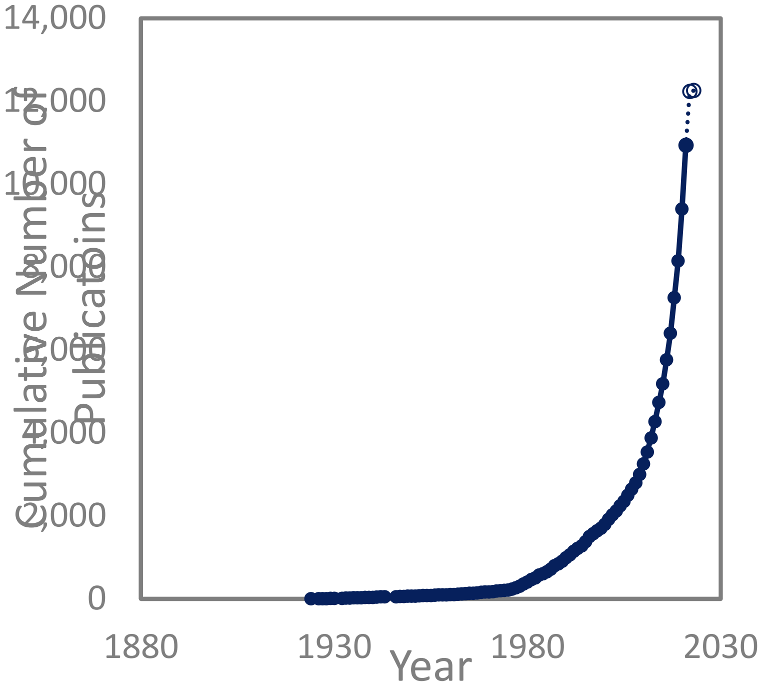
The MCTC does technology transfer around the country targeting the concrete construction community.

Resistivity is a technique highlighted on site visits and is a part of a virtual training series and equipment loan program.

Contact: Michael.Praul@dot.gov

Scientifically-based

- 1920: Introduced in Japan.
- 1970s – 1990s: Why it's a good technique:
  - Corrosion of steel in concrete.
  - Microstructure quality for concrete.
- 2000s: Economical, handheld devices helped accelerate use.



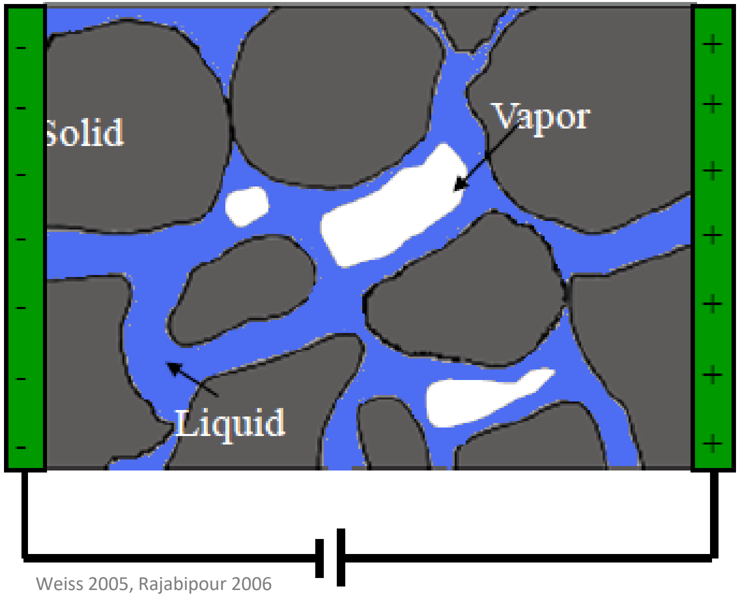
Data obtained from Scopus, 2022.

Bottom Line Up Front:

Resistivity is an economical, practical, and scientifically-based technique to assess the **durability of concrete**. It is implementation-ready in both agency QA programs and contractor quality control operations.

Electrical Properties of Concrete

- Solid Phase (reactants, products, and aggregates)
  - $\rho_{solids} \approx 10^9\ \Omega \cdot \mathrm{m}$
- Vapor Phase
  - $\rho_{vapor} \approx 10^{15}\ \Omega \cdot \mathrm{m}$
- Liquid Phase (ionic pore solution)
  - $\rho_{liquid} \ll 1\ \Omega \cdot \mathrm{m}$



Weiss 2005, Rajabipour 2006

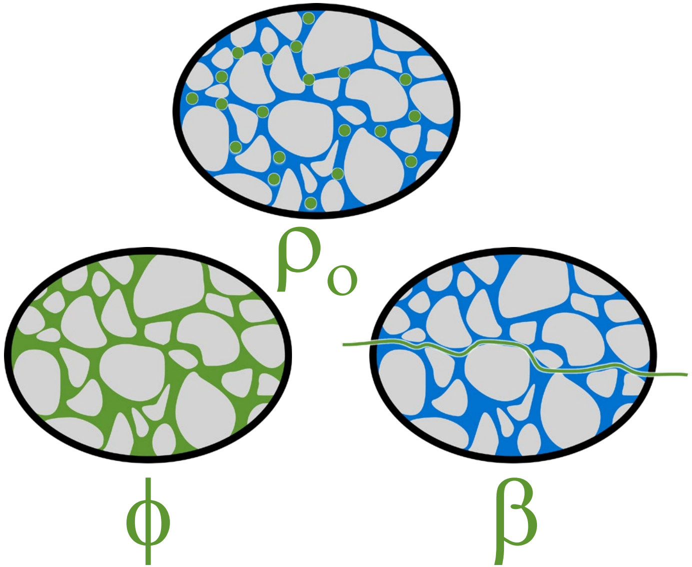
Electricity is conducted primarily through the liquid

Modified Parallel Model

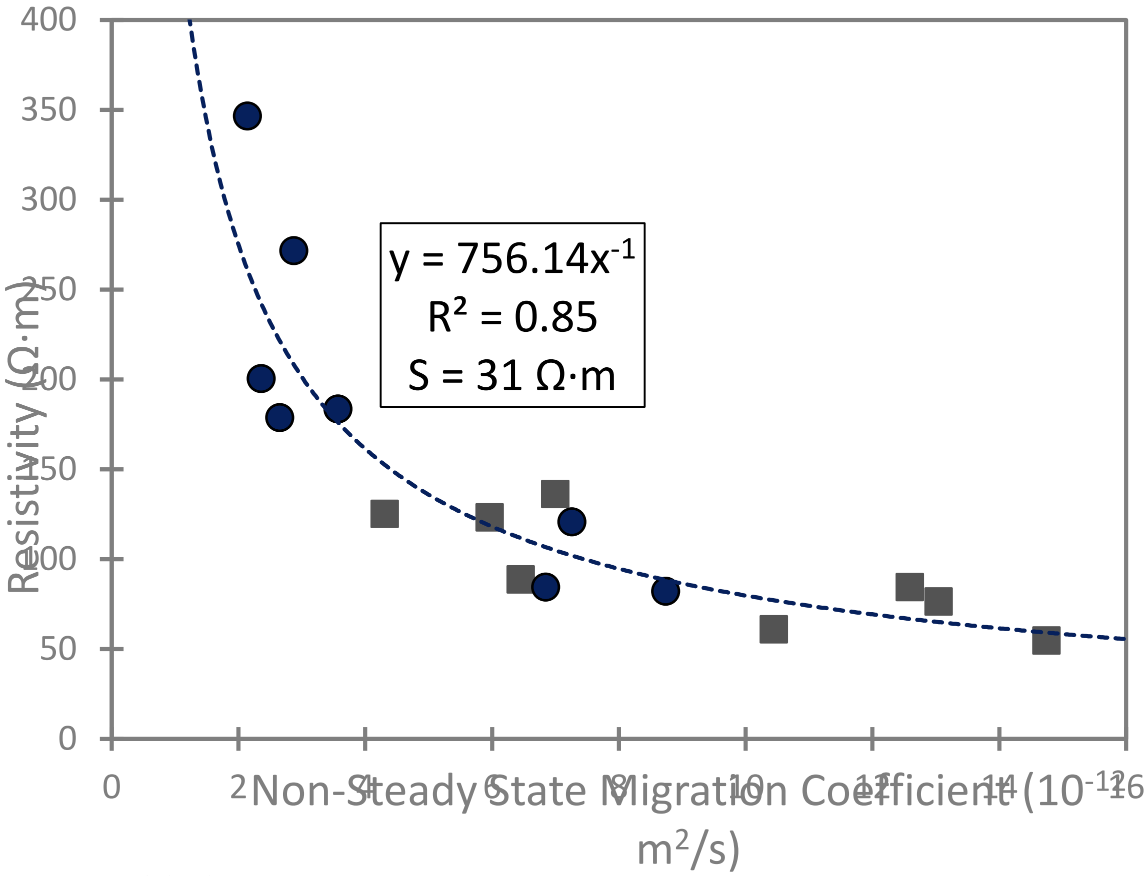
- Helps to understand electrical response with one conductive phase (liquid)
- Function of three parameters
  - Pore solution resistivity (ρ_o)
  - Fluid filled pores, porosity (ϕ)
  - Connectivity (β)
- Nernst-Einstein

$$\frac{\boldsymbol{\rho}}{\boldsymbol{\rho_o}} = \frac{\boldsymbol{D_o}}{\boldsymbol{D}}$$

