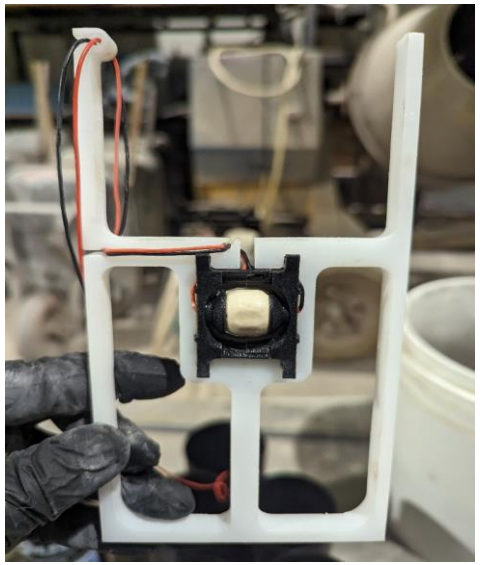
“Embedded pore solution resistivity sensor for concrete materials”

ACI Concrete Convention – Philadelphia, PA, USA

Tuesday November 5th, 2024



✾*Developed Sensor*✾

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Project Background

Literature Review

Objectives and Scope

Methodology

Results

Application

Conclusion

Why measure concrete Pore Solution Resistivity (PSR) ?

AASHTO R101

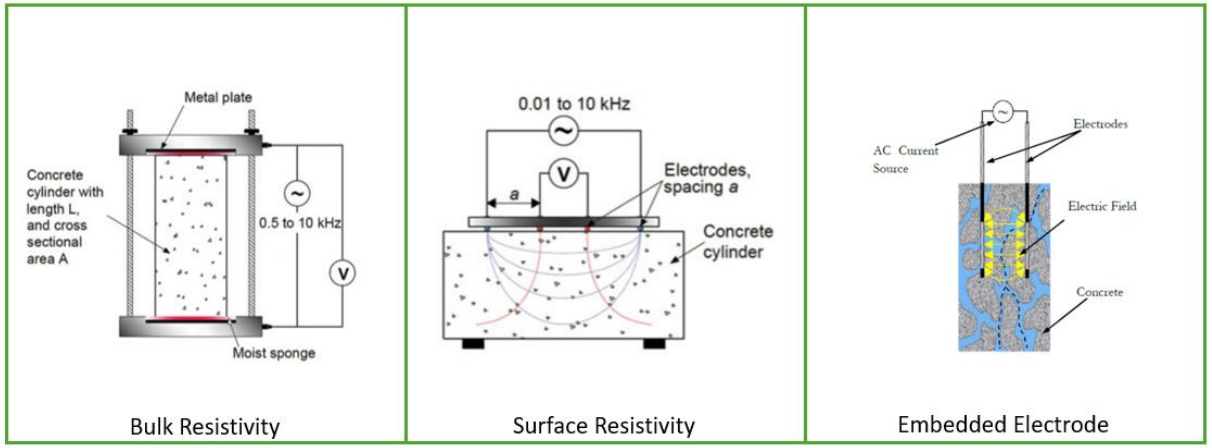
to ensure adequate durability
(chloride penetration and corrosion)

