Determining the Optimized Traffic Opening Time Using in-situ NDT for Concrete Monitoring

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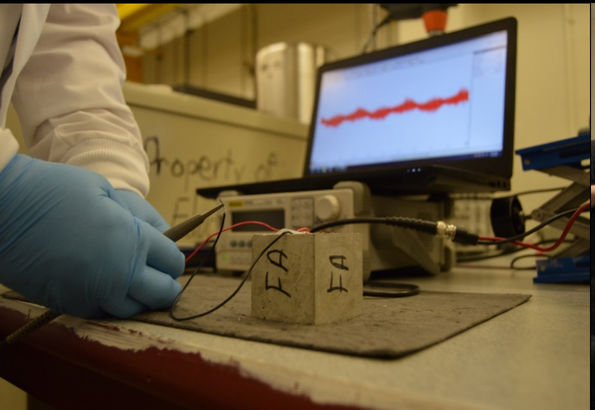

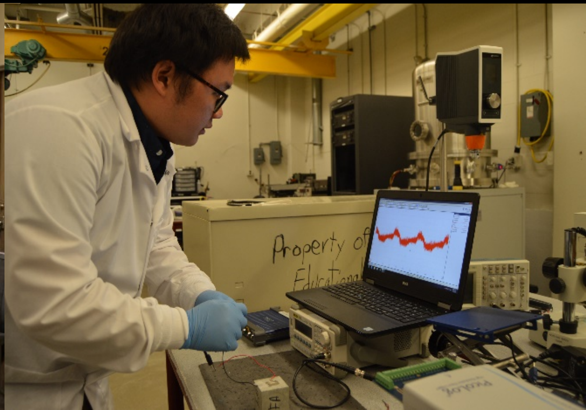

PURDUE UNIVERSITY

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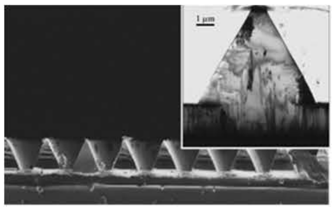
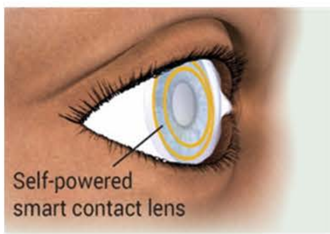
SMART™

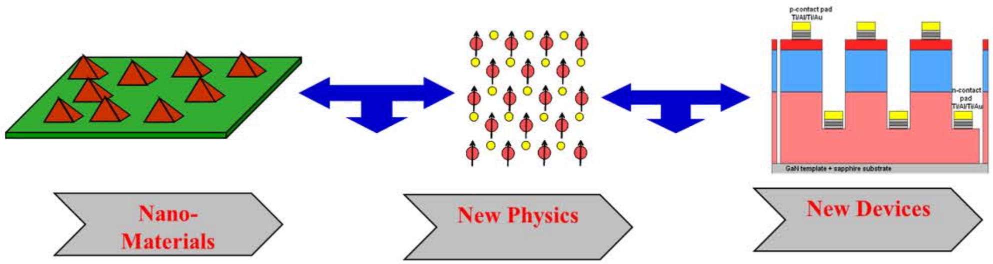
Thermoelectric Energy Harvesting





TE devices can directly converts heat into electricity which can be used for IoT technologies, self-powered sensors for district energy plants and oil & gas industries.

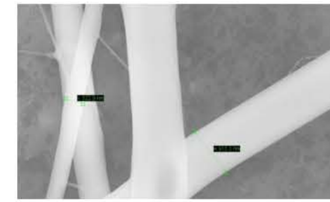
Nanotechnology in Civil Engineering

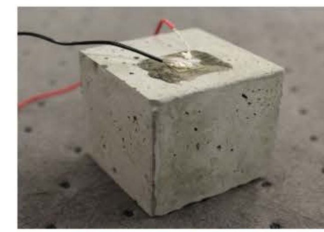


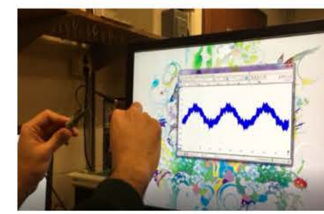
We are a multi-disciplinary research group that develops nanostructured materials and devices for energy harvesting, sensing and non-destructive testing. Currently, we study thermoelectric, piezoelectric, solar cells and their applications in energy fields and in civil infrastructures.

NSF · Department of Energy, United States of America · Indiana Department of Transportation INDOT · DARPA

Piezoelectric Sensing & NDT



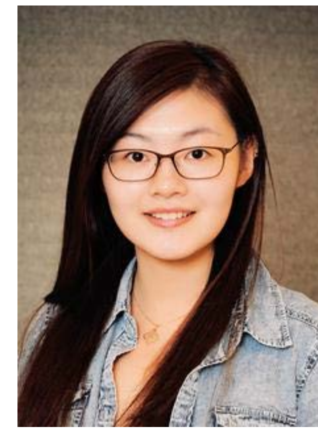




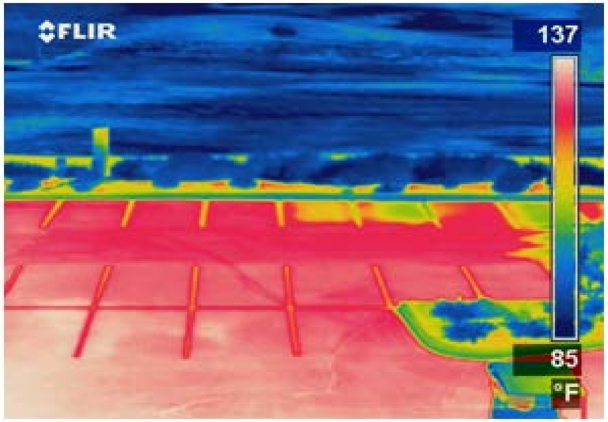
Piezoelectric devices can convert mechanical or vibrational forces into electricity which can be used for energy harvesting, NDT, and structural health monitoring(SHM) .

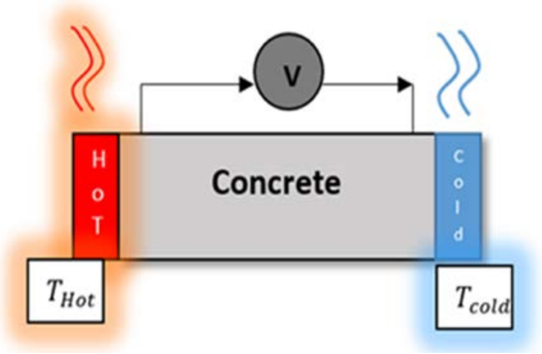
What Are Thermoelectric Materials?

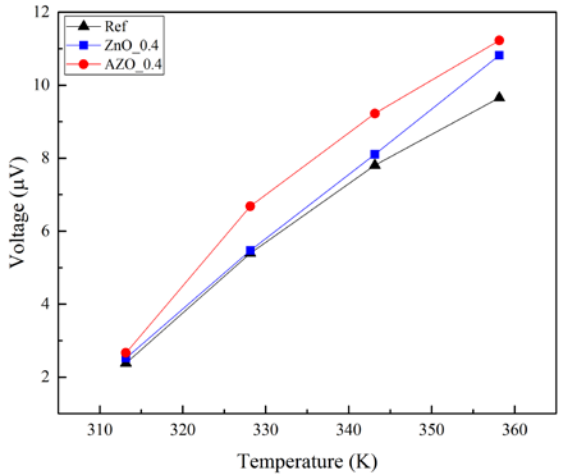
- Thermoelectricity – Convert thermal energy into electrical current flow.
- Discovered by Thomas Seebeck in 1821.
- Materials with high electrical conductivity but low thermal conductivity



Effects of Oxide Nanoparticles on Thermoelectric Behavior of Cement for Energy Harvesting





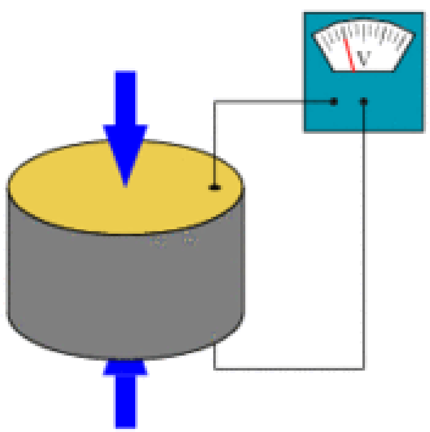


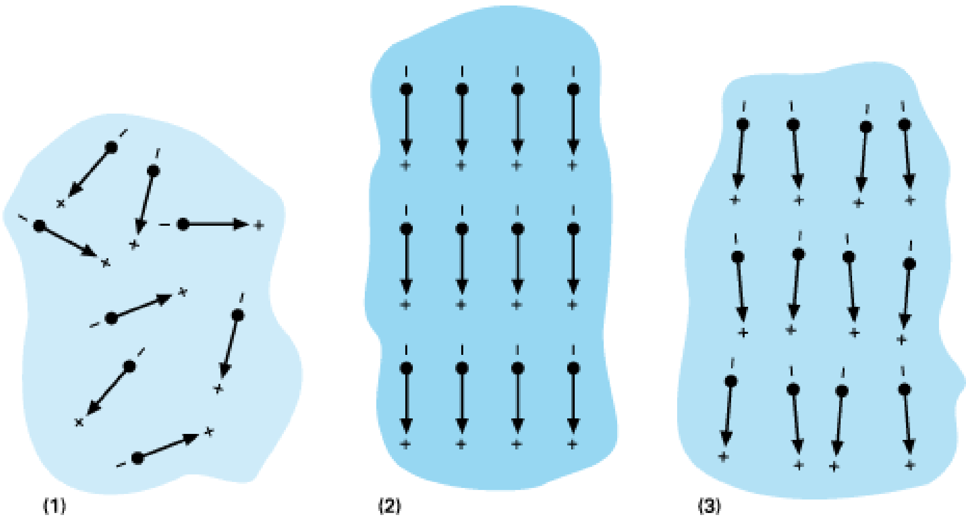
- Delta T between concrete pavement surface temperature vs air temperature ranges from 25ºF to 58ºF.
- AlZnO nanoparticles with 0.4% wt. shows the best results
- The improved TE behaviors are likely due to enhanced thermopowers

E. Ghafari, et. al, Composites B, 105, 160, 2016
G. Ghahari, et al, Construction & Building Materials, 146, 755, 2017

What Are Piezoelectric Materials?