$$\rho = \rho_o \cdot \frac{1}{\phi\beta}$$

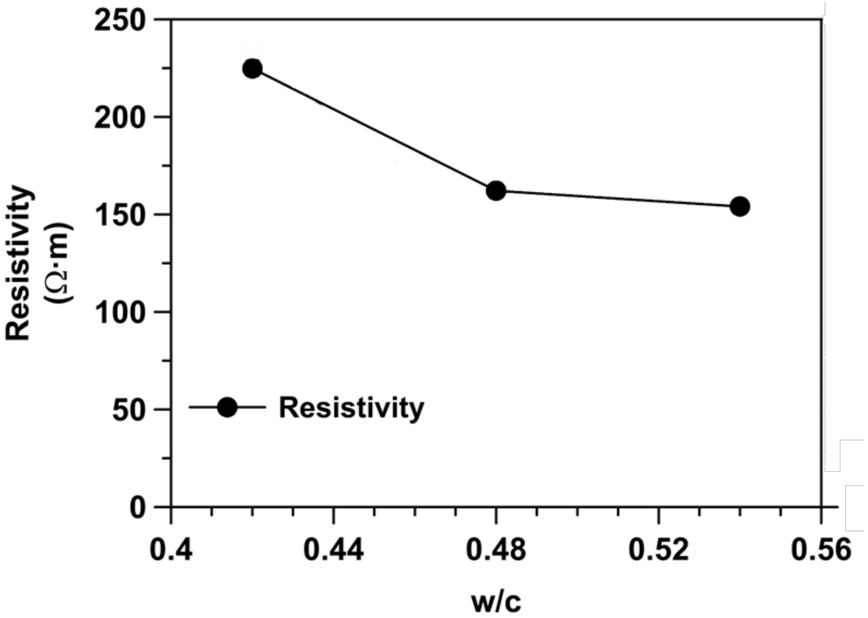


Archie 1942; Garboczi 1990; Samson and Marchand 2007

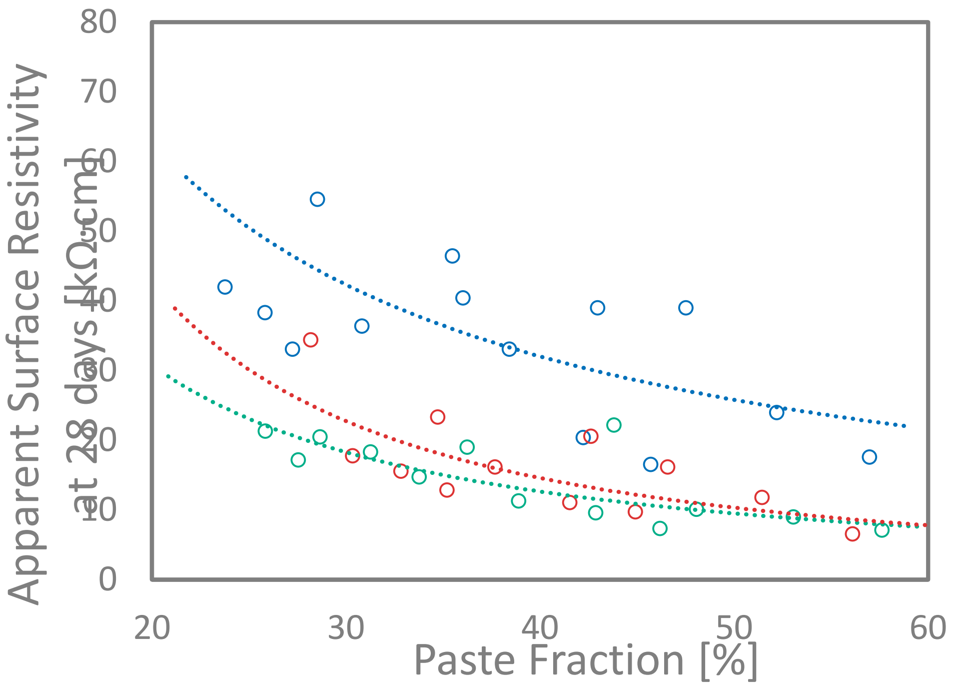


Helsel et al. 2022.

Empirical Correlations



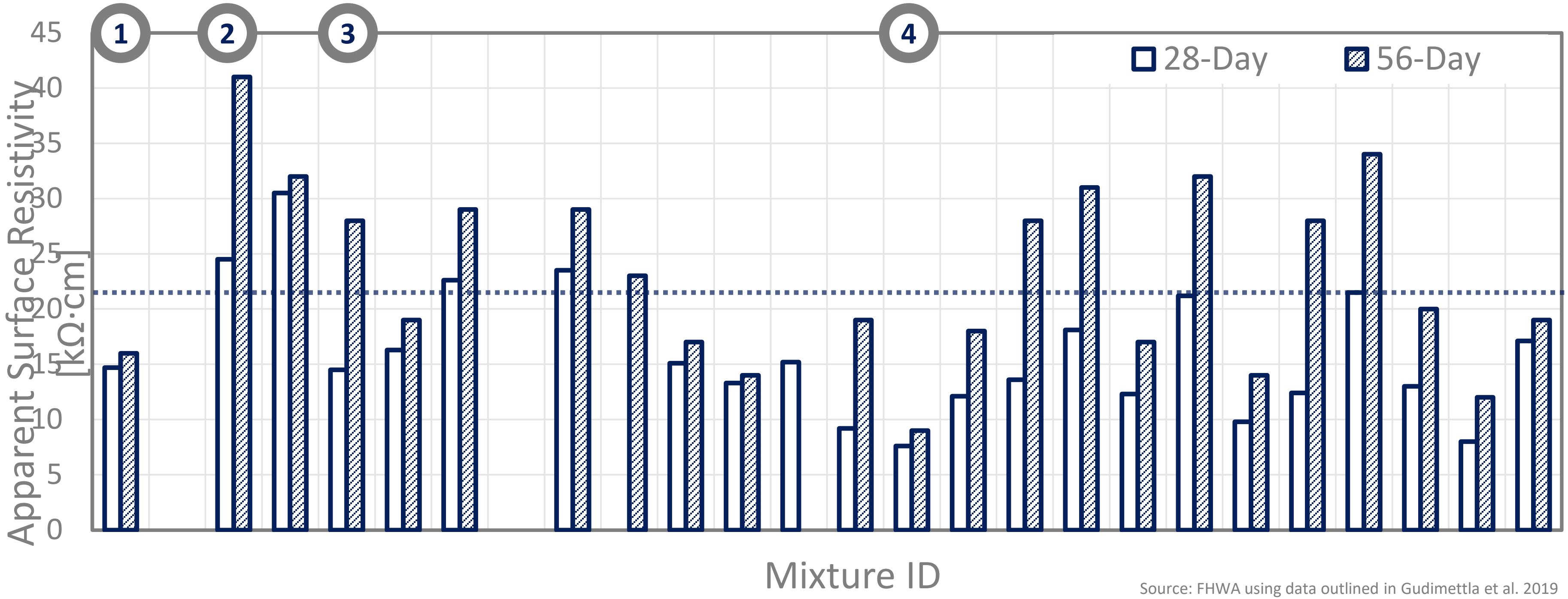
Source: Spragg et al. 2016



Source: FHWA using data outlined in Yurdakul et al. 201322

Comparable Data from MCTC*

* FHWA's Mobile Concrete Technology Center



Source: FHWA using data outlined in Gudimettla et al. 2019

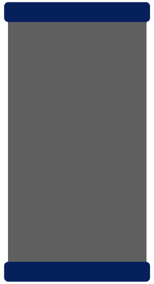
Bottom Line Up Front:

Resistivity is an economical, practical, and scientifically-based technique to assess the durability of concrete. It is **implementation-ready** in both agency QA programs and contractor quality control operations.

Implementation-Ready

AASHTO T 358

Surface Resistivity



AASHTO TP 119

Uniaxial Resistivity

Steps to Implementation

- Choose a test method:
  - AASHTO T 358 (v. 2022) is the easiest and most widespread.
  - There are many others out there (AASHTO, ASTM, BS, etc.).
- Purchase a Concrete Resistivity Meter ($3,800 and above).
- Measure resistivity on samples. This can include be existing samples.
  - Conditioning is a big factor: **Consistency!**
  - Samples for strength: 4x8s or 6x12s .
  - Beams have worked too.

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NCDOT’s Movement Toward Resistivity Specifications for Concrete Mixtures

Tara L. Cavalline, PhD, PE
Brett Q. Tempest, PhD, PE
University of North Carolina at Charlotte

Brian Hunter, PE
North Carolina Department of Transportation

Presented at TRB Webinar
Resistivity and Concrete Durability
October 11, 2022

Background

- NCDOT specifications for concrete have changed little over the past 85 years
  - Prescriptive specification
  - Little room for innovation
  - Mixtures typically over-designed for strength

- Resource reductions drive the need to reduce maintenance cost, increase service life

- Desire fly ash in most of our mixtures because of the benefits
  - Encounter fly ash shortage throughout the years
  - Need to find equivalent performance of mixtures without fly ash ("what if" scenario)

- Recently (2018) increased allowable fly ash substitution rate from 20% to 30%
  - Needed data to support/encourage use of higher substitution rate, account for slower early age strength gain

- Needed data to support decision to allow use of portland limestone cement

TABLE 1000-1
REQUIREMENTS FOR CONCRETE

Class of Concrete	Min. Comp. Strength at 28 days	Maximum Water-Cement Ratio				Consistency Max. Slump		Cement Content			
		Air-Entrained Concrete		Non Air-Entrained Concrete				Vibrated		Non-Vibrated	
		Rounded Aggregate	Angular Aggregate	Rounded Aggregate	Angular Aggregate	Vibrated	Non-Vibrated	Min.	Max.	Min.	Max.
Units	*psi*					*inch*	*inch*	*lb/cy*	*lb/cy*	*lb/cy*	*lb/cy*
AA	4,500	0.381	0.426	-	-	3.5	-	639	715	-	-
AA Slip Form	4,500	0.381	0.426	-	-	1.5	-	639	715	-	-
Drilled Pier	4,500	-	-	0.450	0.450	-	5-7 dry 7-9 wet	-	-	640	800
A	3,000	0.488	0.532	0.550	0.594	3.5	4	564	677	602	602
B	2,500	0.488	0.567	0.559	0.630	2.5	4	508	610	545	654
B Slip Formed	2,500	0.488	0.567	-	-	1.5	-	508	610	-	-
Sand Light-weight	4,500	-	0.420	-	-	4	-	715	715	-	-
Latex Modified	3,000 7 day	0.400	0.400	-	-	6	-	658	658	-	-
Flowable Fill excavatable	150 max. at 56 days	as needed	as needed	as needed	as needed	-	Flow-able	-	-	40	100
Flowable Fill non-excavatable	125	as needed	as needed	as needed	as needed	-	Flow-able	-	-	100	as needed
Pavement	4,500 design, field 650 flexural, design only	0.559	0.559	-	-	1.5 slip form 3.0 hand place	-	526	-	-	-
Precast	See Table 1077-1	as needed	as needed	-	-	6	as needed	as needed	as needed	as needed	as needed
Prestress	per contract	See Table 1078-1	See Table 1078-1	-	-	8	-	564	as needed	-	-

What if…

- Emphasis on durability
- Sustainability considerations

- Flexibility for innovation
- Buffer against material shortages
- Opportunity for cost-savings

- Opportunity for contractors to innovate and optimize

Resistivity is one of several PEM tests/approaches being studied for implementation

- Resistivity/formation factor
- Shrinkage
- Super Air Meter
- Some prescriptive measures
  - paste content
  - w/cm ratio
  - cementitious materials constraints
- Other tests for QC use
  - Box Test

We have:

- Collected a lot of field/lab data
- Established proposed testing targets and shadow specifications
- Completed a pilot study for pavement concrete

We are now:

- Trying selected tests out on additional pilot projects (structural concrete)
- Evaluating and refining targets
- Gathering stakeholder feedback
- Engaging more stakeholders in the testing

NCDOT PEM efforts so far…

- Participation in Pooled Fund

- Two internally funded projects
  - RP 2018-14 (2017 - 2019) "Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures."
  - RP 2020-13 (2019 - 2022) "*Continuing Towards* Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures."

- FHWA Implementation Funds

  Category A: Incorporating tests in the mix design/approval process (shadow testing)
  Category B: Incorporating tests in the acceptance process (shadow testing)
  Category D: Requiring the use of control charts, as called for in AASHTO PP 84-17.