→

we must measure the
formation factor of concrete

Mixture resistivity

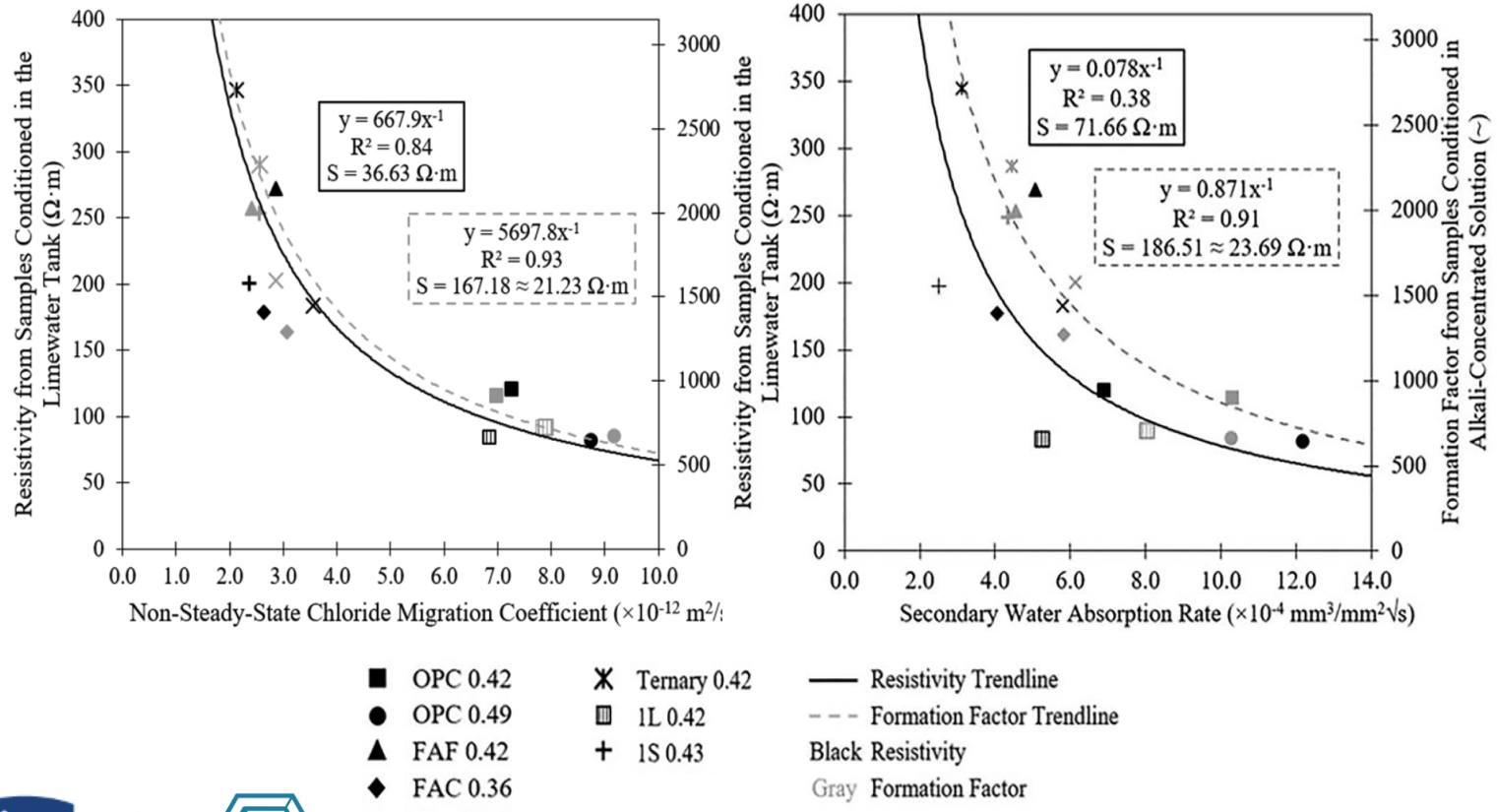
AASHTO T 358 & T 402



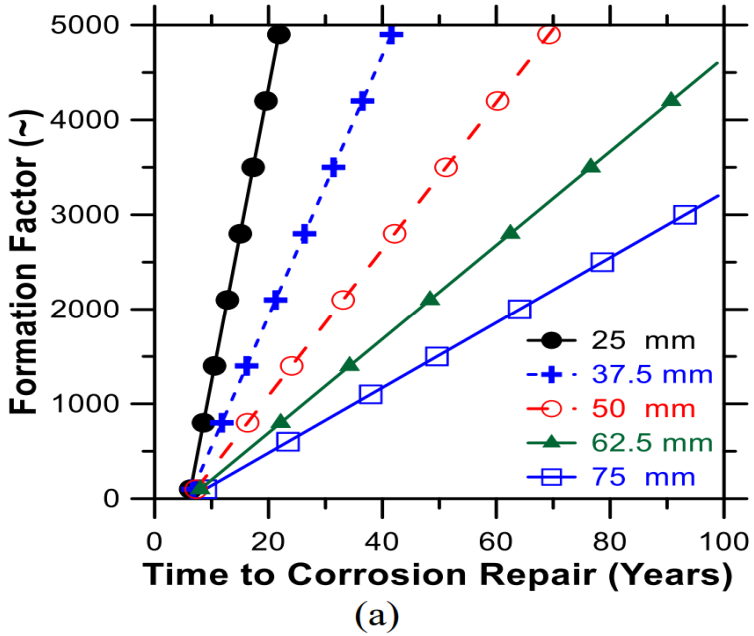
Pore Solution Resistivity

What are the applications of PSR and FF?