- Piezoelectricity – Convert mechanical energy into electrical current flow.
- Discovered by French Physicists Pierre and Jacques Curie in 1880
- Generally exhibited in crystal materials with no Inversion Symmetry





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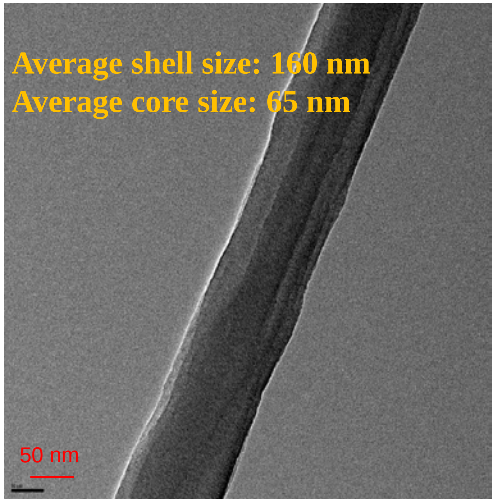
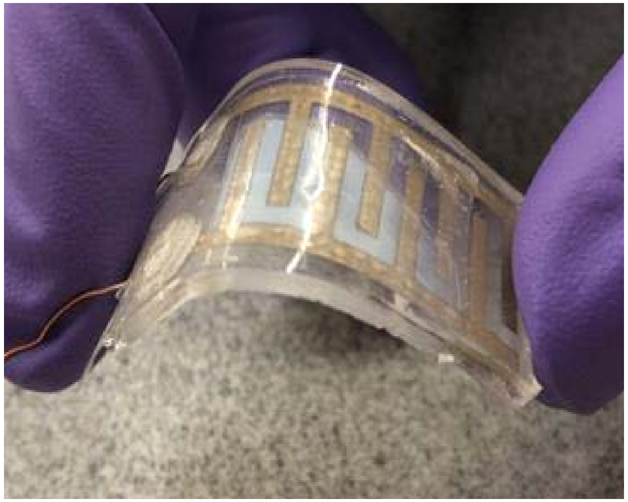
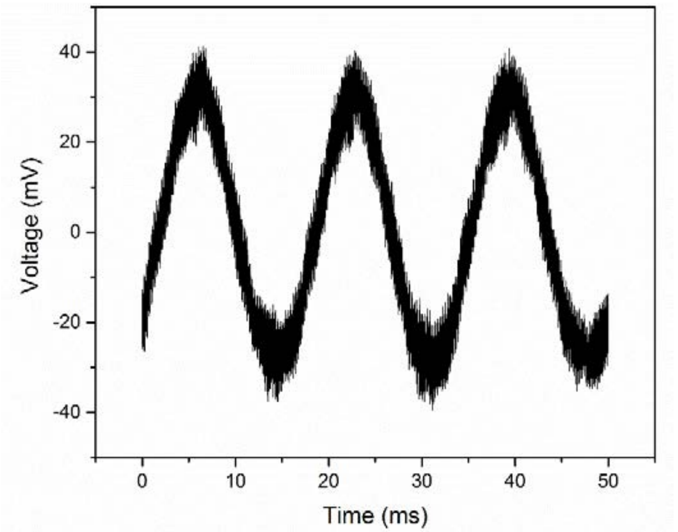
PVDF-GO Piezoelectric Nanogenerator







- Developed electrospinning methods to produce nanofibers
- Inkjet printing was used to create low-cost and flexible sensors
- Power output ~ 40mV, Sufficient to power sensors

E. Ghafari, N. Lu, et. al, Composites B: Engineering, 116, 40, 2017.

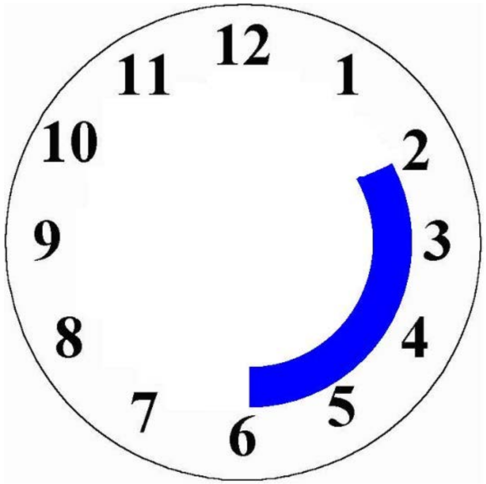
N. Lu , et. al, Advanced Composites & Hybrid Materials, 2018, 1:332-304

E. Ghafari, N. Lu, et. al, ACS Applied Materials and Interfaces, 2018, In Review

How does this apply to traffic opening time?

Research Motivation

Requirement for Determining Early-Age Concrete Strength



Curing time & open to traffic

Research Motivation

Current Methods

- Compression/ Flexure tests
- Concrete maturity test

Disadvantages

- Not very reliable
- Time consuming
- Requires labor
- Repetition of calibration processes

http://civilblog.org/2013/05/10/compressive-strength-test-of-concrete-is516-1959/

http://www.pcte.com.au/intellirock-wireless-and-intellirock-live

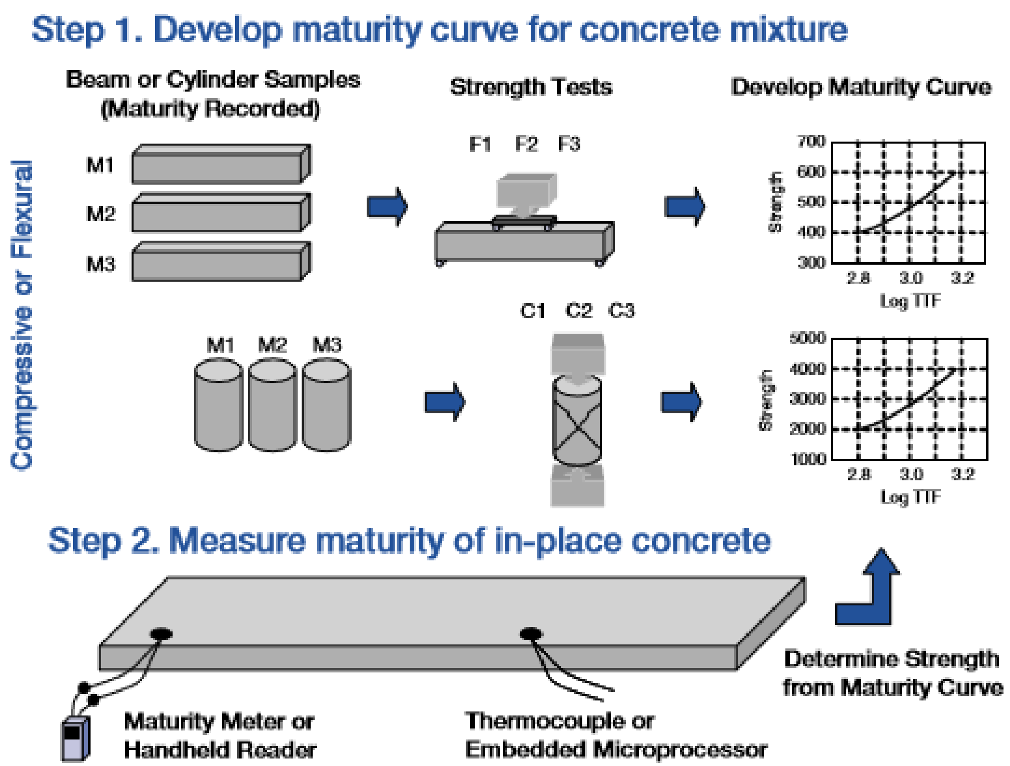
Flexural Strength Testing

- Samples are heavy and inconvenience for transport
- Large variation of testing results between lab and field