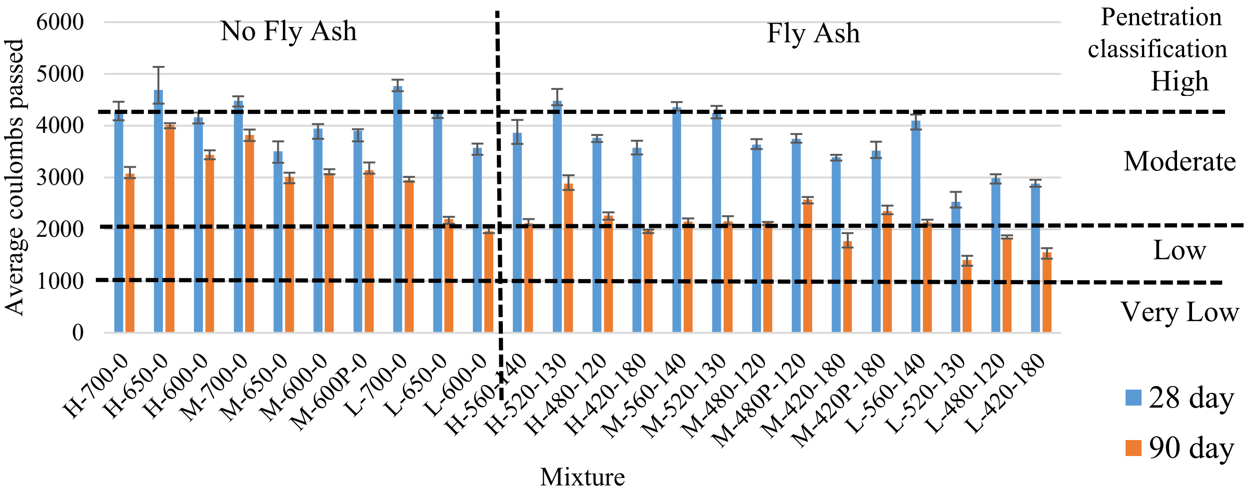
- RP 2019-41 "Performance Engineered Concrete Mixtures – FHWA Implementation Funds" – technology transfer activities

NCDOT RP 2018-14 Mixture Matrix

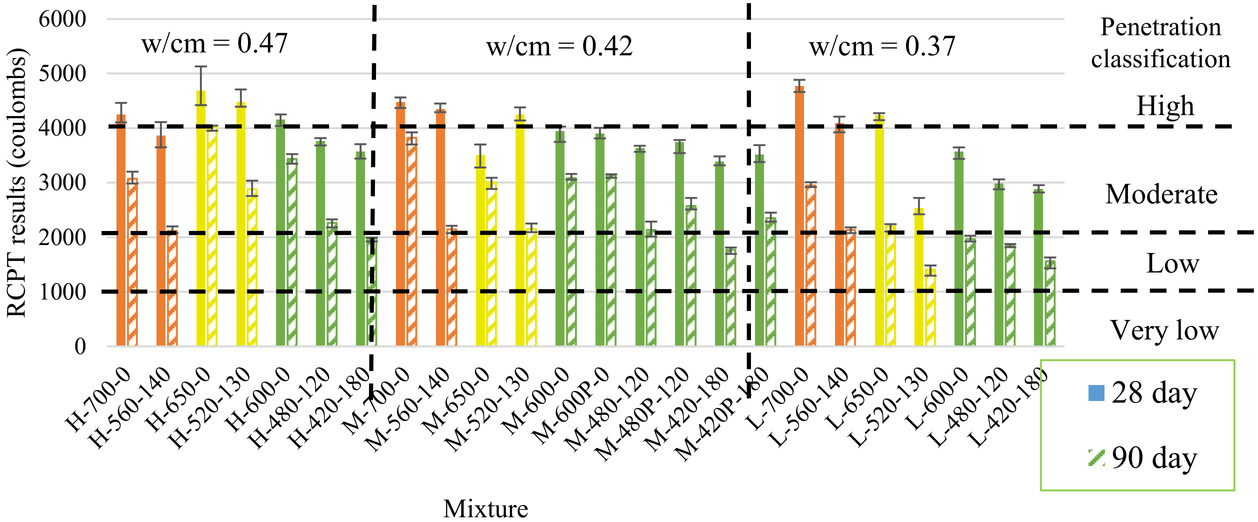
Mixture ID **W-XXX-YYY,** where **W** is *w/cm* ratio, **XXX** is cement content, **YYY** is fly ash content	Mixture Characteristics			Mixture Proportions, pcy					
	Mixture type	**Cement type**	***w/cm***	**Fly ash replacement (%)**	**Cement**	**Fly ash**	**Coarse aggregate**	**Fine aggregate**	**Water**
H-700-0	AA (high and medium cm content)	OPC	0.47	0	700	0	1659	1072	329.0
H-560-140				20	560	140	1659	1022	329.0
H-650-0				0	650	0	1659	1175	305.5
H-520-130				20	520	130	1659	1129	305.5
H-600-0				0	600	0	1659	1277	282.0
H-480-120				20	480	120	1659	1235	282.0
H-420-180				30	420	180	1659	1214	282.0
M-700-0			0.42	0	700	0	1659	1163	294.0
M-560-140				20	560	140	1659	1114	294.0
M-650-0				0	650	0	1659	1259	273.0
M-520-130				20	520	130	1659	1214	273.0
M-600-0				0	600	0	1659	1356	252.0
M-480-120				20	480	120	1659	1313	252.0
M-420-180				30	420	180	1659	1292	252.0
M-600P-0		PLC		0	600	0	1659	1356	252.0
M-480P-120				20	480	120	1659	1313	252.0
M-420P-180				30	420	180	1659	1292	252.0
L-700-0	AA (low cm content) and Pavement	OPC	0.37	0	700	0	1659	1254	259.0
L-560-140				20	560	140	1659	1205	259.0
L-650-0				0	650	0	1659	1344	240.0
L-520-130				20	520	130	1659	1298	240.0
L-600-0				0	600	0	1659	1434	222.0
L-480-120				20	480	120	1659	1392	222.0
L-420-180				30	420	180	1659	1370	222.0

Rapid Chloride Permeability

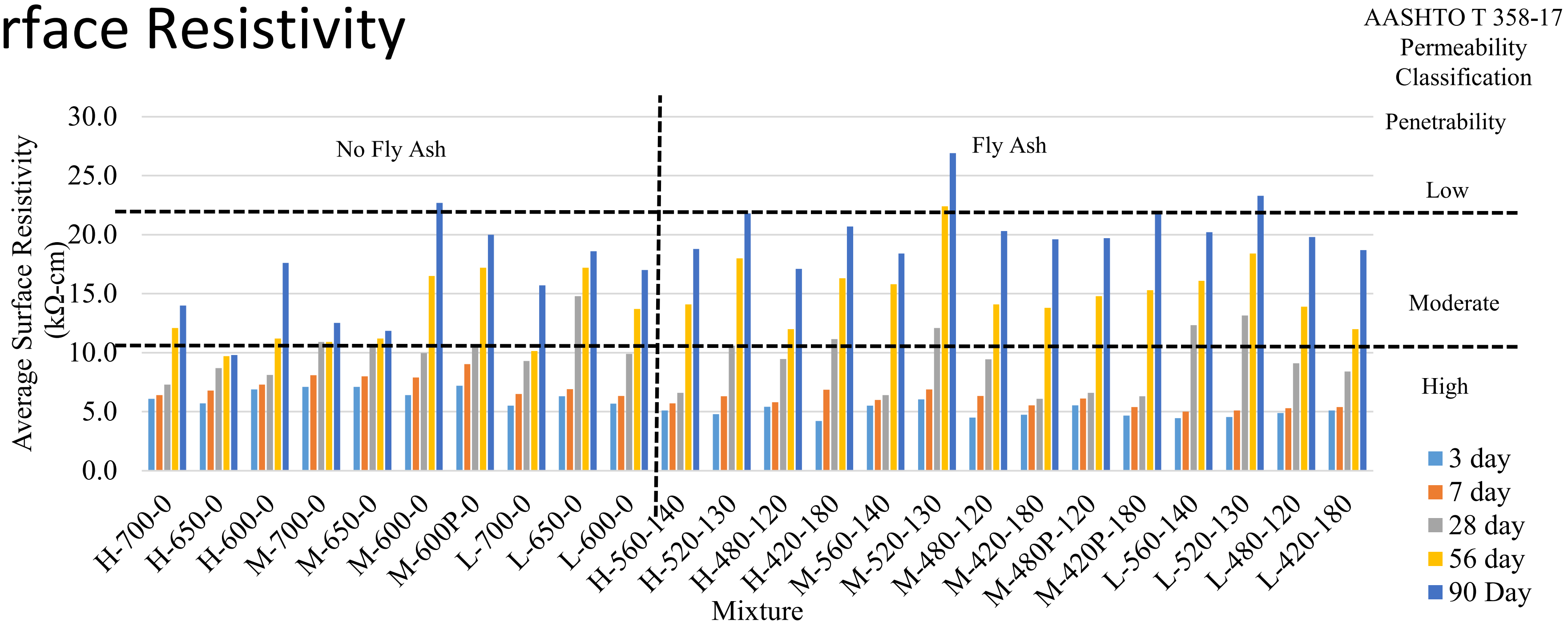
- Fly ash drives reduction in permeability at later ages.



- Fly ash can mitigate impact of higher w/cm on permeability.

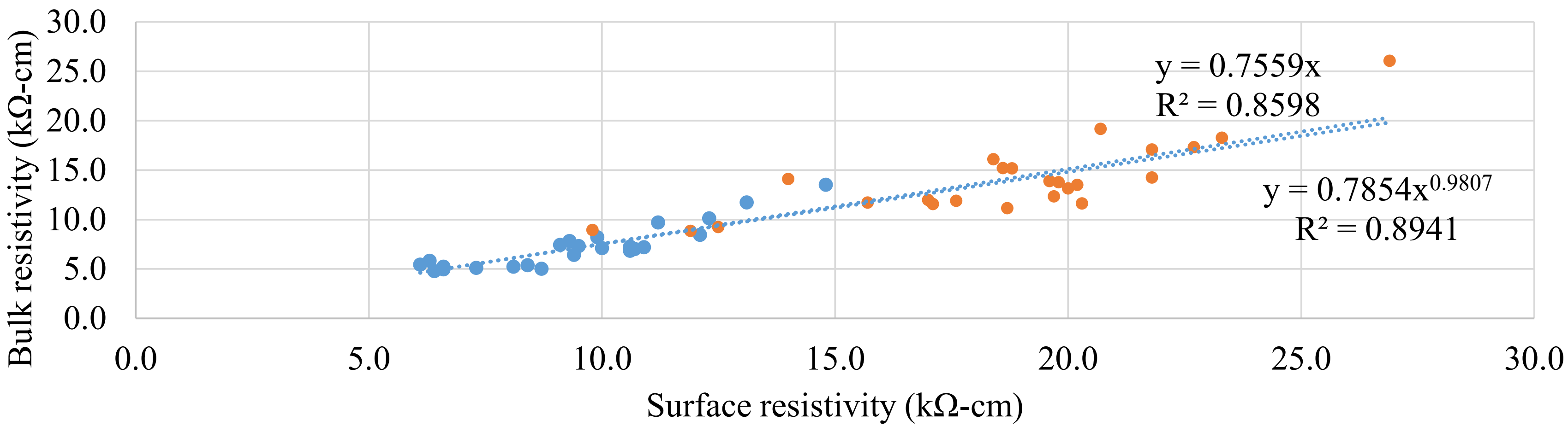


Surface Resistivity



- Later-age benefits of fly ash readily evident
- Influence of total cementitious material content on resistivity values was evident.
- Resistivity of PLC mixtures improved with a fly ash replacement, specifically the higher (30%) replacement rate.