Helsel et al. – TRR (2023)



Weiss - TRB (2017)

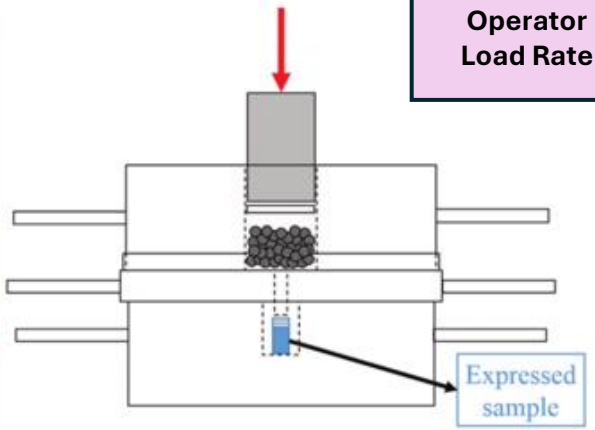


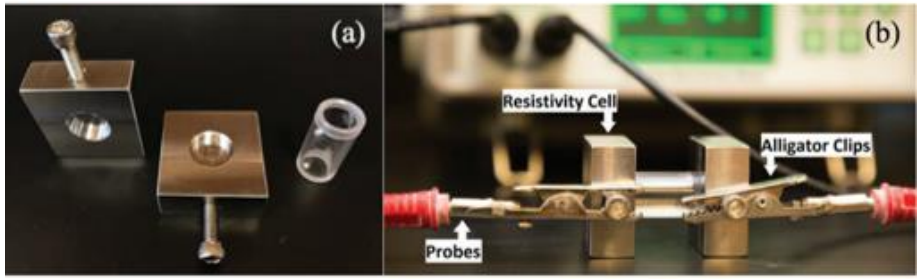
(a)

How to estimate Pore Solution Resistivity (PSR) ?

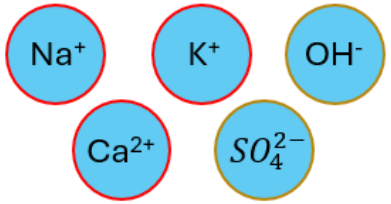
PSE: Pore Solution Extraction

Energy Consumption + Operator Load Rate





NIST Model



(1) Estimate ionic concentrations of PS

(2) Use Snyder equation to estimate cond.

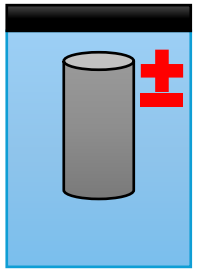
$$\frac{1}{PSR} = \sigma_{cal} = \sum z_i c_i \lambda_i = \sum z_i c_i \left(\frac{\lambda_i^0}{1+G_i\sqrt{\frac{1}{2}\sum z_i^2 c_i}}\right)$$

Inaccurate: SCMs

DOH

SCMs

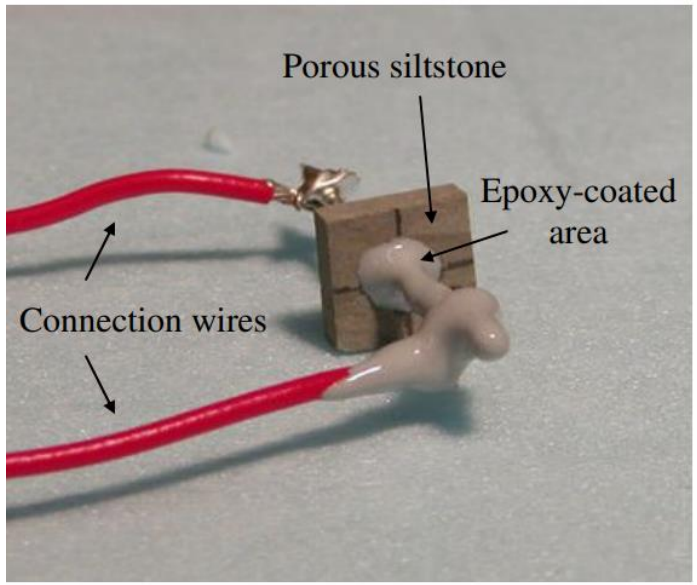
Bucket Test



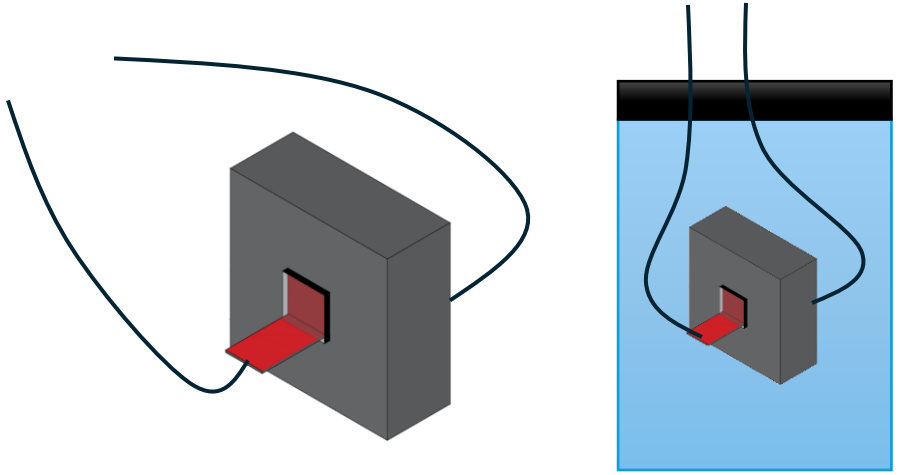
Solution of a known molar ionic strength

Equilibrium (long process) + depends on porosity

How to estimate Pore Solution Resistivity (PSR) ?