http://docs.trb.org/prp/13-1986.pdf

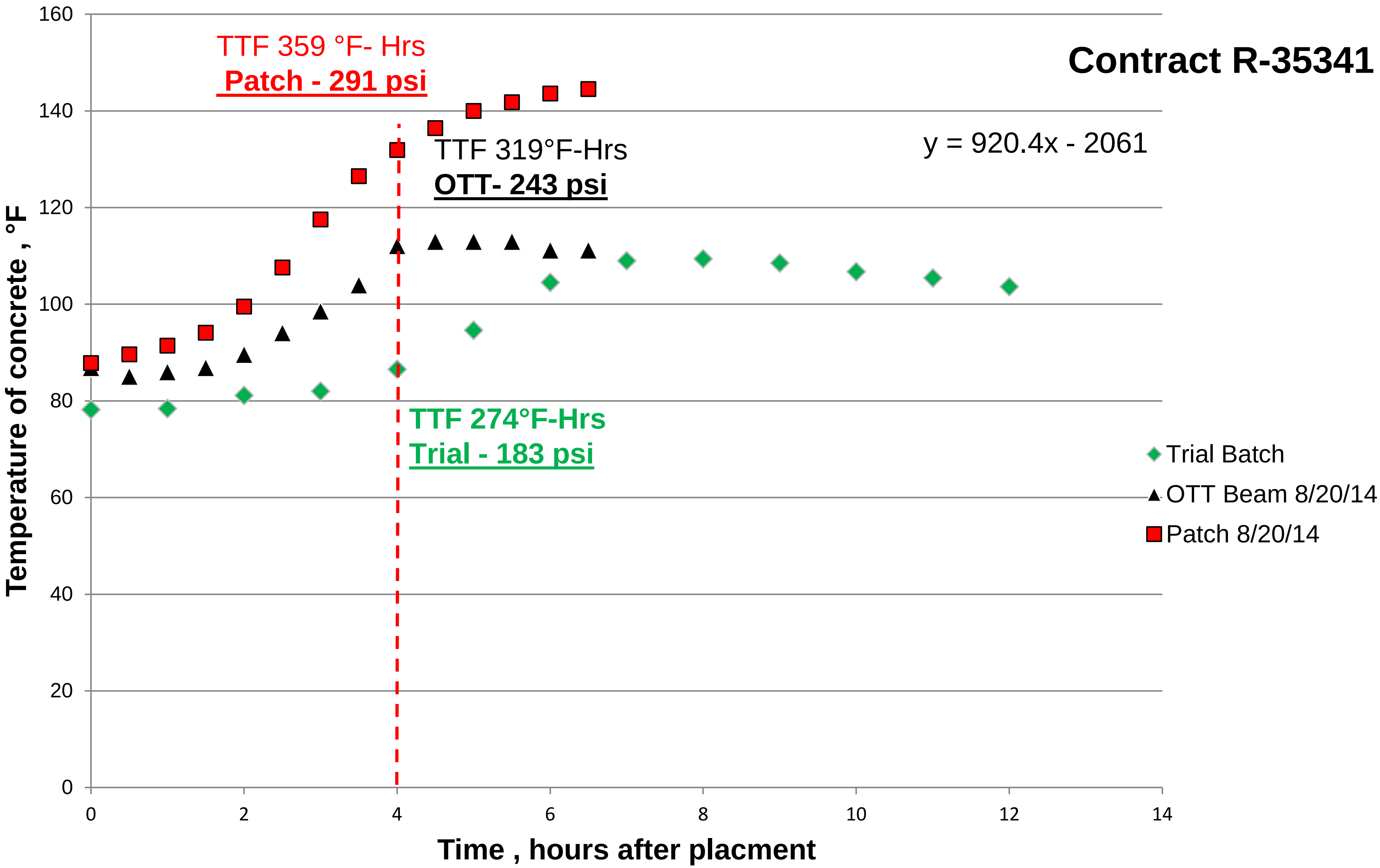
Maturity testing (ASTM C-1074, IMT 402-15T)

Concrete strength (and other properties) is directly related to both age and its temperature history.



http://wikipave.org/index.php?title=Maturity_Testing

INDOT Experience with Maturity



Research Needs

- An NDT field testing method for **in-situ monitoring** of concrete properties is needed to determine the optimal traffic opening time.

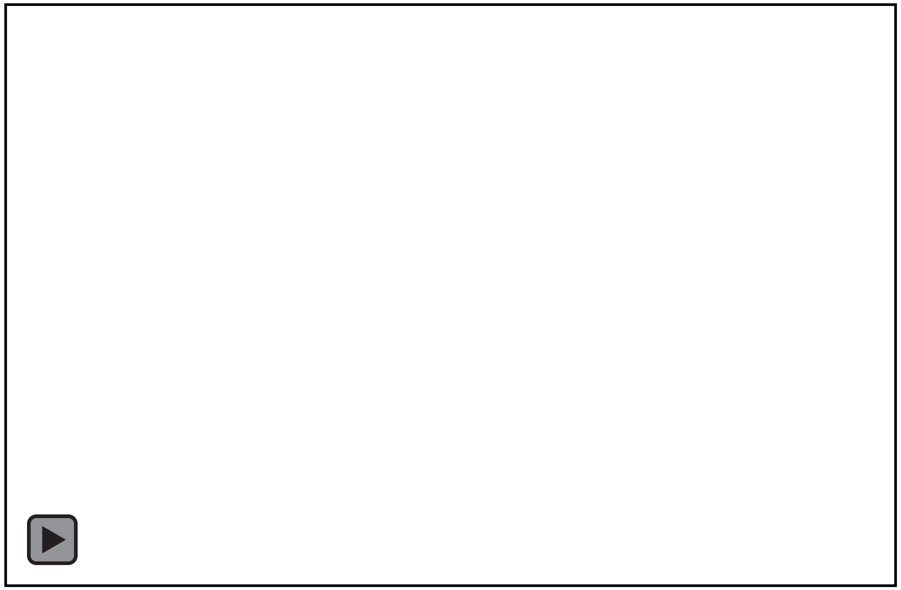
- Provides **accurate data to** ensure high level quality control

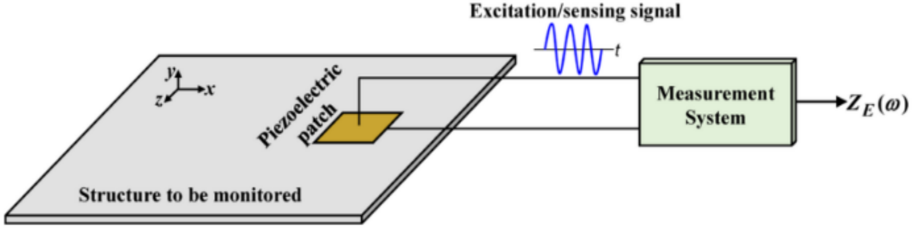
- **Easy operation, no calibration required** to reduces the time and cost involved in determining the schedule of construction operations

Electro-mechanical Impendence (EMI) with Piezoelectric Sensor

- Our approach is using **Piezoelectric Sensors with Electromechanical Impedance Technique**.

- we can understand the **materials/structure mechanical properties (modulus)** due to electromechanical coupling effect.





Principle of EMI Methods

- A mathematical formulation of the electrical admittance of the piezoelectric transducer bonded onto the concrete specimen

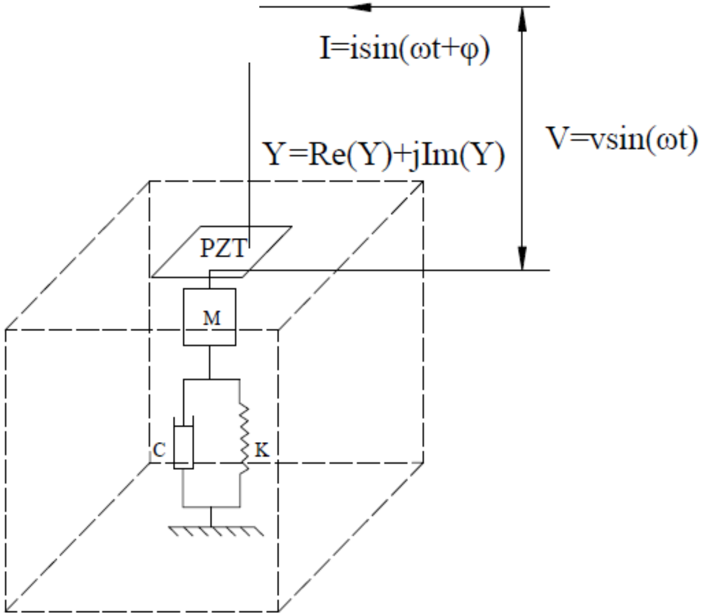
Coupled electric admittance of the PZT patch

$$Y(\omega) = \frac{I}{V} = i\omega \frac{w_a l_a}{h_a}\left[\bar{\varepsilon}_{33}^T + \left(\frac{z_a}{z_s + z_a}\right) d_{31}^2 \bar{E}_p \left(\frac{\tan \kappa l_a}{\kappa l_a}\right) - d_{31}^2 \bar{E}_p\right)]$$

Mechanical impedance of the PZT actuator Z_a

$$z_a = \frac{\bar{E}_p w_a h_a}{i\omega l_a} \cdot \frac{\kappa l_a}{\tan \kappa l_a}$$