Bulk Resistivity and Formation Factor



- Bucket Test to help standardize the pore solution within the cylinder prior to testing using surface resistivity / bulk conductivity
- Procedure has been refined over past few years, so these results are informational only
- Lay groundwork for potential shift to formation factor testing after resistivity is implemented

Development of Resistivity Shadow Specification: Review of Existing State Specifications

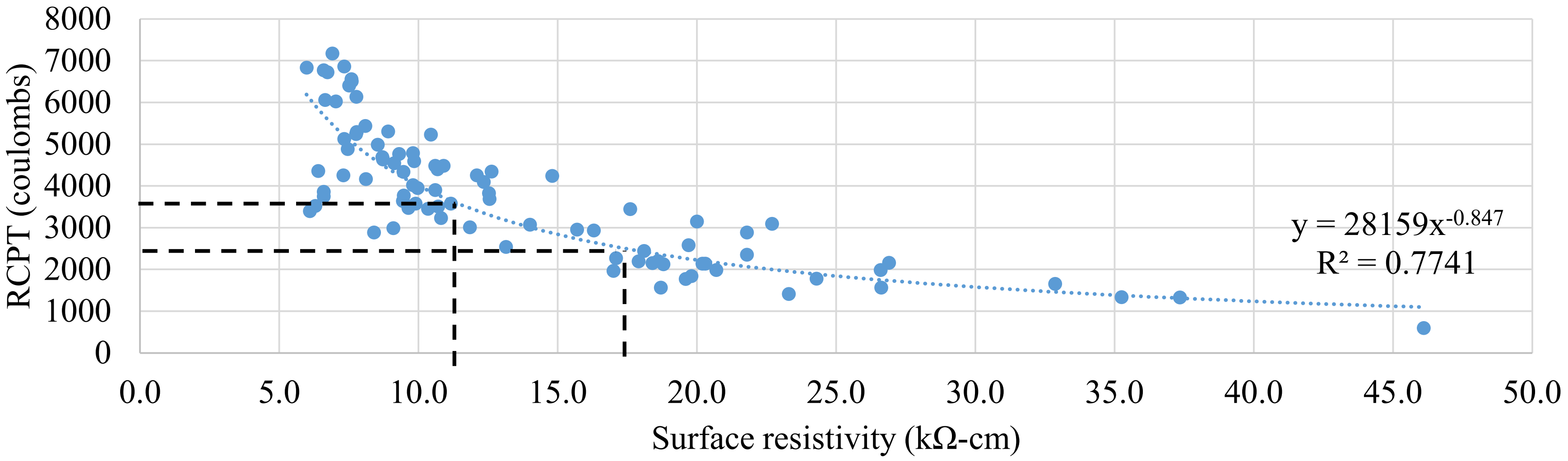
- Virginia, Florida, Louisiana, New Hampshire, Kansas, New Jersey, New York, Rhode Island, Texas, Utah, West Virginia, and Montana had specification provisions on resistivity at this time (2018).

- A variety of approaches, with targets generally linked to the type(s) of mixtures and importance/exposure of element

- Many states have 28-day targets. Some states have 56-day targets.
  - Trade off between ease of use at earlier age (28-days) vs. capturing value of fly ash on permeability reduction (56-days)

- Surface resistivity highly correlated to RCPT, which has historically been linked to field performance
- Virginia DOT provides RCPT targets for pavements (3,500 coulomb) and bridges (2,500 coulomb)
  - Field performance of these targets verified in similar climate/traffic conditions
  - Use 28-day values, but use of same targets at 56-days could also show promise

Surface Resistivity



- Pavement target of 3,500 coulombs RCPT corresponds to ~ 10.5 kΩ-cm resistivity
- Bridge target of 2,500 coulombs RCPT corresponds to ~ 17 kΩ-cm resistivity

- VDOT uses these targets at 28 days which would preclude many NC mixtures with lower w/cm, fly ash, good historical performance
- Use of targets at 56 days is recommended (NJDOT and NHDOT use 56-day targets)
- Alternatively, could identify 28-day target that correlates to 56-day value (mixture specific)

Suggested Specification for Resistivity (Section 1000-4C)

(C) Strength and Surface Resistivity of Concrete

The compressive strength *and surface resistivity* of the concrete will be considered the average test results of two 6 inch x 12 inch cylinders, or two 4 inch x 8 inch cylinders if the aggregate size is not larger than size 57 or 57M. Make cylinders in accordance with AASHTO T 23 from the concrete delivered to the work. Make cylinders at such frequencies as the Engineer may determine and cure them in accordance with AASHTO T 23 as modified by the Department. Copies of these modified test procedures are available upon request from the Materials and Tests Unit. Testing for compressive strength should be performed in accordance with AASHTO T 22. *Testing for surface resistivity should be performed in accordance with AASHTO T 358.* When the average compressive strength or surface resistivity of the concrete test cylinders is less than the minimum targets specified in Table 1000-1 and the Engineer determines it is within reasonably close conformity with design requirements, these properties will be considered acceptable. *When the Engineer determines average cylinder strength or surface resistivity is below the specification, the in-place concrete will be tested.* Based on these test results, the concrete will either be accepted with no reduction in payment or accepted at a reduced unit price or rejected as set forth in Article 105-3.

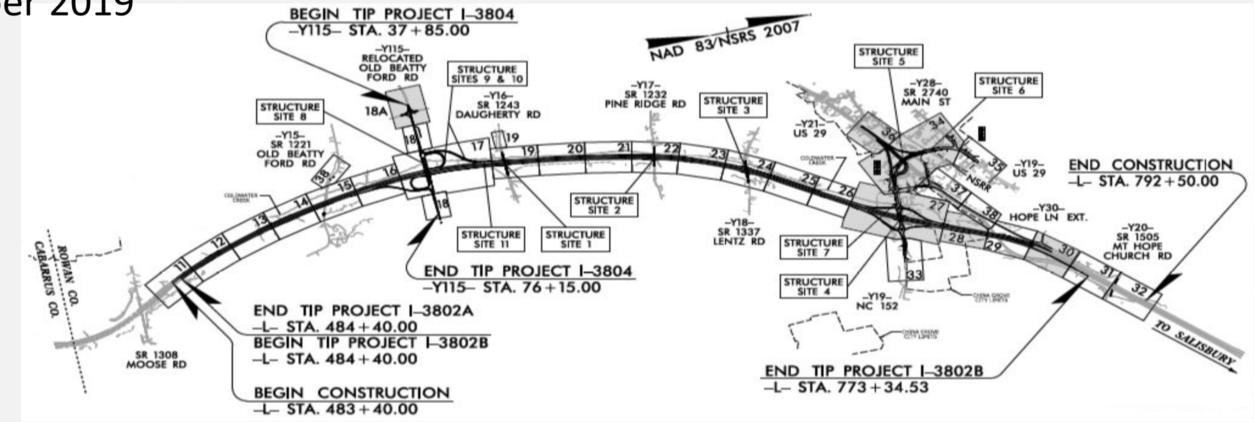
Suggested addition to Table 1000-1

Class of Concrete	Minimum surface resistivity at 56 days (kΩ-cm)
AA	15.0*
Pavement	11.0

*A 56 day minimum of 16.0 kΩ-cm can be required at the engineer's discretion for applications where risk of chloride ion penetration is high.

FHWA Implementation Project – Concrete Pavement

- I-85 widening project north of Charlotte, NC
  - 5.3 miles long
  - Existing 4-lane interstate widened to provide 4 additional travel lanes
    (2 lanes in each direction)
  - 500,000 SY of concrete pavement construction (12” thick JPCP)
  - Two phases:
    - April 2018 to September 2018
    - April 2019 to October 2019



FHWA Implementation Project Outcomes

This project resulted in:

- Engagement of a contractor to implement PEM tests for QC on a pavement project:
  - Box Test
  - SAM
  - surface resistivity
- Technology transfer to regional/divisional NCDOT personnel

★ Support of a contractor and commitment to use of PEM tools on their next project ★





Surface Resistivity

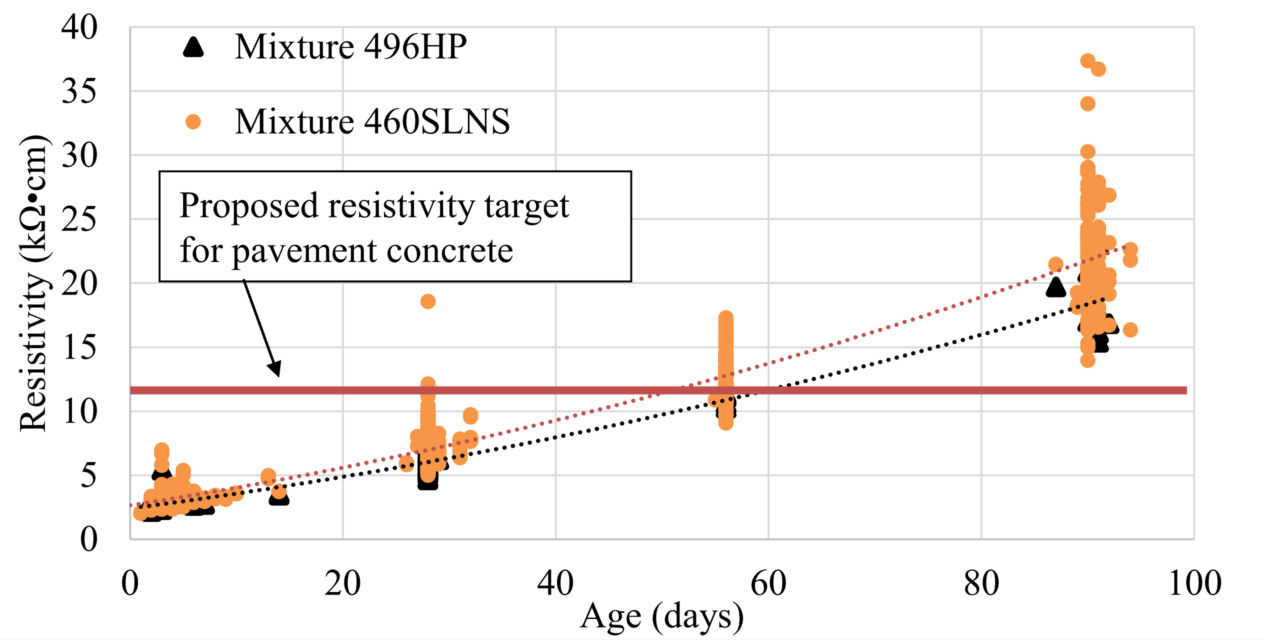
All lots of slipformed (460SLNS) and hand placed (496HP) mixtures met the proposed target of 11 kΩ·cm by 90 days.