Rajabipour – Doctoral Dissertation (2006)



Simulated Pore Solution: 1.0M SPS

Formation Factor

$$FF_{sensor} = \frac{R_{sensor} * GF}{\rho_{Soaking\ Solution}}$$

$$\rho_{SPS} = R_{sensor} * \left(\frac{GF_{sensor}}{FF_{sensor}}\right) = R_{sensor} * TF_{sensor}$$

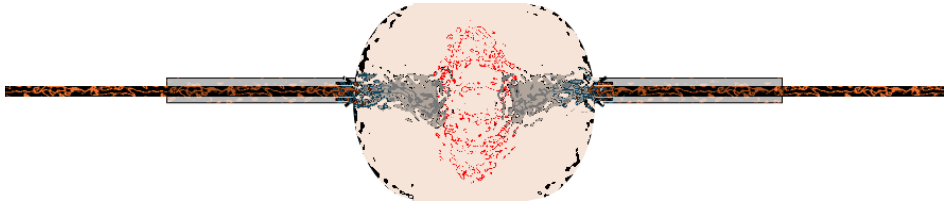
Translation Factor

How to develop the matrix for a PSR sensor?

Matrix

Proprietary Recipe

Making the Sensor



Criteria

High porosity
(55.5%) → High diffusibility & capable of reaching equilibrium quickly

High fraction Pores (FP) with d < 20 nm
(96.3%) → Reduce/Prevent drying

Kelvin equation: $$Radius = \frac{-2\gamma V_m Cos\theta}{\boldsymbol{\mathcal{R}_g} T \cdot ln(R\,H/a_l)}$$

At RH =90%, PS evaporates from pores with diameter <20 nm

What challenges did we overcome? *(to ensure reliable readings)*

- Stability of sensor matrix microstructure
- Minimizing current leakage
- Durability of sensor electronics and packaging
- Calibration of the sensor (TF, testing frequency, saturation solution)
- Temperature fluctuation
- Shipping of the sensor, ensure saturation

Sensors can **accurately predict** the PSR of Simulated Solutions.