Mechanical impedance of the concrete Z_s



S. Shin, *et. al.* Smart. Mater. Struct. *17*, (2008) 055002

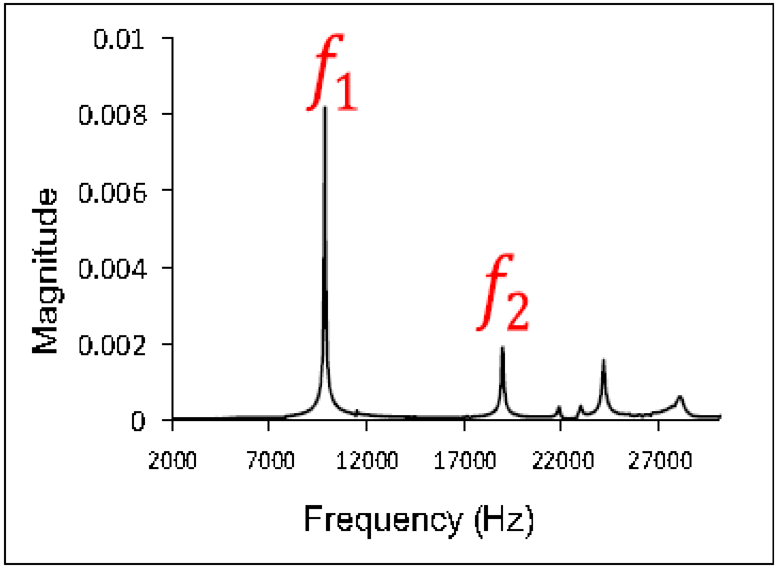
Calculation References

- A mathematical formulation of the Young's Modulus (*E*) and resonant frequency (*f*) of electrical admittance

$$E = 2(1 + \nu_m)\rho_m \left(\frac{2\pi R_0 f_1}{f_n'}\right)^2 \quad (3)$$

and

$$f_n' = \left[-0.2792\left(\frac{L}{D}\right)^2 + 1.4585\left(\frac{L}{D}\right) - 2.1093\right](\nu_m)^2 + \left[0.0846\left(\frac{L}{D}\right)^2 - 0.5868\left(\frac{L}{D}\right) + 1.3791\right](\nu_m) + \left[0.285\left(\frac{L}{D}\right)^2 - 1.7026\left(\frac{L}{D}\right) + 3.3769\right] \quad (4)$$



A. Narayana, *et. al.* J. Nondestructive Evaluation, (2017) 36-64

Statistical Techniques

Statistics metrics such as **RMSD, MAPD and CCD** to analyze EMI spectra

- Root Mean Square Deviation (RMSD)
- Mean Absolute Percentage Deviation (MAPD)
- Correlation Coefficient Deviation (CCD)

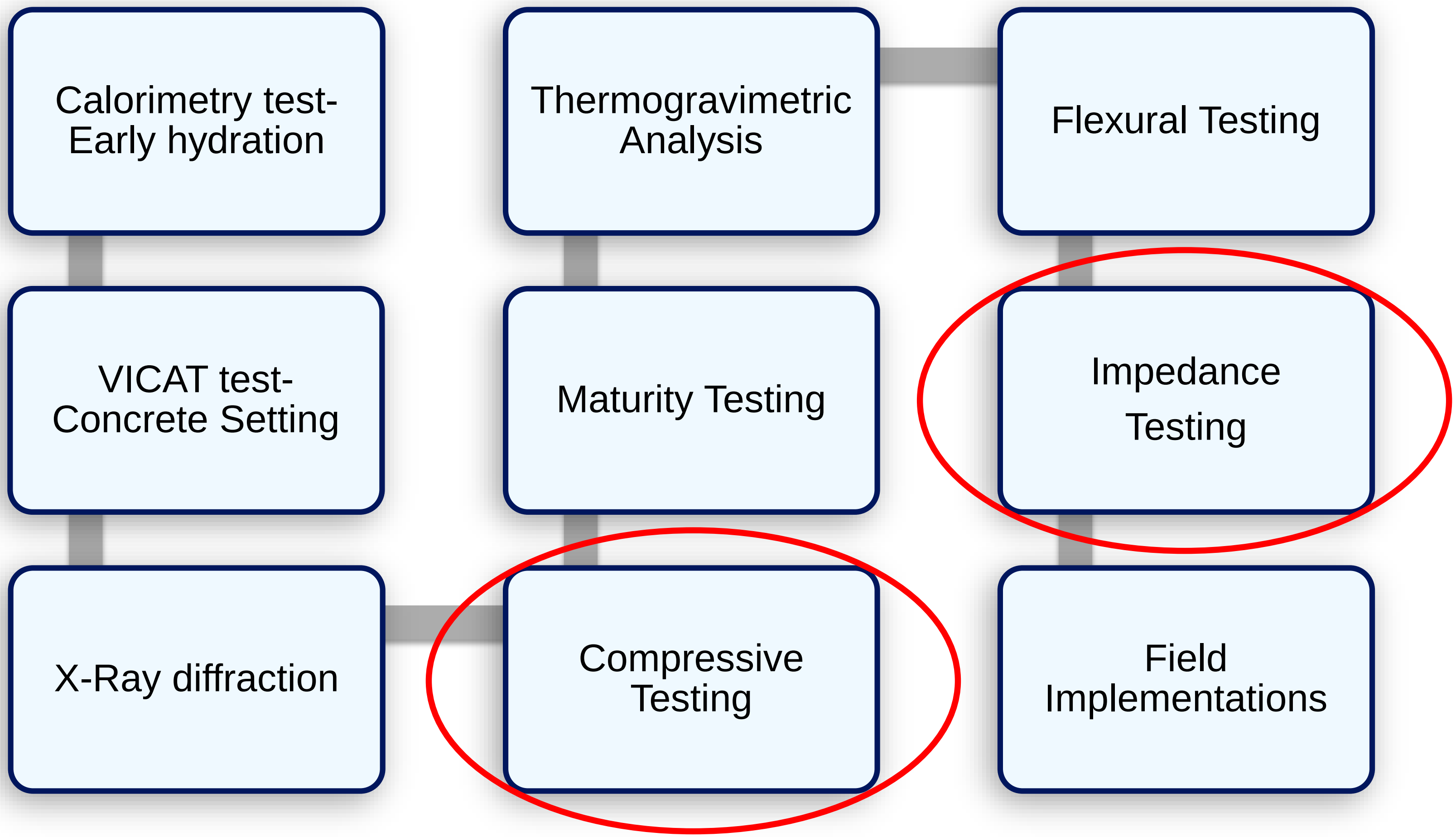
$$\mathrm{RMSD}\ (\%) = \left(\sum_{k=1}^{N} \left[\mathrm{Re}(Y_k)_j - \mathrm{Re}(Y_k)_i \right]^2 \Big/ \sum_{k=1}^{N} \left[\mathrm{Re}(Y_k)_i \right]^2 \right)^{1/2}$$

$$\mathrm{MAPD}\ (\%) = \frac{1}{N} \sum_{k=1}^{N} \left| [\mathrm{Re}(Y_k)_j - \mathrm{Re}(Y_k)_i] / \mathrm{Re}(Y_k)_i \right|$$

$$\mathrm{CCD}\ (\%) = \frac{1}{N \sigma_{Y_j} \sigma_{Y_i}} \sum_{k=1}^{N} \left[\mathrm{Re}(Y_k)_j - \mathrm{Re}(\bar{Y})_j \right] \cdot \left[\mathrm{Re}(Y_k)_i - \mathrm{Re}(\bar{Y})_i \right]$$

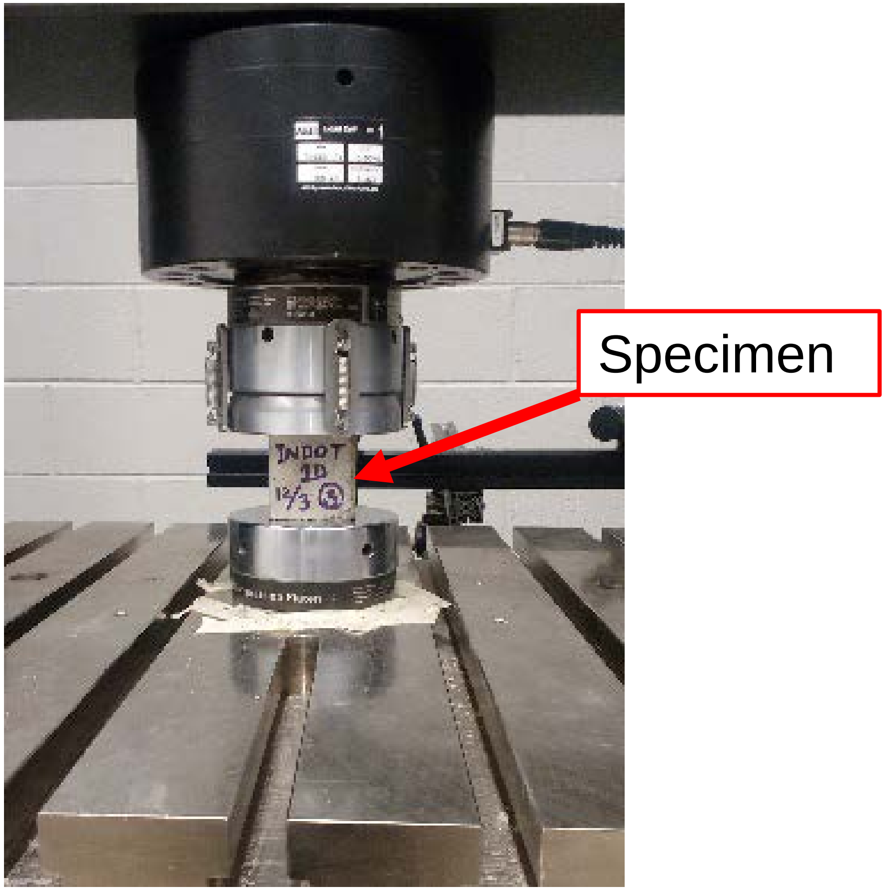
Experiments Conducted in This Study

The Process


Calorimetry test-
Early hydration
Thermogravimetric
Analysis
Flexural Testing
VICAT test-
Concrete Setting
Maturity Testing
Impedance
Testing
X-Ray diffraction
Compressive
Testing
Field
Implementations

