Determining In-place Strength of Concrete Using Piezoelectric Sensor

- Pooled fund study 1499

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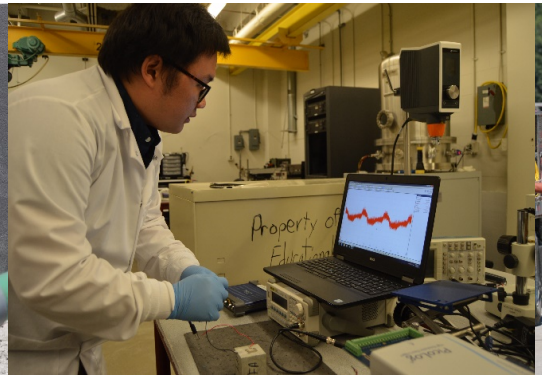


Inside Science by American Institute of Physics

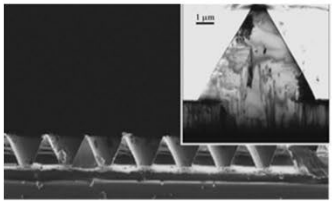
PURDUE UNIVERSITY

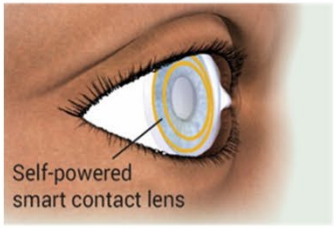
Sustainable Materials And Renewable Technology Lab

Prof. Na (Luna) Lu
Email: Luna@purdue.edu
https://engineering.purdue.edu/SMARTLab

SMART

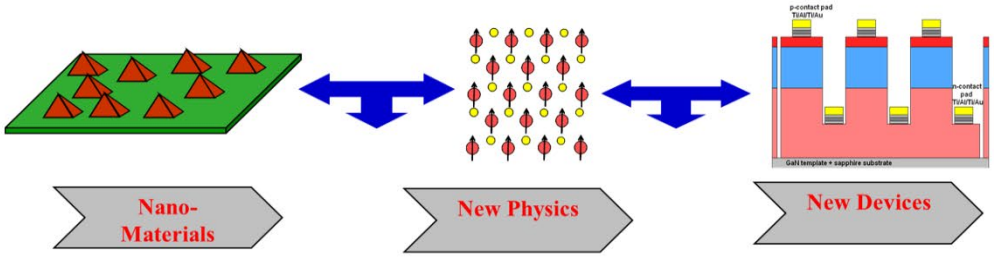
Thermoelectric Energy Harvesting





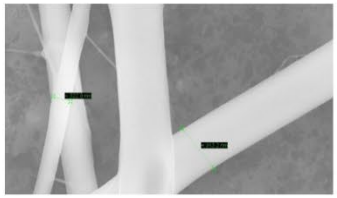
TE devices can directly converts heat into electricity which can be used for IoT technologies, self-powered sensors for district energy plants and oil & gas industries.

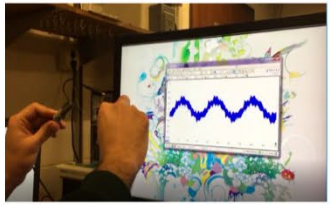
Nanotechnology in Civil Engineering



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.