Slipformed mixture:

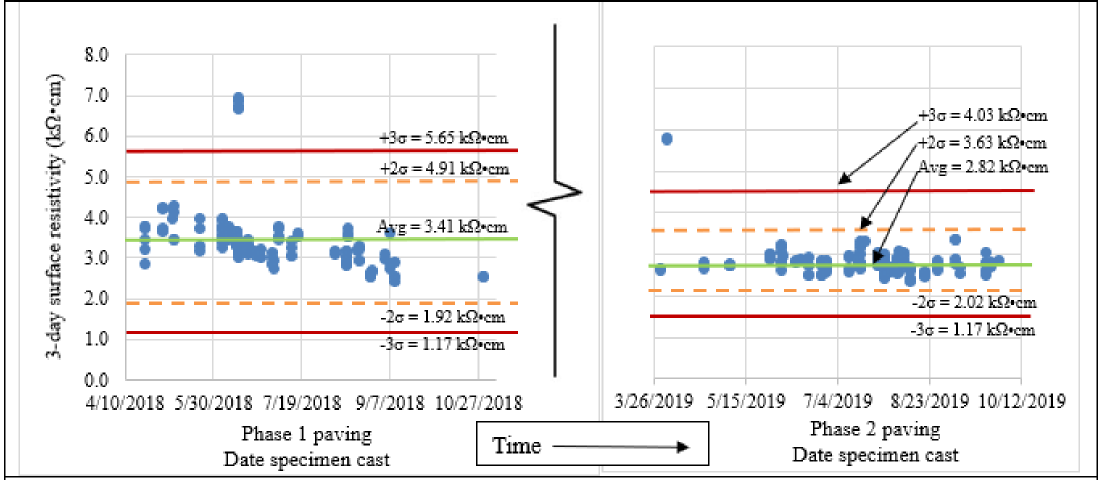
- 85 of 106 (80.1%) met target by 56 days
- 11 of 21 lots not making the target were very close (>10.5 kΩ·cm) at 56 days

Handplaced mixture:

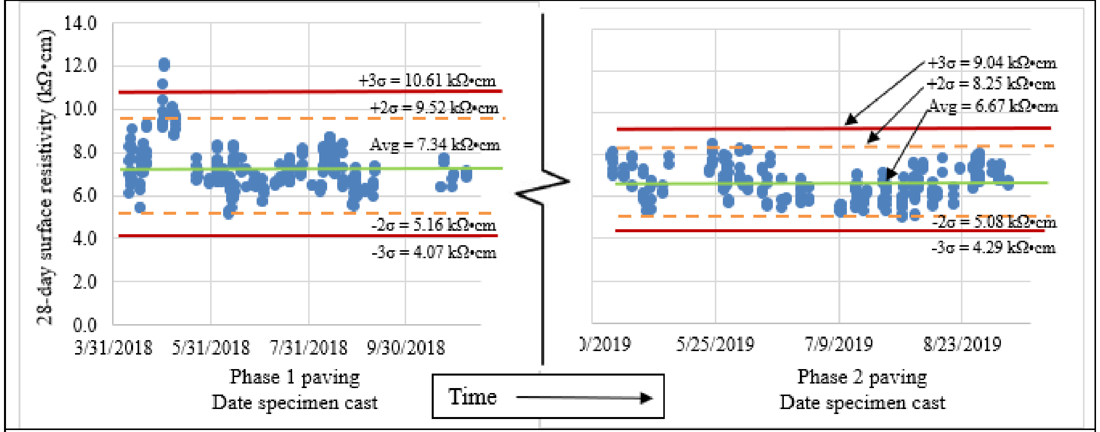
- 4 lots of hand placed mixture that didn't make 56-day target were >10 kΩ·cm at 56 days



Surface Resistivity



Control chart showing 3-day resistivity for mixture 460SLNS during Phase 1 and Phase 2 paving.



Control chart showing 28-day resistivity for mixture 460SLNS during Phase 1 and Phase 2 paving.

- Control charts show reduction in variability of the concrete produced.
- Standard deviation for 3-day resistivity reduced by almost half between Phases 1 and 2.
- Standard deviation for 28-day paving also showed significant reduction (1.09 kΩ·cm to 0.79 kΩ·cm)

Ongoing research at UNC Charlotte (RP 2020-13)

1) Laboratory tests to expand the catalog of data to refine PEM specifications

   - same mixture matrix as RP 2018-14, with optimized aggregate gradations
   - refine targets, sampling/testing plan for resistivity, shrinkage, and SAM
   - expand specification guidance to include w/cm ratios, aggregate gradations and/or paste contents
   - use of surface resistivity meter as a QA tool for overlay quality

2) Implementation of PEM tests/shadow specifications at additional pilot projects
   - bridge elements and deck overlays
   - additional data from supplier, testing lab, and previous contractor

3) Development of guidance to support contractor QC plans

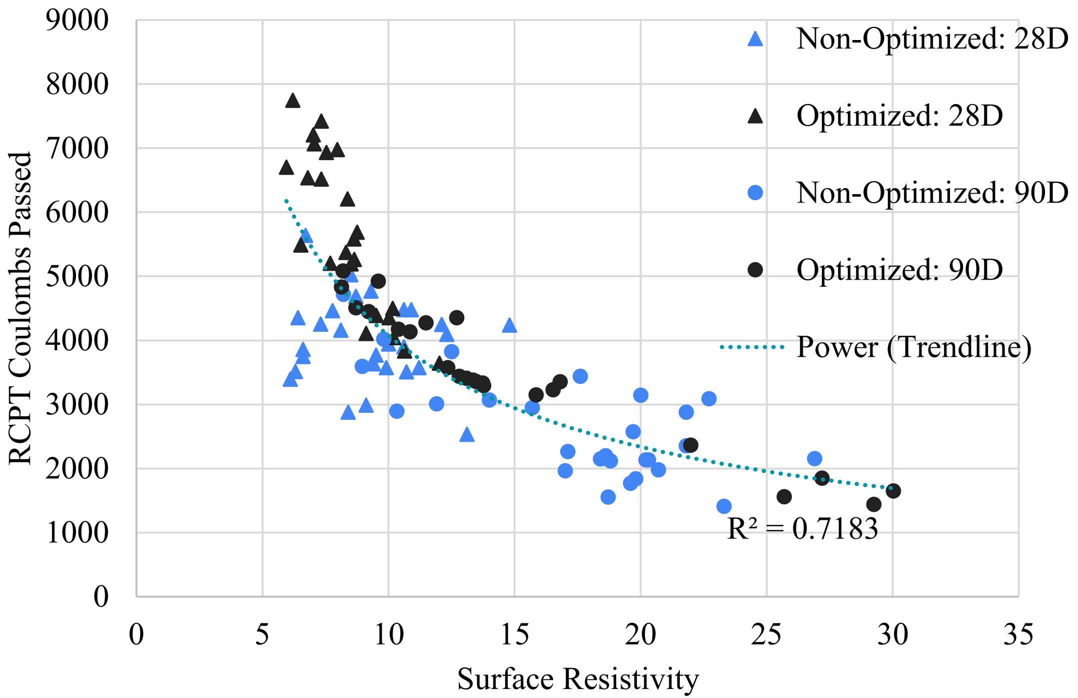
Resistivity Testing

- Results added to data collected from other projects
- Assessing proposed targets

- Optimized aggregate gradations tended to have lower resistivity/higher charge passed in RCPT

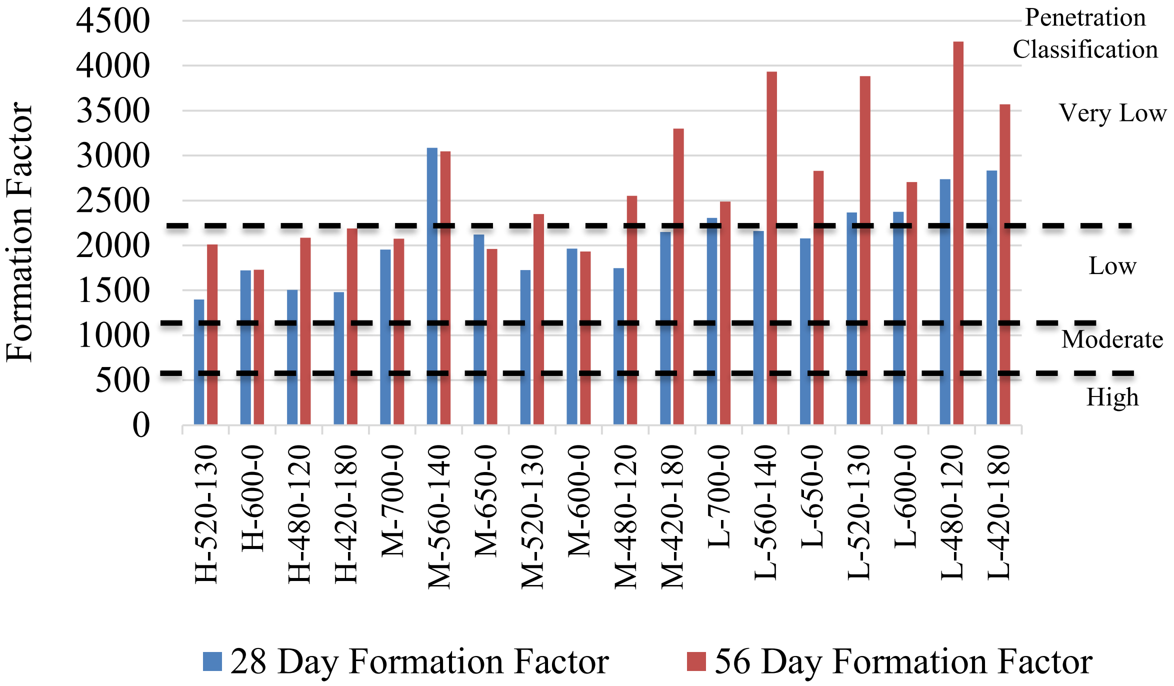
- BUT, also had 10% reduced cement content (2-4% paste reduction) with similar mechanical performance

- May be due to increased ITZ volume?