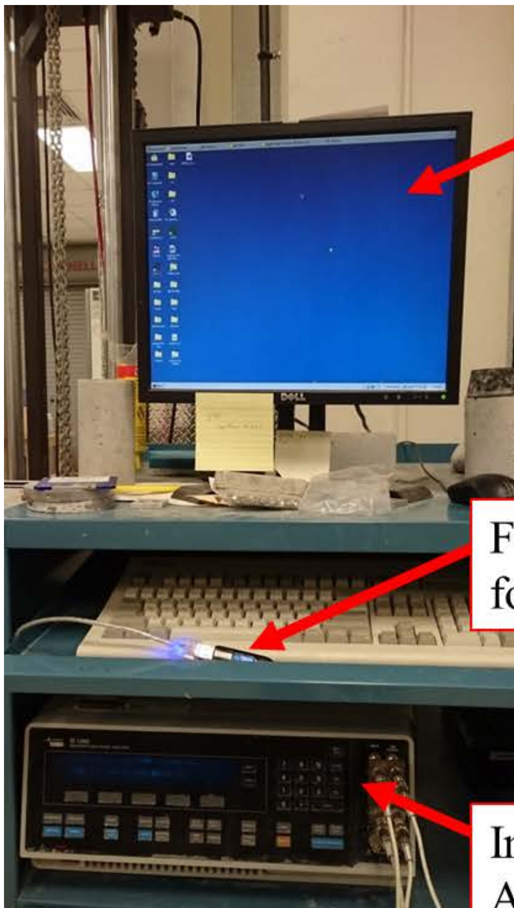
Test Setup – Compression Test

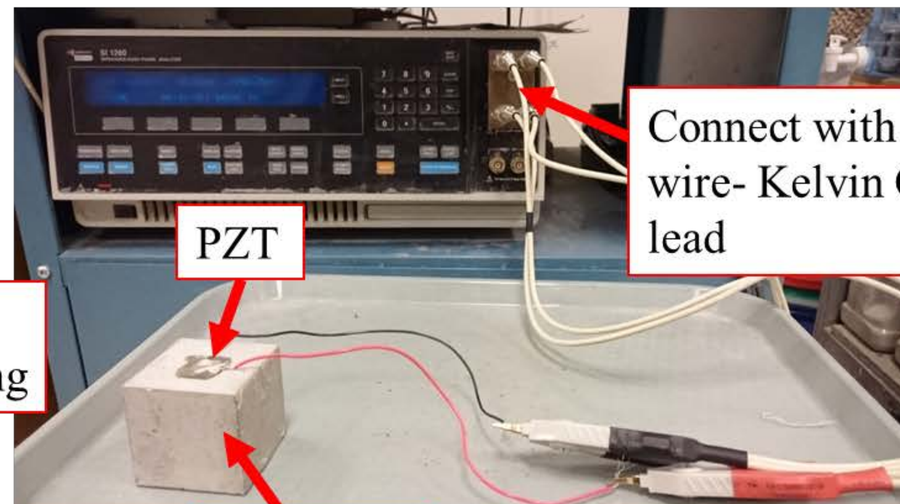
The MTS testing machine was used to perform compression test



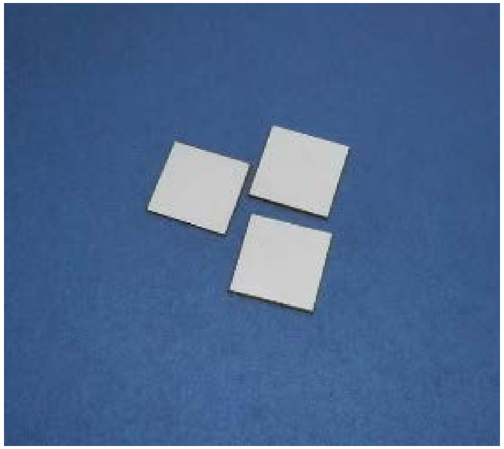
Test Setup – EMI Test

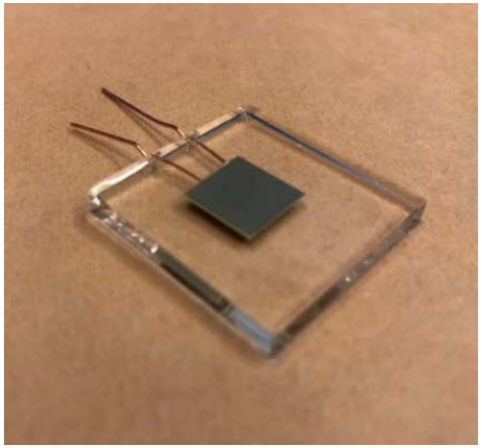
The Impedance/Gain-Phase Analyzer parts and setup