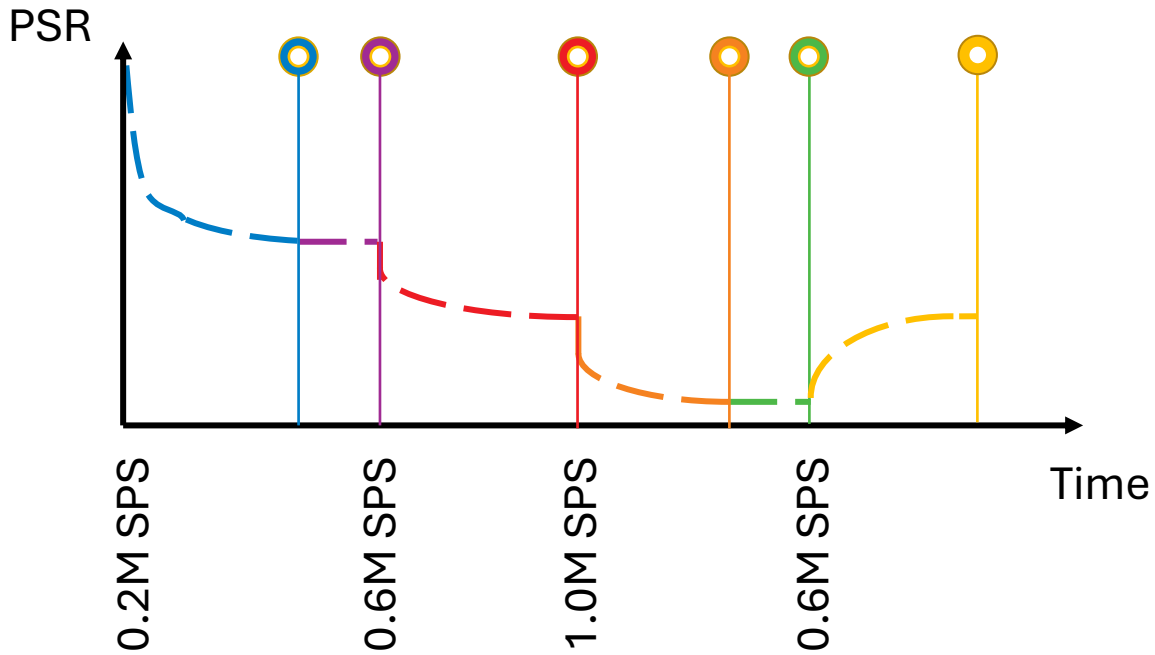
Data Recorded

R_{sensor} | *Temp.* | *Time*

TF

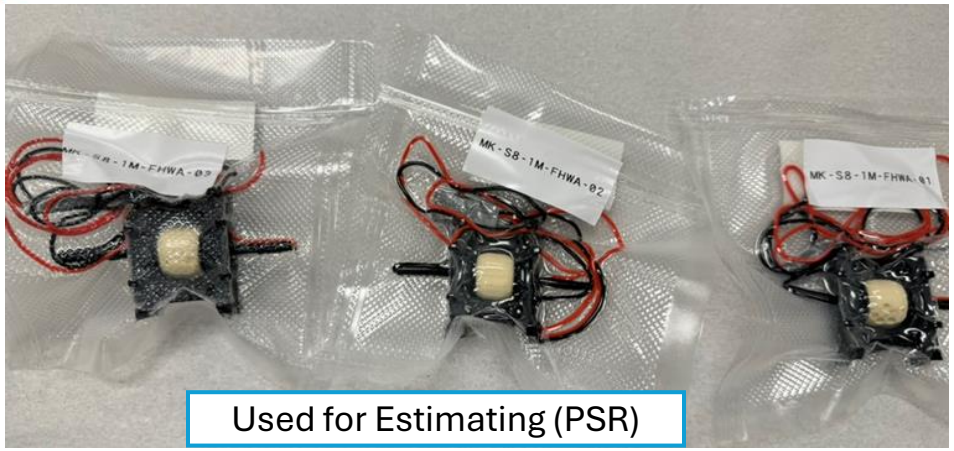
Temp Correction

ρ_{PS} *at 23C & time =t*

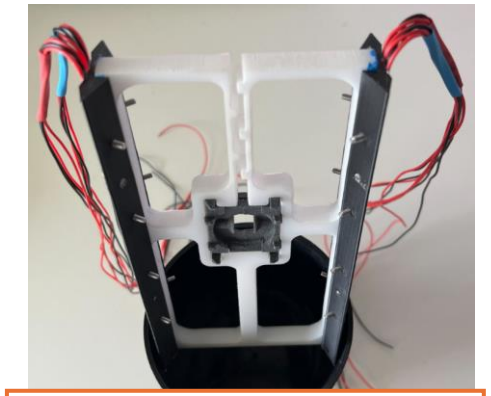


- Phase I : Saturation in 0.2M SPS
- Phase II : Saturation completed
- Phase III : placed in 0.6M SPS
- Phase IV : placed in 1.0M SPS
- Phase V : Equilibrium reached
- Phase VI : Reversibility is achievable.

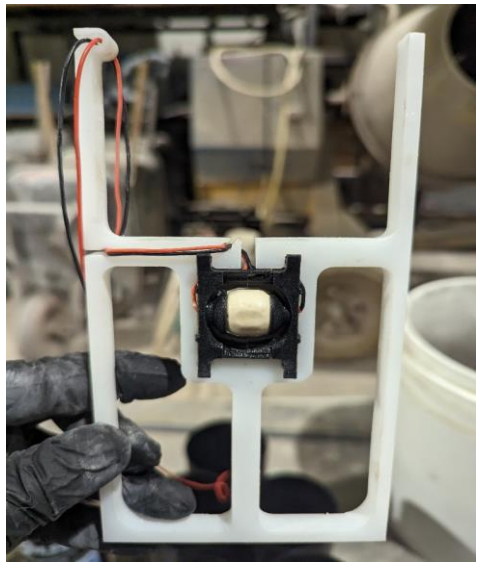
How to use the sensor to measure PSR in cylindrical concrete samples?



Used for Estimating (PSR)



Used for Mixture Resistivity



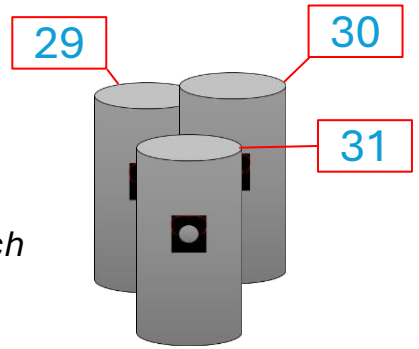
What are the criteria for evaluating its performance in concrete?