Formation Factor Testing

- Limited range of mixture materials and proportions
- Data collected for preliminary purposes
- Hoping to broaden this dataset in future work
- Importance of basics:
    - Control w/cm
    - Importance of SCMs

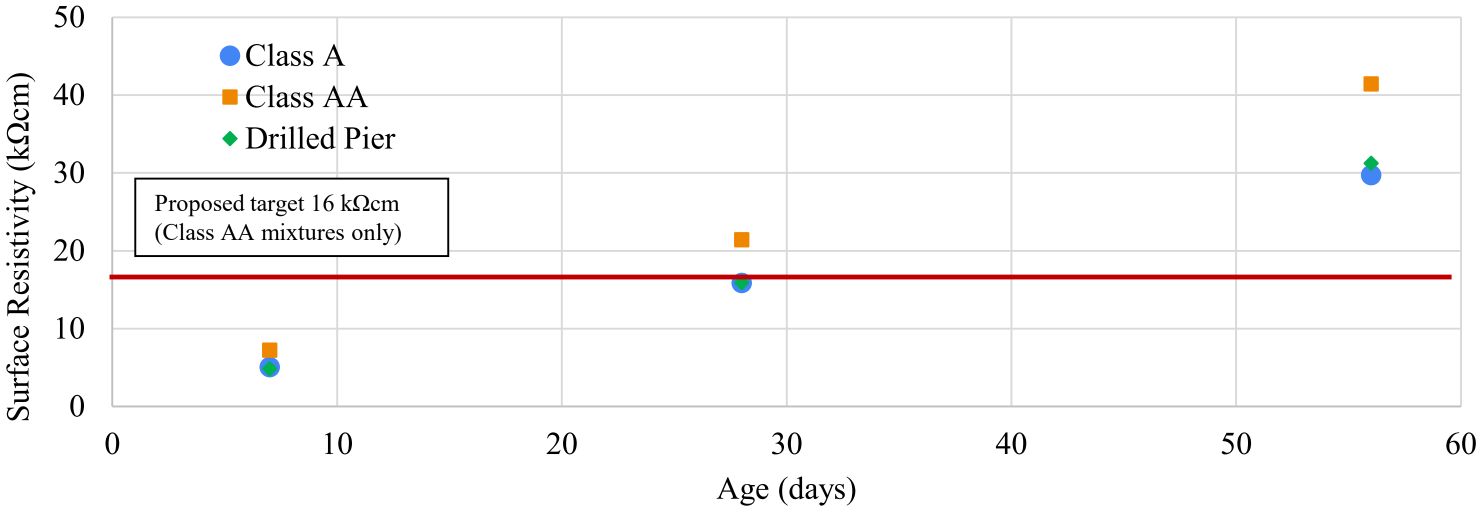


Structural Concrete PEM Implementation Project
I-485 Widening (I-5507 Design Build)

- I-485 widening project south of Charlotte, NC
  - 18.2 miles long
  - High-occupancy toll (HOT) lanes along entire stretch of roadway
  - 17 structures, 15.3 miles of new sound wall
  - 3-year duration
- Ready-mixed supply company is providing most structural mixtures
  - AA, Drilled Pier, A
- PEM Shadow Testing
  - Surface resistivity, SAM shrinkage
  - Testing Spring/Summer/Fall 2021 and Spring 2022

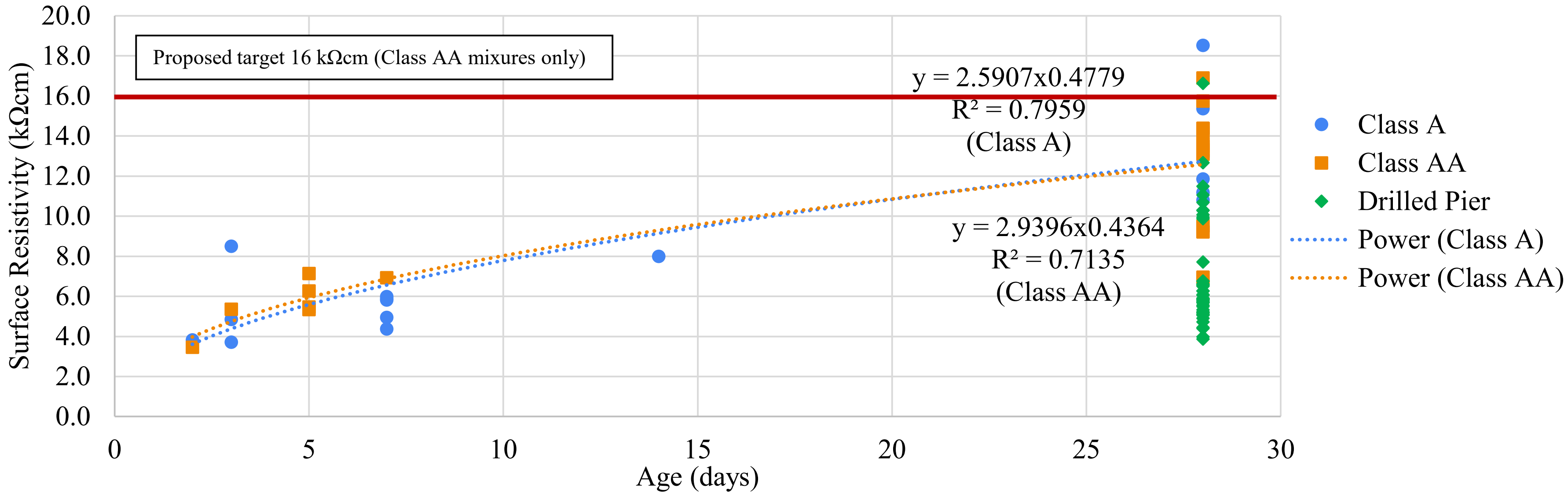
Resistivity Data for Structural Concrete at Pilot Project

- Class AA (4500 psi), Class A (3000 psi), and Drilled Pier mixtures tested
- NCDOT regional laboratory only has capacity to store cylinders for 28 days
- Will need to identify a 28-day target that gives strong likelihood of seeing desired resistivity at future age (56 days? 90 days?) particularly for fly ash mixtures
- QC data from ready mix laboratory showed targets met by 56 days



Resistivity Data for Structural Concrete at Pilot Project

- Resistivity measurements for mixtures produced in field typically slightly lower
- Class AA (4500 psi), Class A (3000 psi), mixtures appeared to be on track to meet target at later ages
- Additional study is planned to obtain more 28/56 day resistivity data using field mixtures to help identify “early” target (28-day resistivity)



Closing Thoughts and Next Steps

- Resistivity is an easy to implement technology that shows promise to improve NCDOT concrete infrastructure
  - Can help mitigate impacts of material shortages
  - Drives use of fly ash, controlled w/cm ratios
  - Shifts focus to durability

- Working to address limitations associated with longer-term storage of cylinders at regional facilities
- Outreach to internal (NCDOT) and external stakeholders through pilot projects, presentations, and other means
  - Training guides for NCDOT personnel
  - Spreadsheets for data collection

Quantifying benefits of PEM implementation will be a goal moving forward

- Benefits to contractor
- Benefits to agency

More information on NCDOT's PEM initiatives

- NCDOT funded research reports - available at Connect NCDOT https://connect.ncdot.gov/projects/research/Pages/default.aspx

  NCDOT RP 2018-14 Final Report – available now
  NCDOT RP 2019-41 Final Report – available now
  NCDOT RP 2020-23 Final Report – posted later this fall

- Pilot Project for Pavement PEM https://intrans.iastate.edu/app/uploads/sites/7/2020/05/Post-Construction-Report-for-North-Carolina-DOT-Demonstration-Project-05-14-2020.pdf

  Transportation Research Record Paper:
  Cavalline, T.L., White, F.D., Tempest, B.Q., Hunter, B.J., Ange, C.M., and Simpson, R.P. (2022). "Performance Engineered Concrete Mixtures: Implementation at an Interstate Rigid Pavement Project." Transportation Research Record: Journal of the Transportation Research Board, 2676(5), 450-459. https://doi.org/10.1177%2F03611981211067981

Thank you!

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New Developments in Resistivity Testing and Use for Practitioners

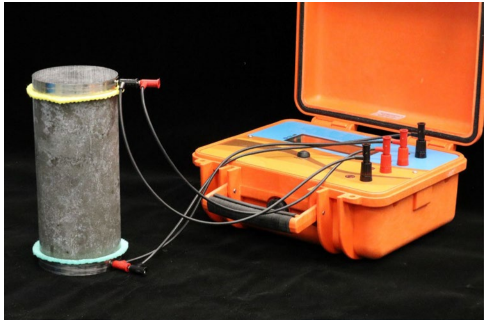
Nima Kargah-Ostadi, PhD, PE
Callentis Consulting Group, LLC
TRB AKM70 Webinar on Resistivity and Concrete Durability
October 11, 2022

New Developments in Resistivity Testing

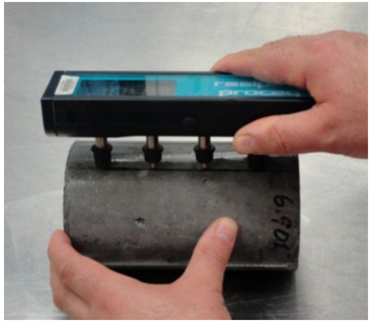
- US DOT Small Business Innovation Research (SBIR) FY21-FH2
  - Why measure pore solution resistivity (PSR)?
  - How to estimate PSR?
  - Why a PSR sensor system?
  - Working theory for PSR sensor
  - Applications in Practice
- Other recent developments:
  - Updated AASHTO resistivity test methods T 358-22 and TP 119-22
  - Study on accuracy/precision of surface/uniaxial resistivity measurements

Why Measure Pore Solution Resistivity (PSR)

- Performance Engineered Mixtures (PEM), per AASHTO R101
- Evaluate chloride diffusivity, water permeability, etc.
- Formation factor $F = \frac{\rho}{\rho_o}$
- Uniaxial test (AASHTO TP 119-22)
- Surface test (AASHTO T 358-22)



AASHTO TP 119-22



AASHTO T 358-22

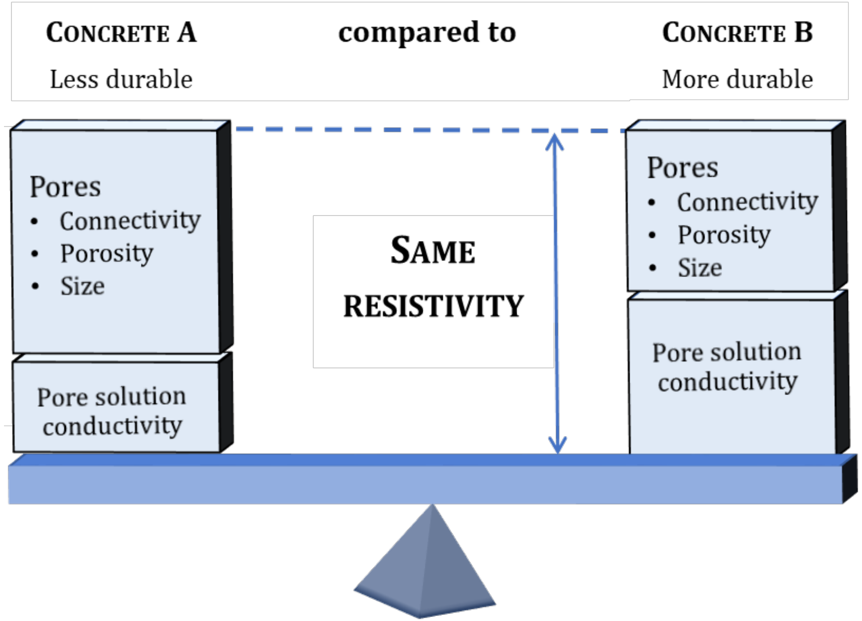
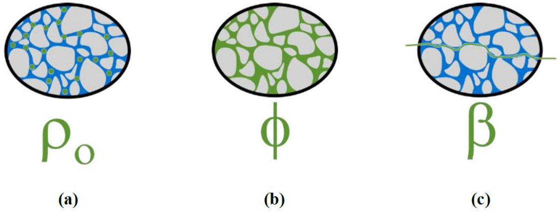


Image Source: FHWA Tech Brief FHWA-HRT-19-030 (2019)