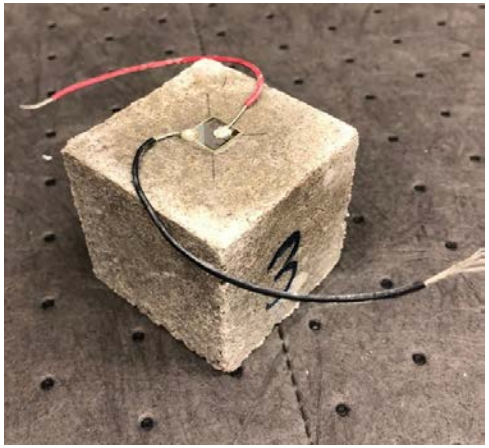


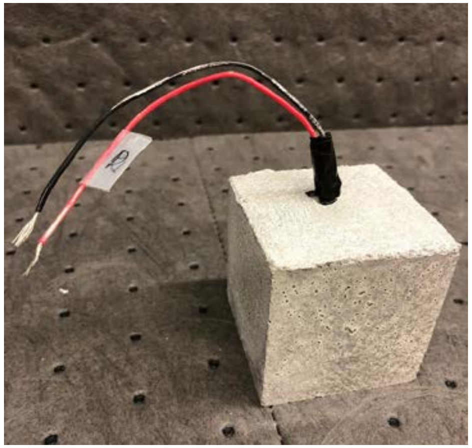


Testing Samples





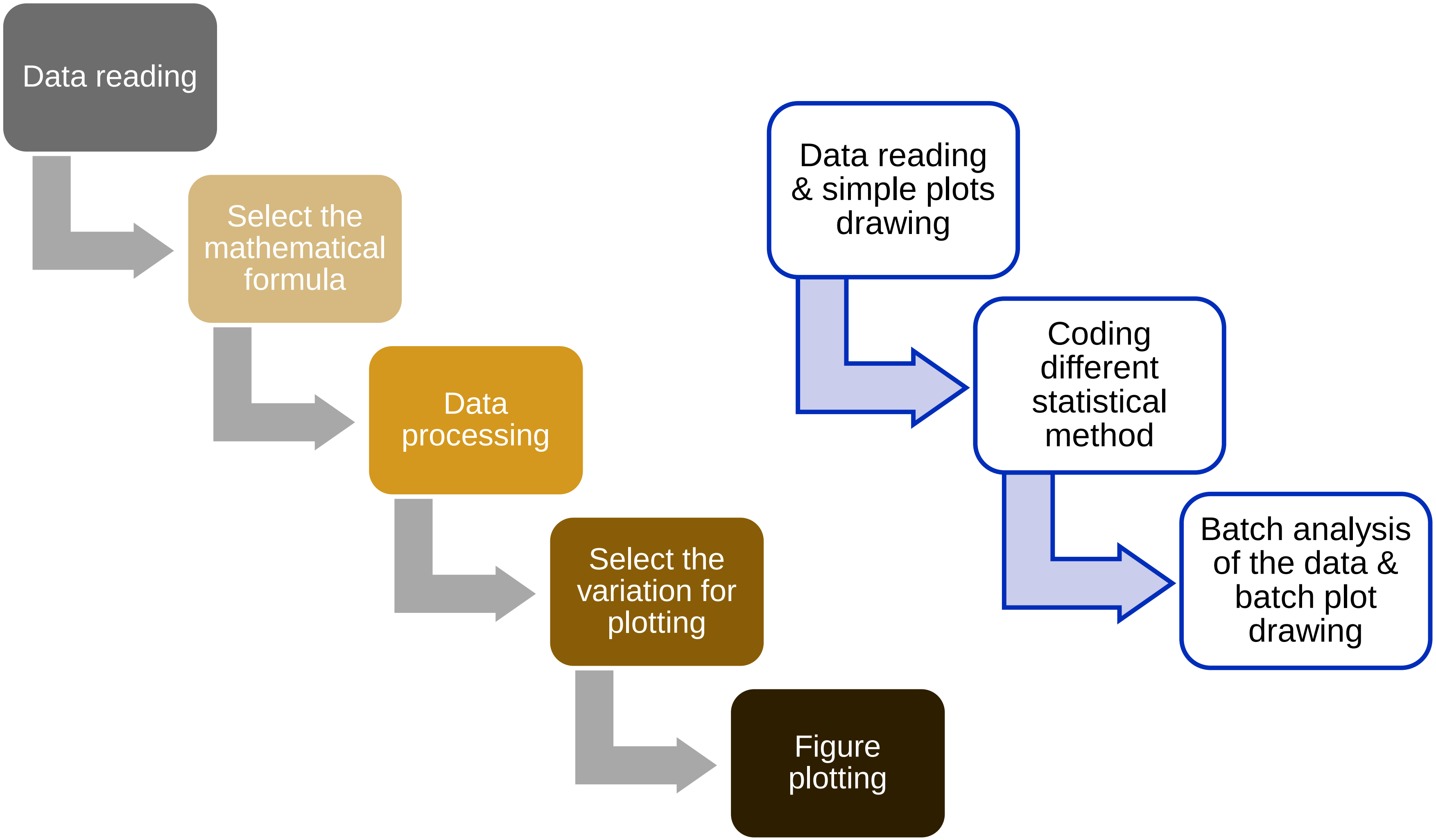




Surface bonded PZT sensor

Embedded PZT sensor

Data Processing – MATLAB code



Test Results on Mortar with Various W/C Ratio

Mortar with Different W/C

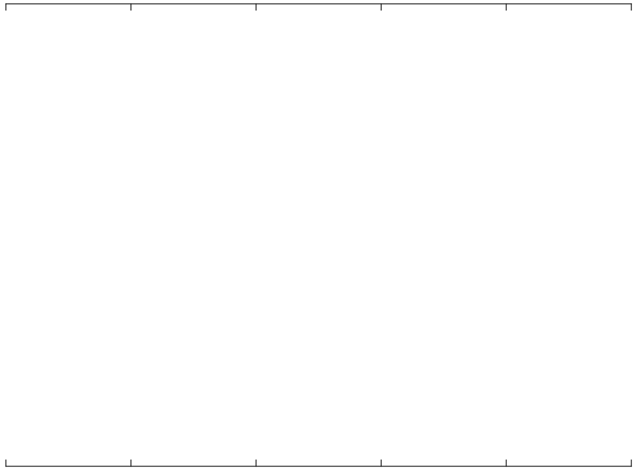
- Mortar experiments
- EMI, Compressive test
- **Very early age (4-8 hrs), early age (1-3days)**

Cement Type	W/C ratio	Testing Age
Type I	0.38	Very early age (4 – 8 hrs)
Type III	0.40	Early age (1–3 days)
	0.42	
	0.44	
	0.46	

EMI Result Typical Spectra

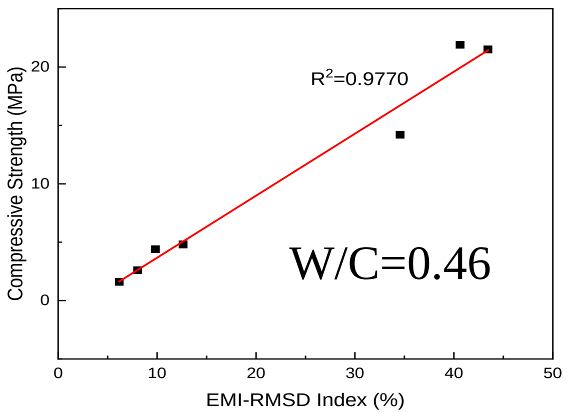
- Conductance decreased with the increase of age
- Porosity and water will reduce with the increase of the age, so that conductance will decrease

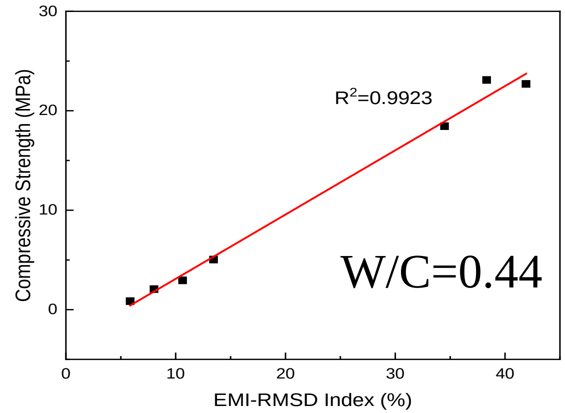
Cement Paste

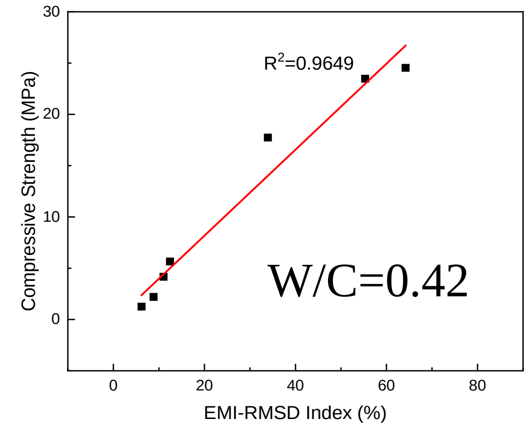


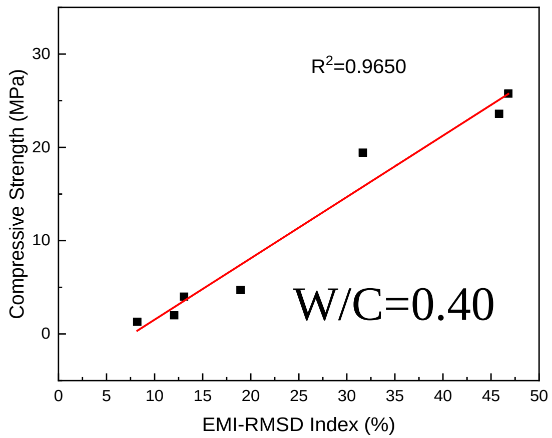
Mortar

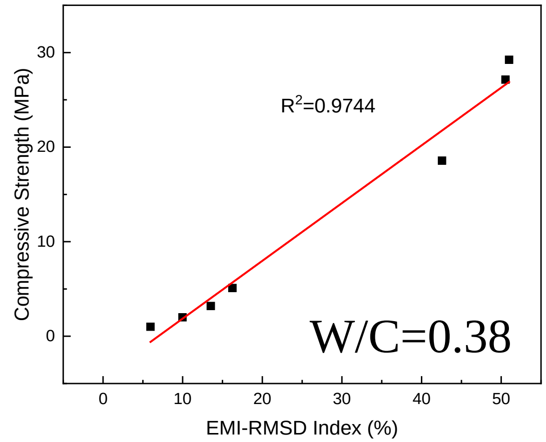
Type I cement -frequency range:100-400 kHz