Piezoelectric Sensing & NDT

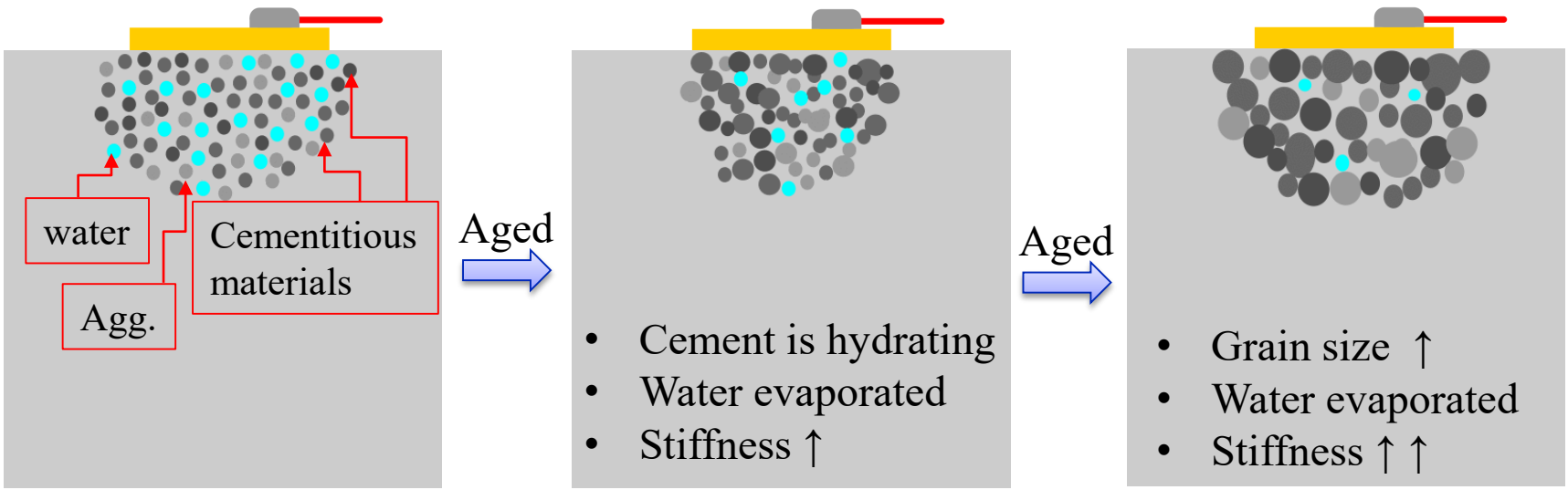




Piezoelectric devices can convert mechanical or vibrational forces into electricity which can be used for energy harvesting, NDT, and structural health monitoring(SHM) .

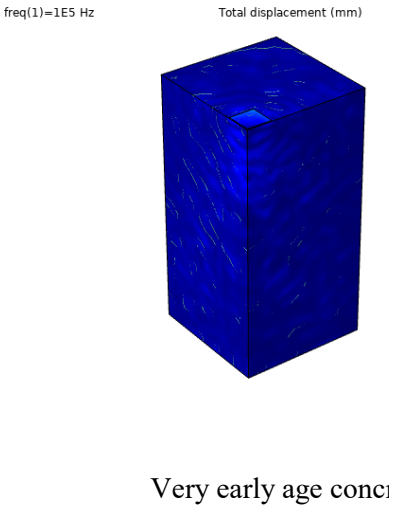
Mechanism of Piezoelectric Sensing Methods