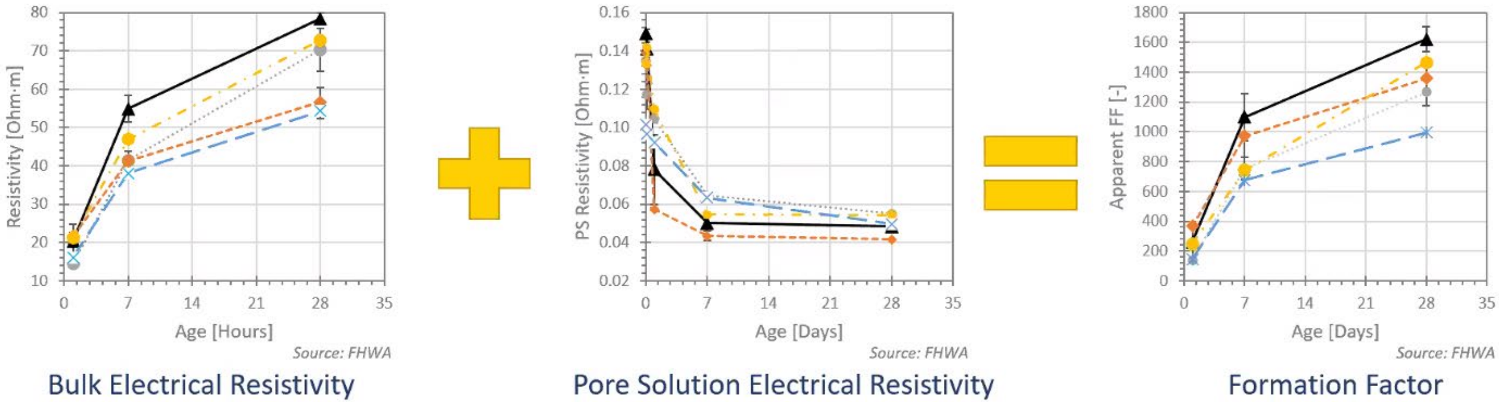
Why Measure Pore Solution Resistivity (PSR)

- Parameters affecting concrete electrical resistivity measurements:
  a) Pore Solution Resistivity: ρ_0
  b) Volume of the pore fluid: ϕ
  c) Pores' connectivity: β



Spragg et al. 2019

$$F = \frac{\rho}{\rho_o} = \frac{1}{\emptyset\beta}$$

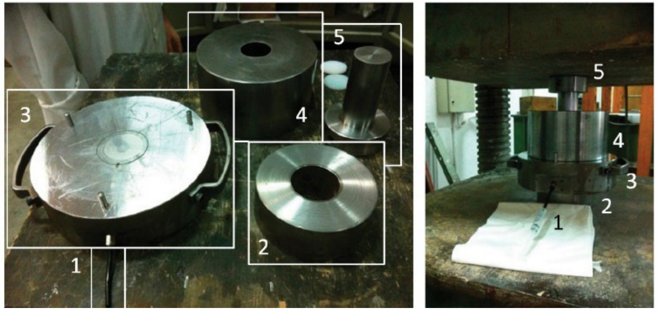


Resistivity Testing of Concrete Repair Materials (Montanari et al. 2022)

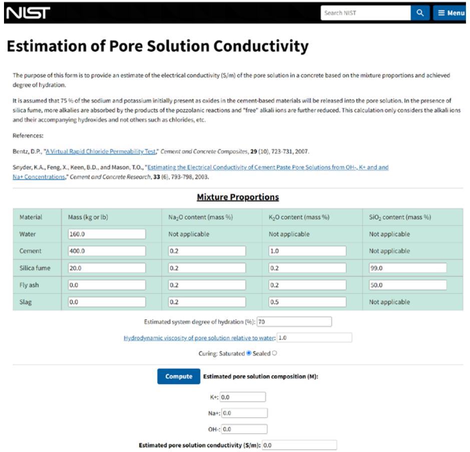
How to Estimate Pore Solution Resistivity (PSR)

- Pore solution extraction → Challenging to conduct
- NIST estimate → Not always accurate, especially when the mixture has SCMs
- Curing in “simulated” pore solution → Needs a long time for chemical equilibrium
- Embedded sensor → USDOT SBIR project

FIGURE 3. Pore-pressing equipment (1. Plastic tube for liquid drain; 2. Support cylinder; 3. Platen; 4. Die Body; 5. Piston assembly). DOI: 10.3989/mc.2017.08515



Pore Solution Extraction (Manso & Aguado 2017)



NIST

Search NIST

Menu

Estimation of Pore Solution Conductivity

The purpose of this form is to provide an estimate of the electrical conductivity (S/m) of the pore solution in a concrete based on the mixture proportions and achieved degree of hydration.

It is assumed that 75 % of the sodium and potassium initially present as oxides in the cement-based materials will be released into the pore solution. In the presence of silica fume, more alkalies are absorbed by the products of the pozzolanic reactions and "free" alkali ions are further reduced. This calculation only considers the alkali ions and their accompanying hydroxides and not others such as chlorides, etc.

References:

Bentz, D.P., "A Virtual Rapid Chloride Permeability Test," *Cement and Concrete Composites*, **29** (10), 723-731, 2007.

Snyder, K.A., Feng, X., Keen, B.D., and Mason, T.O., "Estimating the Electrical Conductivity of Cement Paste Pore Solutions from OH-, K+ and and Na+ Concentrations," *Cement and Concrete Research*, **33** (6), 793-798, 2003.

Mixture Proportions

Material	Mass (kg or lb)	Na_2O content (mass %)	K_2O content (mass %)	SiO_2 content (mass %)
Water	160.0	Not applicable	Not applicable	Not applicable
Cement	400.0	0.2	1.0	Not applicable
Silica fume	20.0	0.2	0.2	99.0
Fly ash	0.0	0.2	0.2	50.0
Slag	0.0	0.2	0.5	Not applicable

Estimated system degree of hydration (%): 70

Hydrodynamic viscosity of pore solution relative to water: 1.0

Curing: Saturated ◉ Sealed ○

Compute **Estimated pore solution composition (M):**

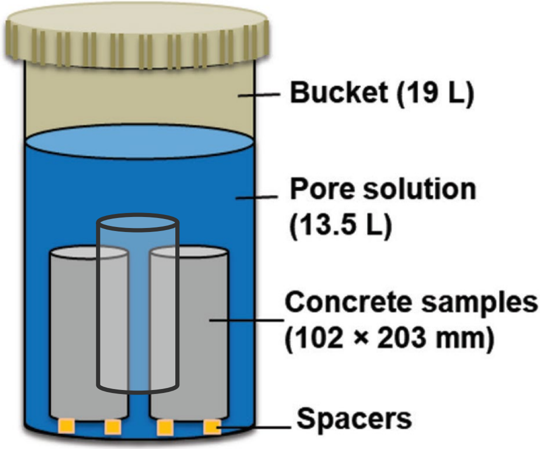
K+: 0.0

Na+: 0.0

OH-: 0.0

Estimated pore solution conductivity (S/m): 0.0

NIST PSR Estimate (Bentz 2007)

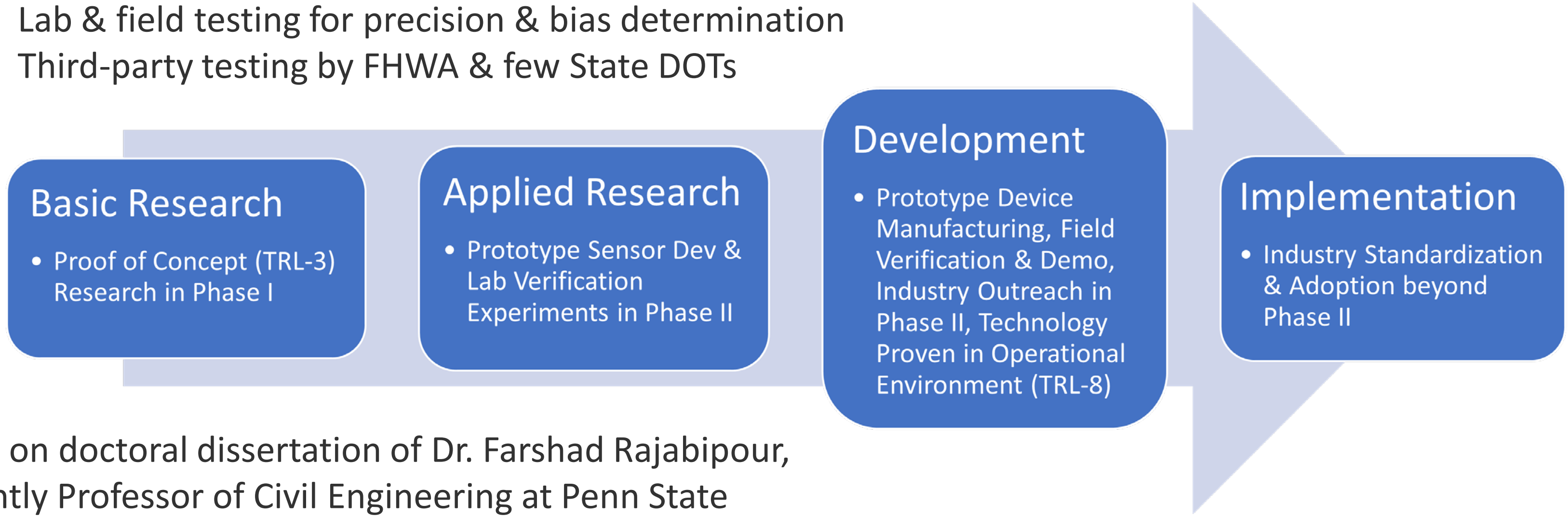


Curing in Simulated Pore Solution (AASHTO TP 119-22)

USDOT SBIR FY21 FH2

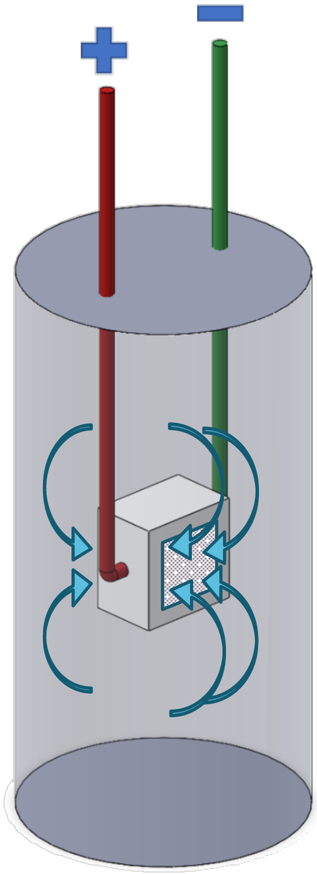
- Phase I: Proof of Concept (July to December 2021)
  - Simulations & Design
  - Sensor matrix materials & manufacturing protocol
  - Electronics components, packaging & placement parts
- Phase II: Technology Development (July 2022 to 2024)
  - Manufacturing & troubleshooting
  - Lab & field testing for precision & bias determination
  - Third-party testing by FHWA & few State DOTs

Callentis Consulting Group
in collaboration with
Penn State University



Based on doctoral dissertation of Dr. Farshad Rajabipour, currently Professor of Civil Engineering at Penn State University