1 Success Metrics

i **Precision**

Repeatability of sensor PSR readings among:

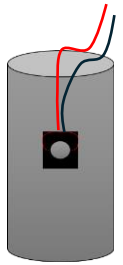
(3) Sensors from the same batch
(3) Batches from the same mix



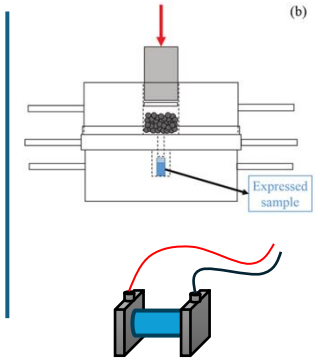
ii **Accuracy**

Calculate **bias** (in PSR) between:

Sensor measured PSR



Reference PSR measured on extracted pore solution



2 Test different concrete curing methods

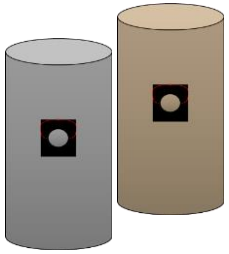
Lime cured

SPS Sealed

3 Test different Concrete Mixtures

1 ≠ w/c

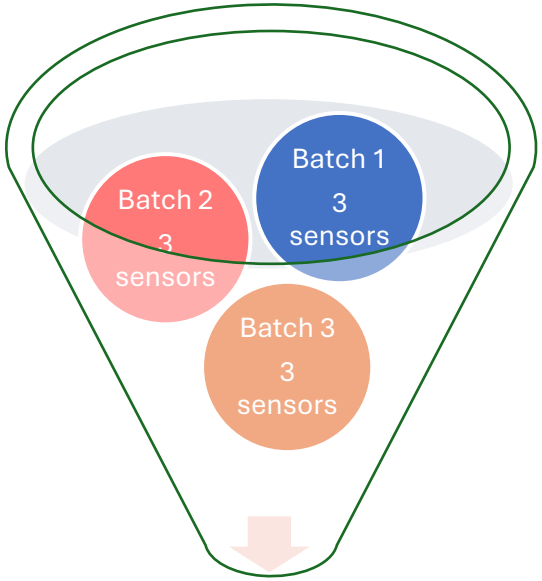
2 SCMs: Fly Ash



Ongoing

Sensors have very **high repeatability** in measuring concrete PSR.

	Repeatability (PSR) index (%)		
	14 days	28 days	56 days
Batch 1	99.6%	99.7%	98.4%
Batch 2	94%	93%	94%
Batch 3	96%	96%	96%
All Batches	93%	92%	92%



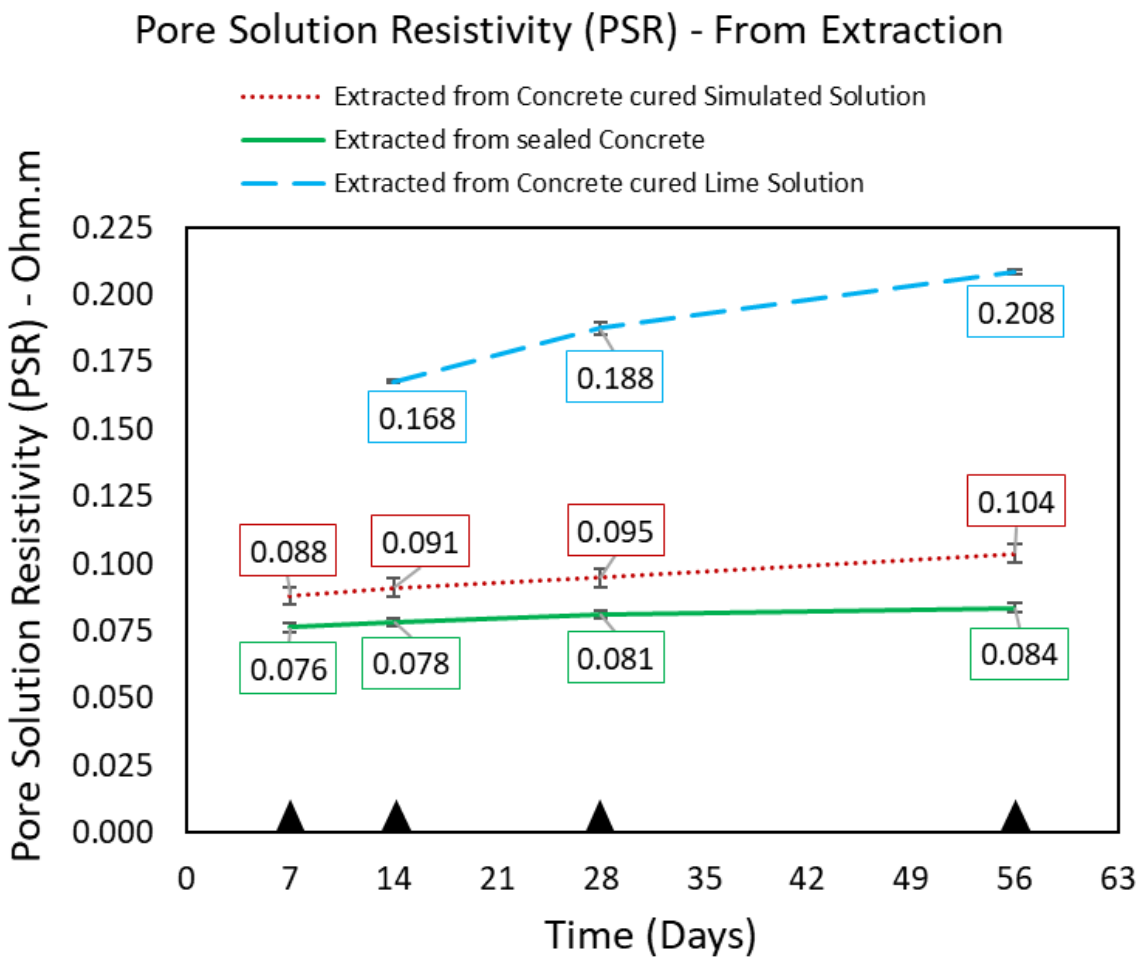
Repeatability (%)