- Thin PZT patch: 10mm x 10 mm x 0.2mm

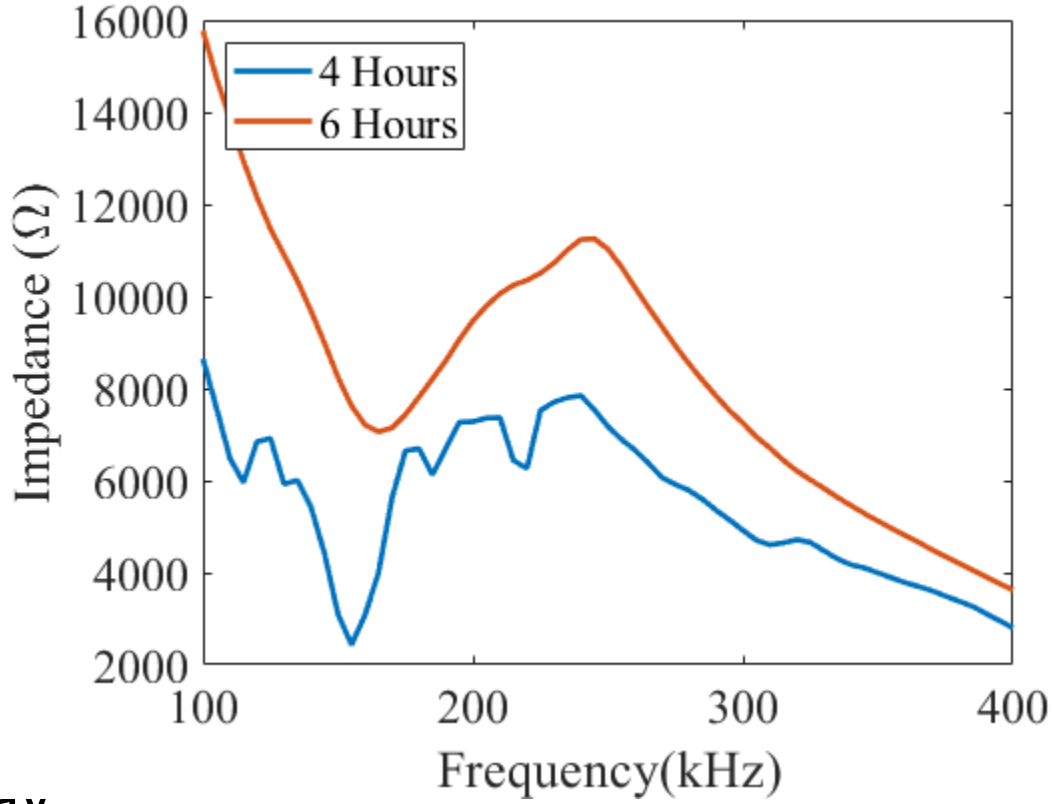


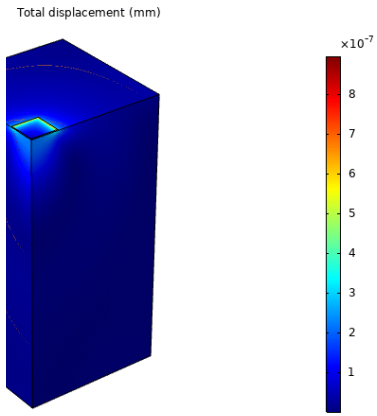
Principle of Sensing Methods

low $\text{Mechanical impedance} = \frac{\text{Force}}{\text{velocity}}$ High



Very early age conc

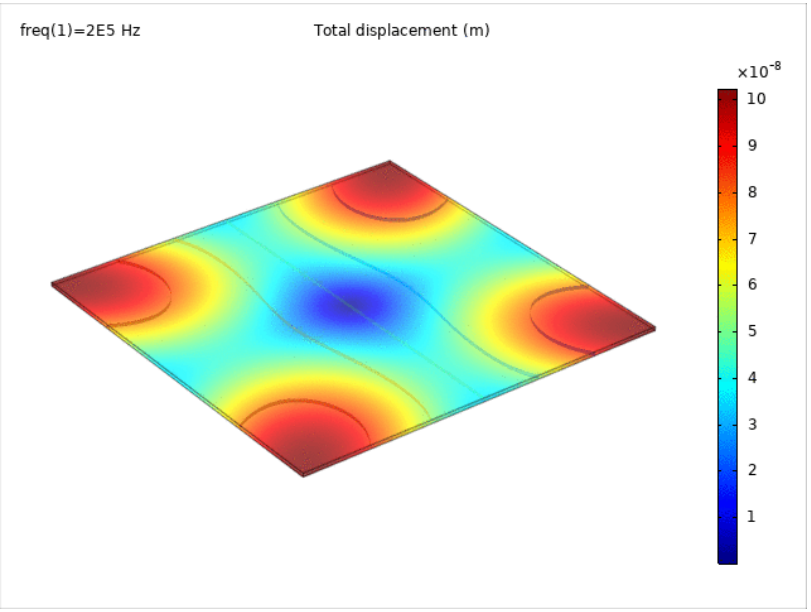




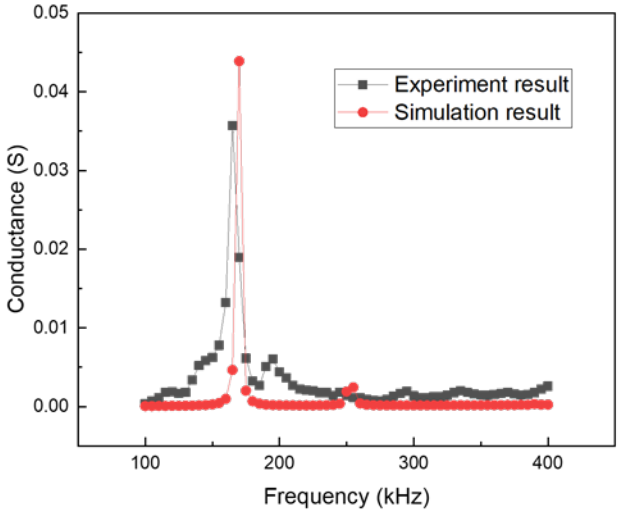
ırdened concrete

- When sens or will vibrate together wi
- Host struct e vibrating in different way.

Simulation & Experimental Results



Free PZT vibrating

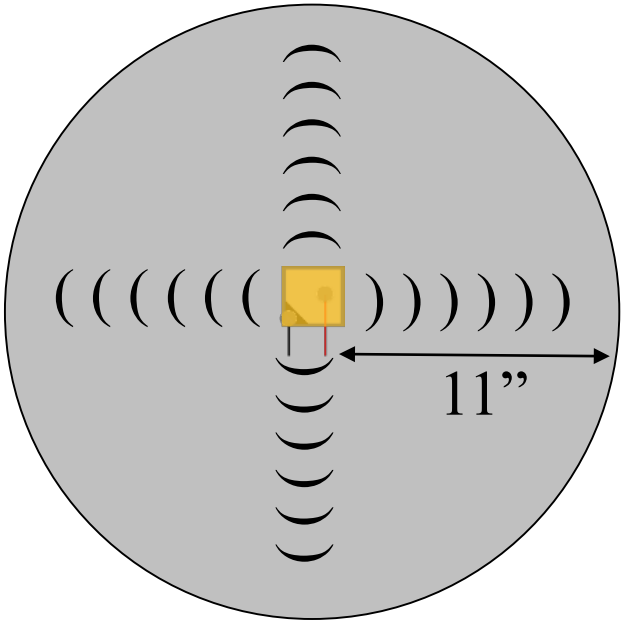


Conductance vs. frequency for free PZT sensor