Working Theory of the PSR Sensor

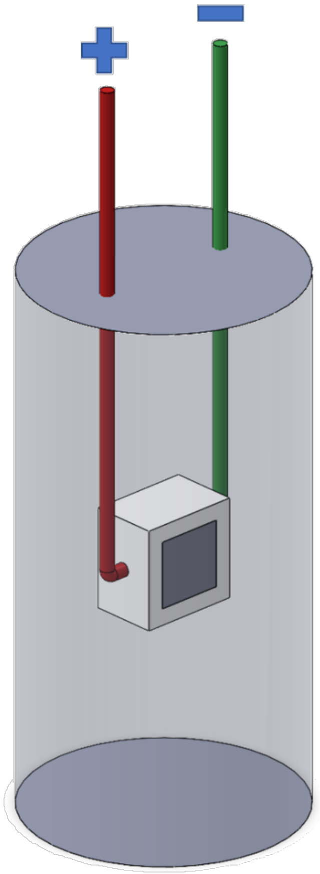


- Porous sensor matrix with known formation factor
  - Median pore size $R_{50} \simeq 10$ to 20nm
  - Not susceptible to drying in Relative Humidity (RH) > 90%
  - Sensor shipped saturated in simulated pore solution
- Sensor is embedded in concrete cylinders or structures
- Pore solution within the sensor comes to equilibrium with that of the surrounding concrete (within <1 week)
- Use available mobile interrogation devices

$$\rho_o = \frac{\rho_s}{F_s} = \frac{R_s k_g}{F_s}$$

- Accuracy: within ±15% compared to the extracted pore solution
- Precision: ±5% repeatability & ±10% reproducibility

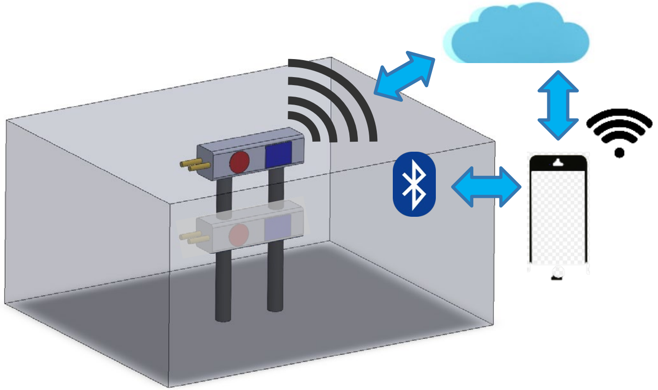
PSR Test Procedure: in cylindrical samples

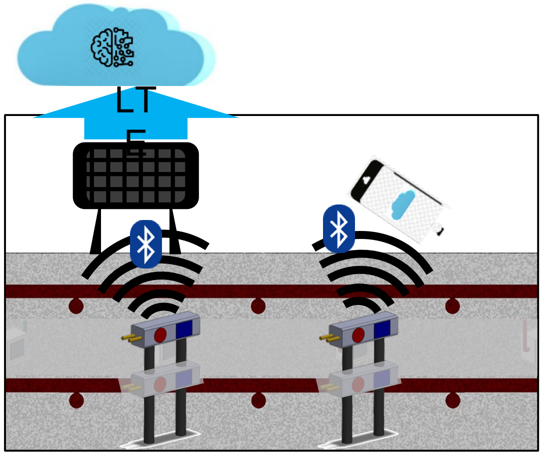


- Rugged sensor package includes:
  - Pre-calibrated porous matrix saturated with simulated solution
  - Attached & insulated electronics
- Field/lab installation
  - Attach package to planar plastic frame
  - Vertically insert assembly in cylindrical mold
  - Fill concrete sample up to top of frame (about 7 inches)
  - Wires to be stored on top of sample under the cap
- Sample Conditioning
  - Preferred conditioning is sealed curing or moist room curing
  - Use the same conditioning as in corresponding mixture resistivity test
- Wait one week before starting measurements
- Maintain & measure the temperature at 23 ± 2 °C (73 ± 4 °F)
- Use similar excitation device as in mixture resistivity tests
- Sensor comes with software to calculate PSR

PSR Test Procedure: embedded in structures

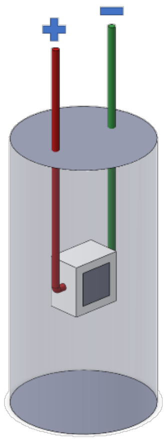
- Rugged sensor package includes:
  - Pre-calibrated porous matrix saturated with simulated solution
  - Electrodes to measure mixture resistivity
  - Thermocouple and relative humidity (RH) sensor
  - Battery, DC-AC inverter, interrogation device, Bluetooth
  - Plastic stands & straps
- Field installation
  - Adjust stands to keep sensor min 1.5 inch from rebars
  - Attach package stands with straps to rebars
  - Pour concrete
  - Wireless or wired with access
- Wait one week before starting measurements
- Check RH measurement to be > 90%
- Sensor comes with software to calculate PSR

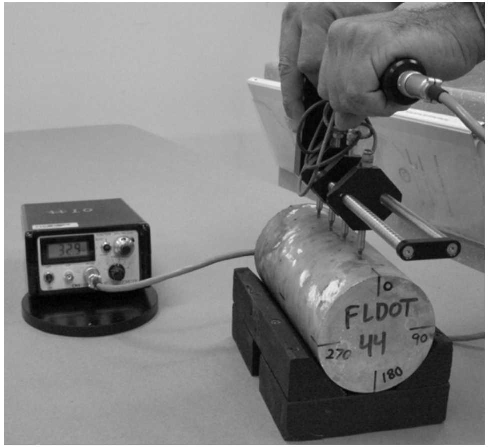


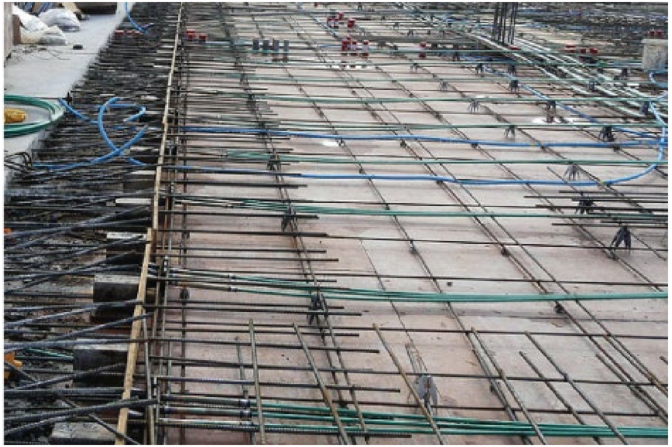


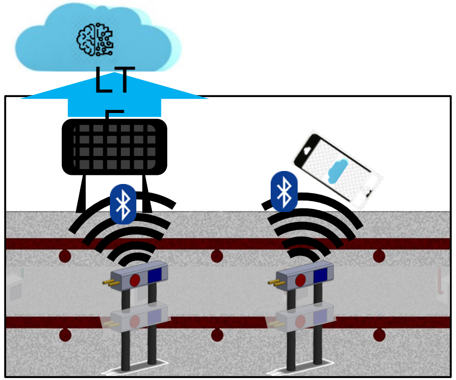
Envisioned Applications

- Mix design qualification
- Construction QC (by contractor) & QA (by agency or representative)
- Monitoring changes in pore solution resistivity of field concrete (e.g., due to Cl penetration)
- Use as pH sensor to assess the risk of Alkali Silica Reaction (ASR) & efficacy of ASR mitigation







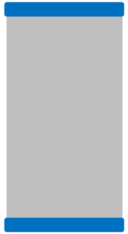


Other On-Going Developments

Concrete Mixture Resistivity & Formation Factor Measurement

Updated AASHTO Test Methods

AASHTO T 358
Surface Resistivity



AASHTO TP 119
Uniaxial Resistivity

- Published August 2022 after 1-year AASHTO Task Force
- Standardized terminology
- Sample conditioning
  - Test results very sensitive to conditioning (more than strength tests)
  - Consistency is key!
  - Shouldn't compare samples with different conditioning
- Report specimen temperature
- Geometry correction for surface resistivity (Appendix X.2)

Resistivity Precision & Bias Study

- Previous precision and bias numbers were generated ~2012
- Curing and conditioning was one of the most critical factors
- Updated test methods
- Ongoing study sponsored by FHWA, conducted by Oregon State University and CP Tech Center with results in 2023
- Inviting labs willing to participate to contact Dr. Jason Weiss at jason.weiss@oregonstate.edu

Today's presenters

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Federal Highway Administration (FHWA)

Dr. Nima Kargah-Ostadi
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Upcoming Events for you

October 12-14, 2022

First U.S.-Africa Frontiers of Science, Engineering, and Medicine Symposium

November 3-4, 2022

TRB's Symposium on Visualization in Transportation

https://www.nationalacademies.org/trb/events

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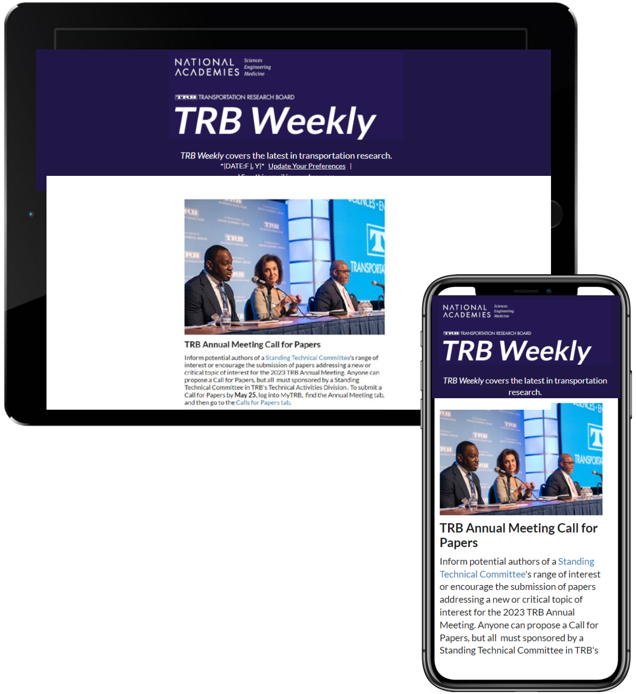

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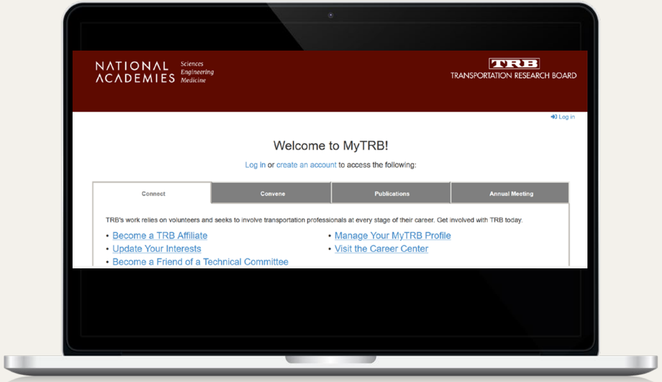

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