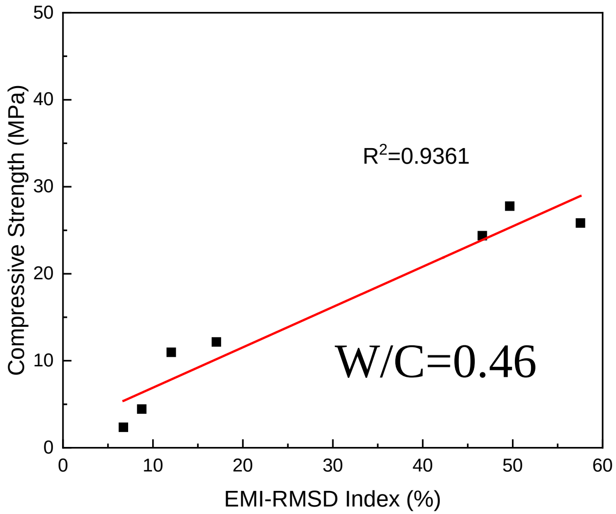


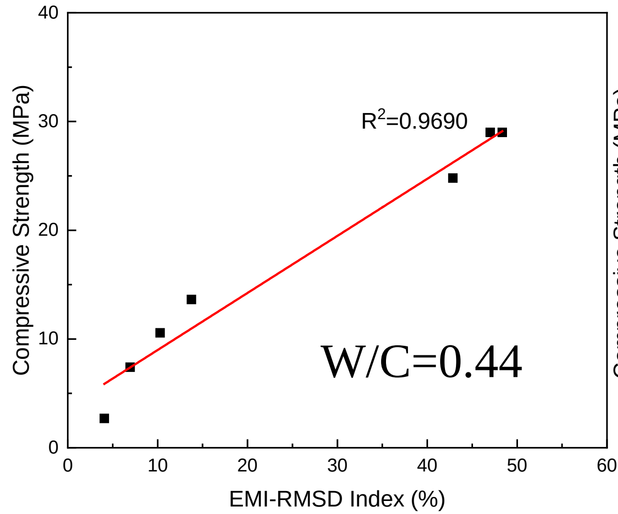


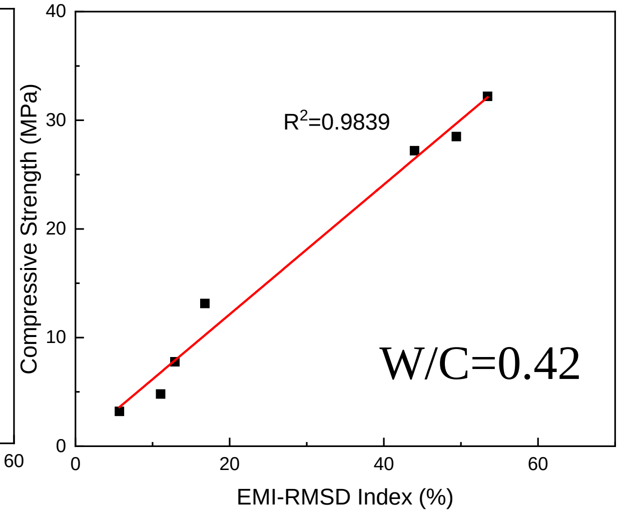


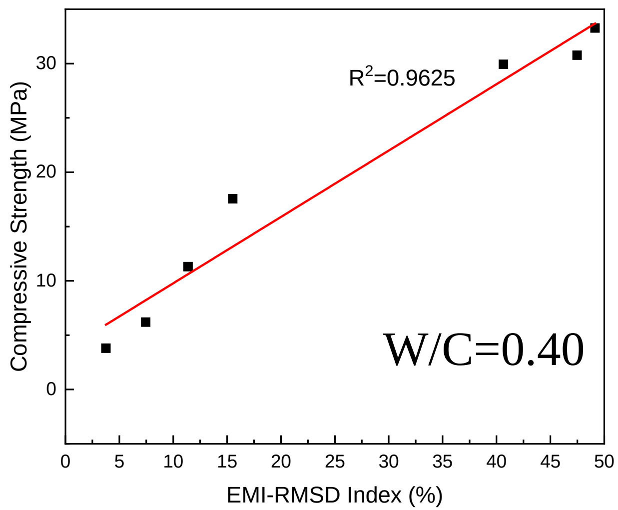
R^2 values are above 0.95, indicating good linear correlation

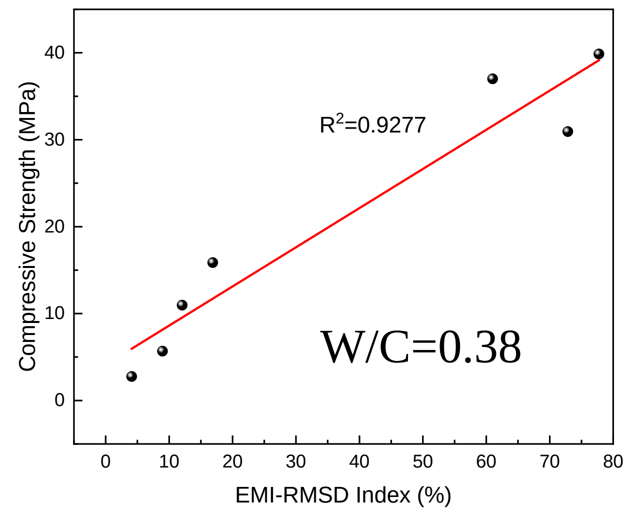
Type III cement -frequency range:100-400 kHz









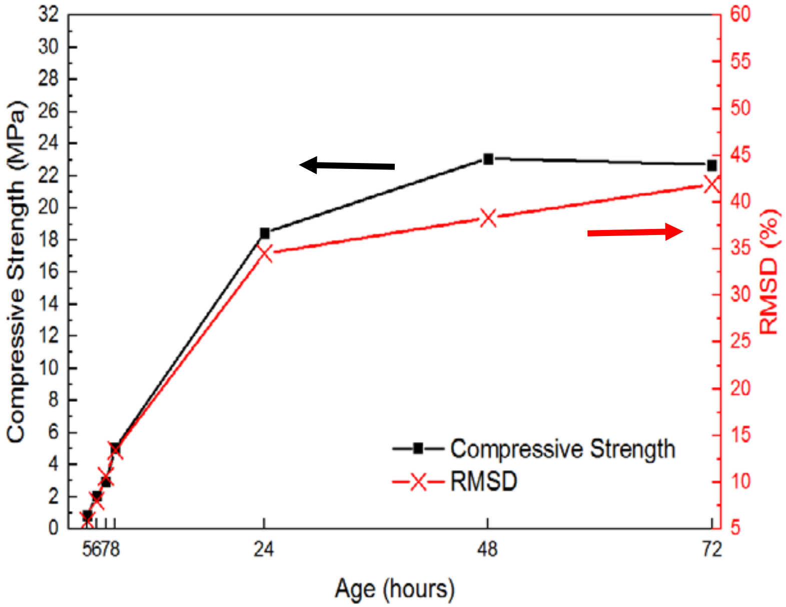


R^2 values are above 0.93 , indicating good linear correlation

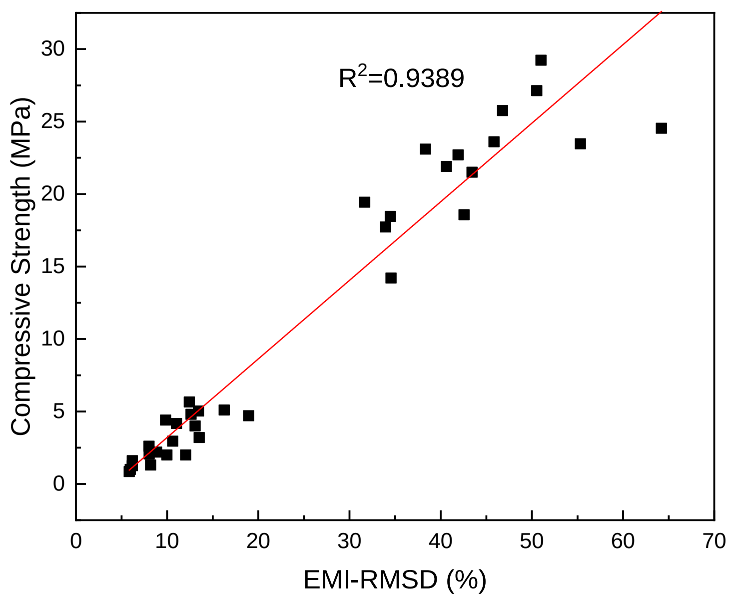
Early-age Property of Mortar

- For the frequency range **100-400 kHz, R^2 value are above 0.94**, showing the range as a favorable interval for the EMI method in early age strength monitoring.

- The **mix design and various water-to-cement ratios does not affect** the results of EMI-RMSD index.



RMSD index verse compressive strength of W/C=0.44 (100-400 kHz) at all ages.

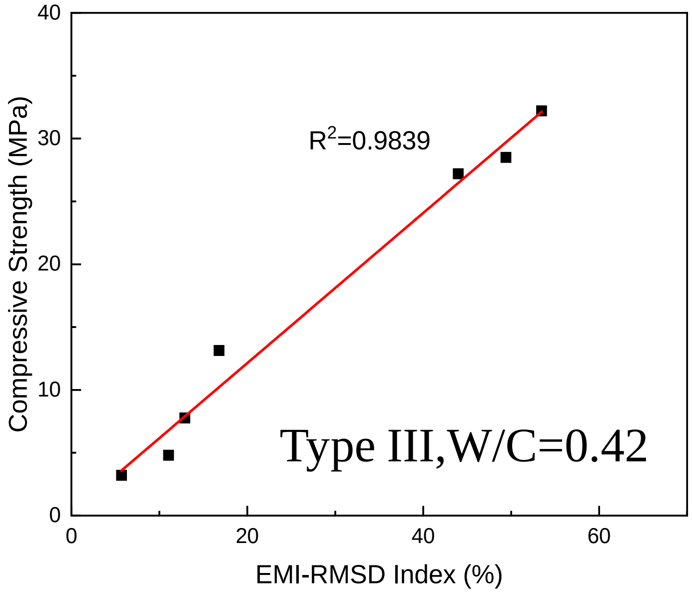


The correlation between compressive strength with all type I w/ different W/C ratio under frequency range 100-400 kHz

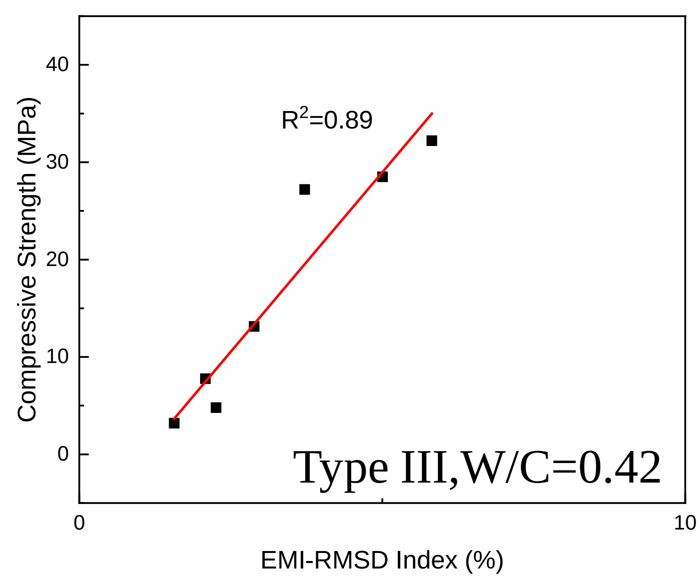
Surface Bonded vs Embedded Sensor

- EMI-RMSD result for <u>surface bonded</u> sensor has higher correlation with the compressive strength
- Surface bonded sensor has higher sensitivity to monitor the compressive strength than embedded sensor