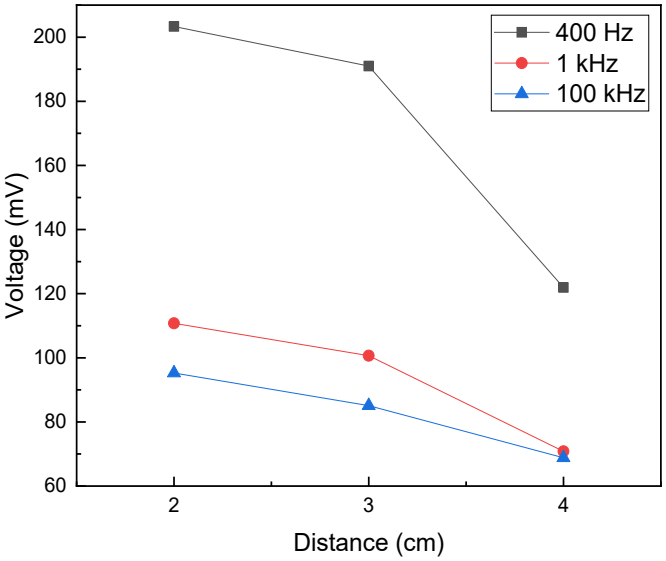
- Piezoelectric sensor start vibrating when excited by AC voltage
- Simulation results match perfectly with experimental ones

Sensing Range

Sensing range schematic



Sensing range at different frequency

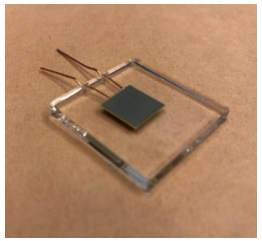


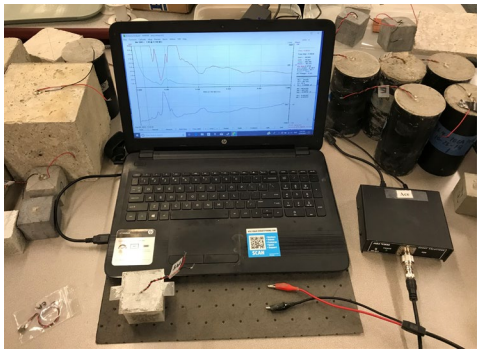
- Voltage is directly proportional to distance at a constant frequency.
- Low frequency has higher wave propagation distance.
- The current estimate of the sensing range in the horizontal direction is approximately 11 inches.