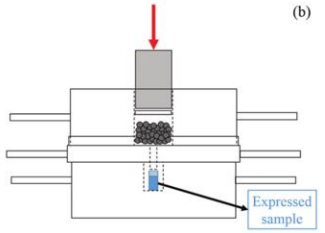
$= 100 - CoV_{PSR}$

Concrete PSR **varies** based on the **curing method**.

Pore Solution Extraction

Concrete - w/c = 0.45



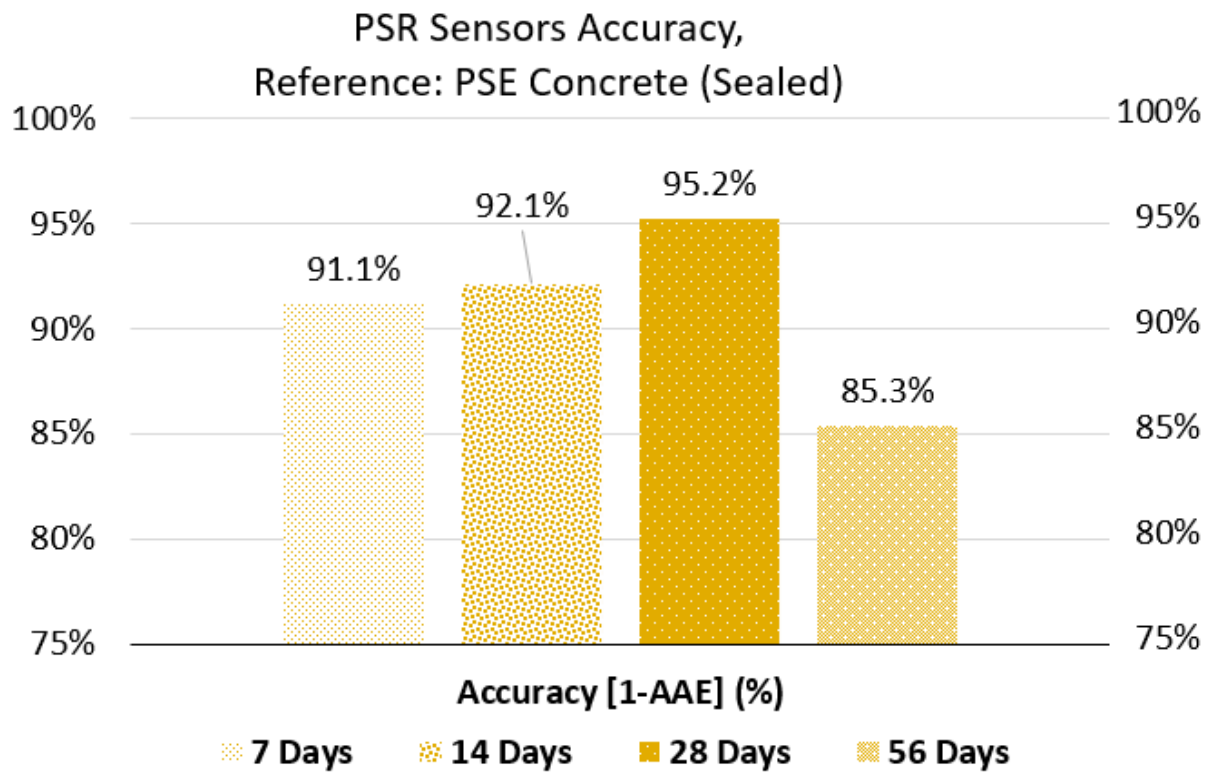


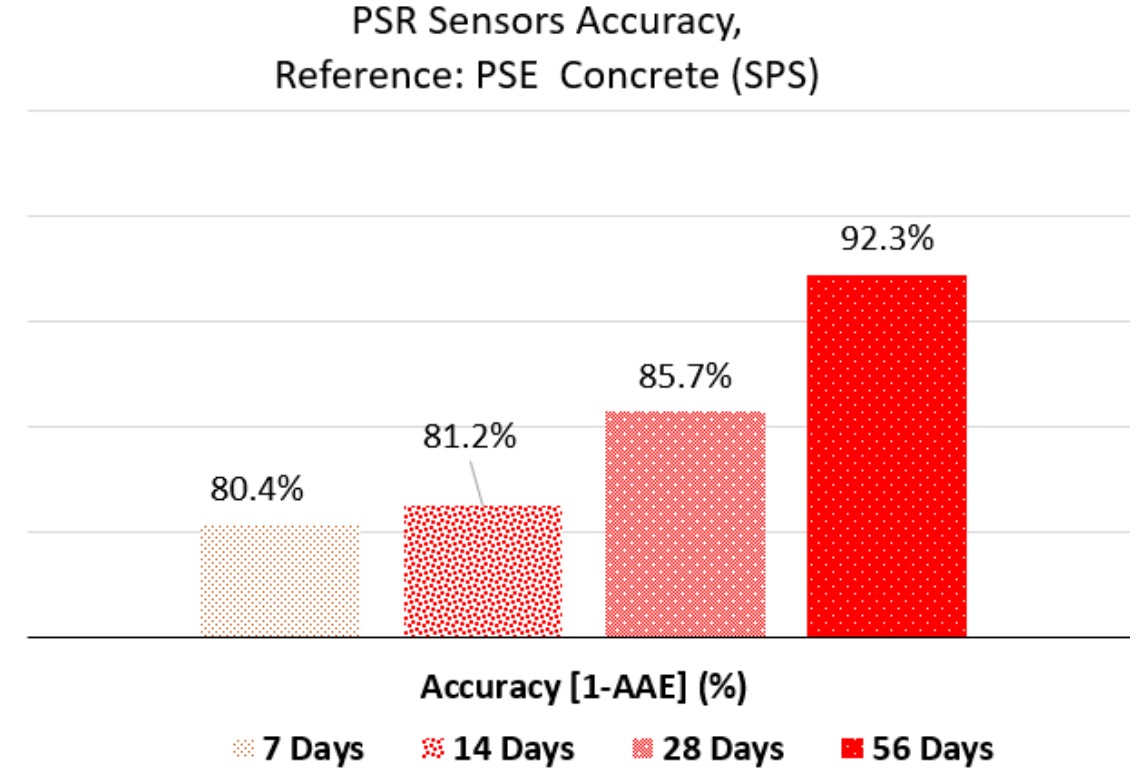
Comparing PSR at 28 days

Concrete (Sealed)	**100%** ***(0.59M)***	**117%** ***(0.52M)***	Concrete (SPS)
Concrete (Sealed)	**100%** ***(0.59M)***	**198%** ***(0.27M)***	Concrete (LC)

Sensor **accuracy** in concrete **depends on** the **curing method.**

PSR sensor in concrete samples cured in simulated solution





Accuracy (%) = 100 – Average Absolute Error (%)

Ongoing work - Study effect of fly ash on sensor PSR readings

Sensors PSR reported at 28 days

i Precision

Without fly ash		With fly ash		
Concrete cured in simulated solution	92%	92%	Concrete cured in simulated solution	
Concrete cured in lime water	92%	97%	Concrete cured in lime water	

ii Accuracy

Without fly ash		With fly ash	
Reference: PSE from sealed concrete	95%	84%	Reference: PSE from sealed concrete
Reference: PSE from concrete cured in simulated solution	86%	77%	Reference: PSE from Concrete cured in simulated solution

Summary & Conclusion

- PSR sensors demonstrate high repeatability, ranging from 93% to 99%.
- The composition of the pore solution around the PSR sensor differs from that extracted from an entire concrete.
- Highest recorded accuracy:
  - with concrete (sealed) is 95% at 28 days
  - with Concrete (SPS) is 92% at 56 days
- Testing on different mix design and field **are ongoing**.

For More information

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