Surface bonded sensor



Embedded sensor



Test Results on Mortar with Various SCM

Mortar with Various SCMs

- **Build the data base for various SCMs**
- EMI, Compressive test
- Very early age (4-8 hrs), early age (1,3,7days)

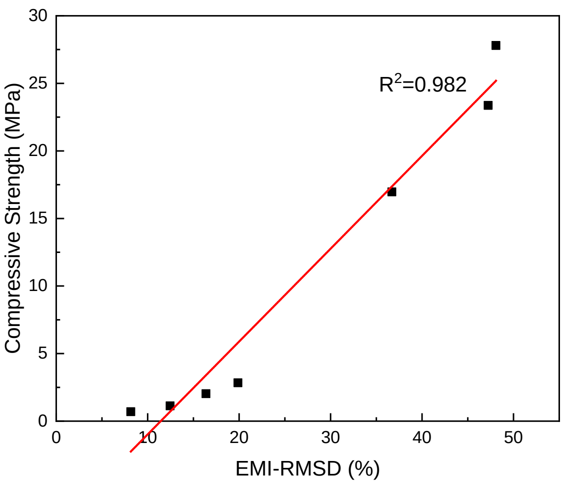
Cement Type	SCMs	Testing Age
Type I, W/C=0.42	Slag 15%	Very early age (4 – 8 hrs)
	Fly ash 15%	Early age (1,3,7 days)
	Silica Fume 15%	

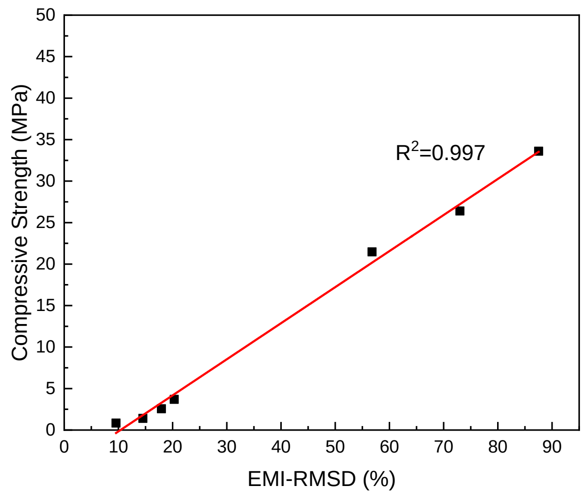
Type I cement with SCMs frequency range:100-400 kHz

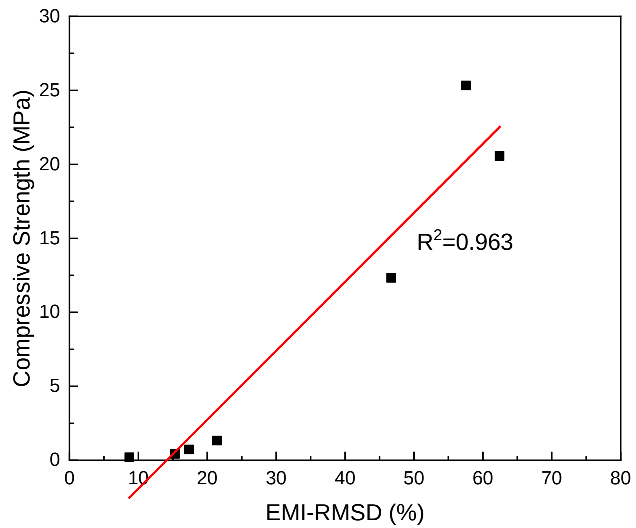
Slag 15%

Silica Fume 15%

Fly Ash 15%







R^2 value are above 0.96 , showing good linear correlation

Test Results on PCC using INDOT Typical Mix Design

EMI testing on PCC

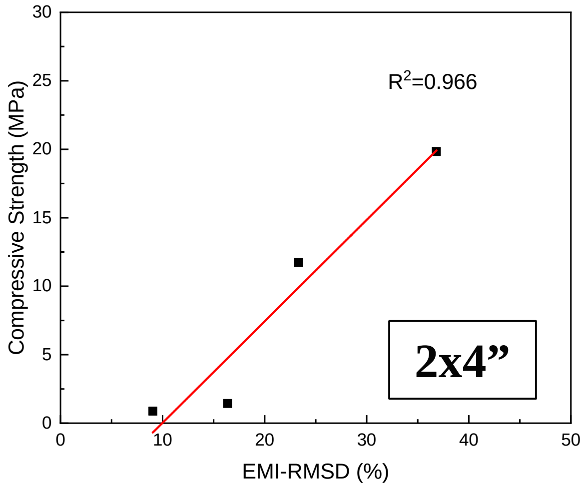
- INDOT PCC W/C=0.42 experiments
- 4-8th hour, 1,3 days

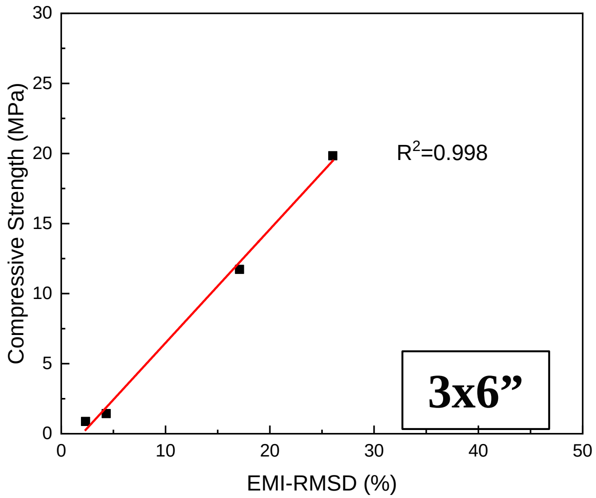
Cylinder Size
2x4”
3x6”
4x8”

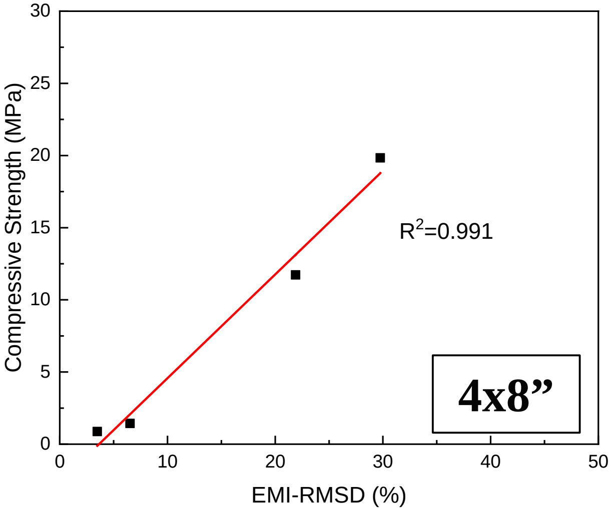
INDOT PCC Mix per cyd (w/c=0.42)

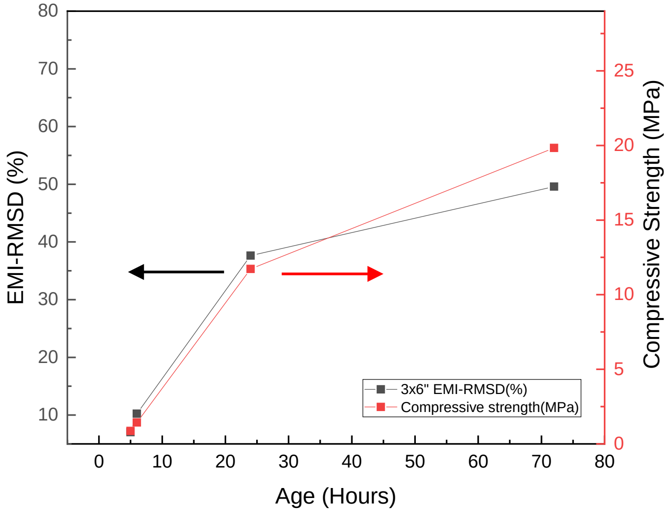
Cement (lb)	Fine Aggregate (lb)	Coarse Aggregate (lb)	Water (lb)	Air Entrainment (oz)	Water Reduce Agent (oz)
564	1430.3	1966.6	186	13.7	41.2

Result- Concrete w/ frequency of 100-1000kHz









EMI results are identical to Compressive Strength results, particularly at the early age

Conclusion

- EMI is a reliable NDT method for in-situ monitoring of the compressive strength gain of mortar, mortar with various SCM additives, and PCC.
- EMI results are independent from the mix design parameters (w/c ratio, SCM additives, etc).
- Surface bonded sensors have very high reliability ($R^2 > 0.98$) and embedded sensors have good reliability ($R^2 > 0.90$).
- Resonate frequency of piezoelectric sensors for very early-age property should be 100-400kHz.

Future Plan

- Build a large big data base to ensure/verify the reliability and validity of EMI results
- Compare EMI methods results with flexural testing and maturity testing
- Field implementation on I-65 concrete patch job
- Publications:

E. Ghafari, *et. al*. Construction and Building Materials, 17(2018) 504-510.
Y. Su, *et. al.* Composites B, 153 (2018) 124-129.
E. Ghafari, *et. al.* SPIE Proceeding, 10599 (2018) 09-10.
Y. Su. *et. al*. Transportation Research Board, 2019, Under Review

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