Lab Experiment Results

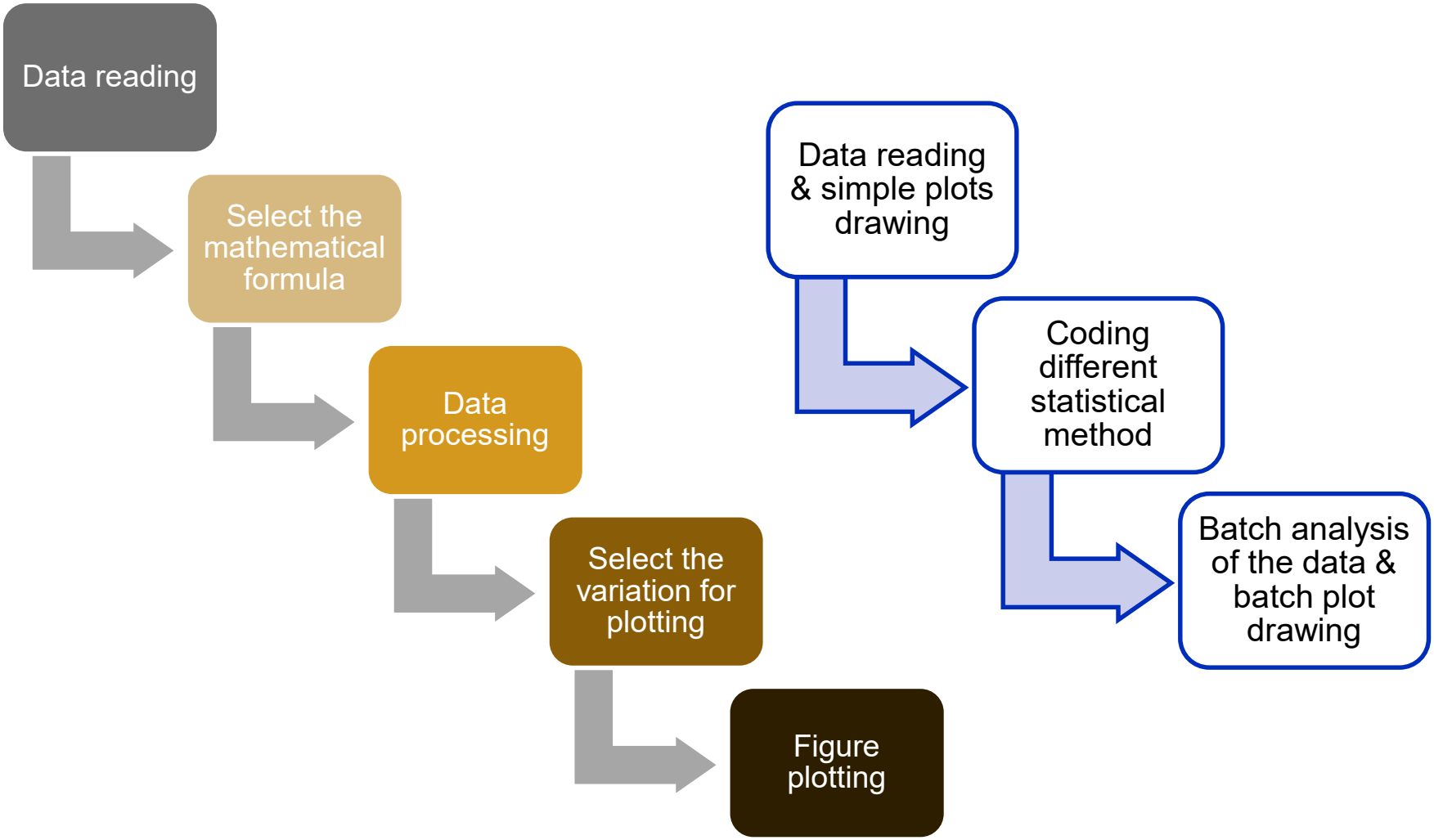
Sensing vs Mechanical Testing

- Comparison between sensing vs mechanical tests





Data Processing – MATLAB code



Mortar with Different W/C

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

Cement Type

Type I

Type III

W/C ratio

0.38

0.40

0.42

0.44

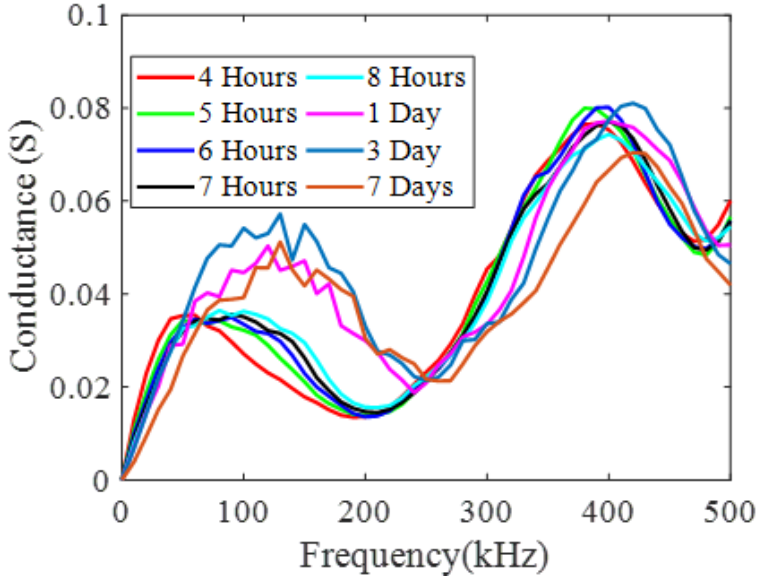
0.46

Testing Age

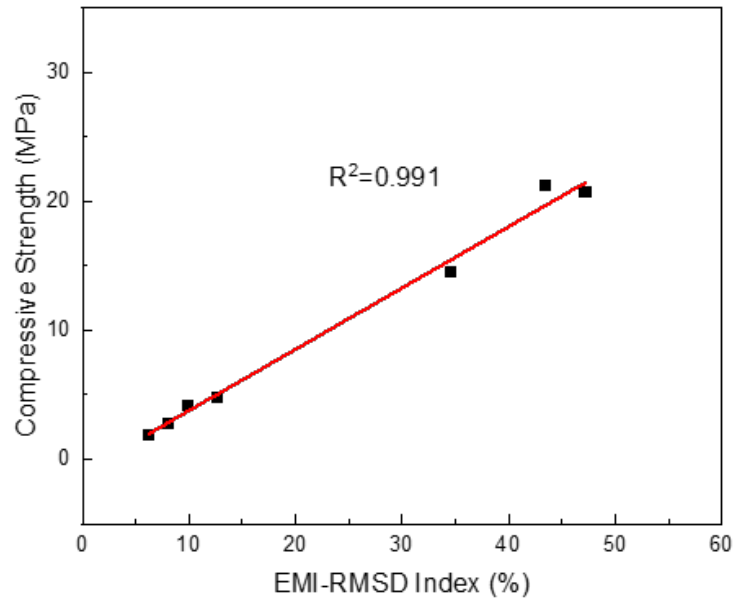
Very early age (4 – 8 hrs)

Early age (1–3 days)

Sensor Performance



Conductance signature of representative sample at different age



The linear correlation fitting between compressive strength with EMI-RMSD index

- The EMI signals changed as cement mortar aged;
- Using linear least square regression analysis to evaluate the EMI index's performance.

Sensor Performance 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

Type I, W/C=0.42

SCMs

Slag 15%

Fly ash 15%

Silica Fume 15%

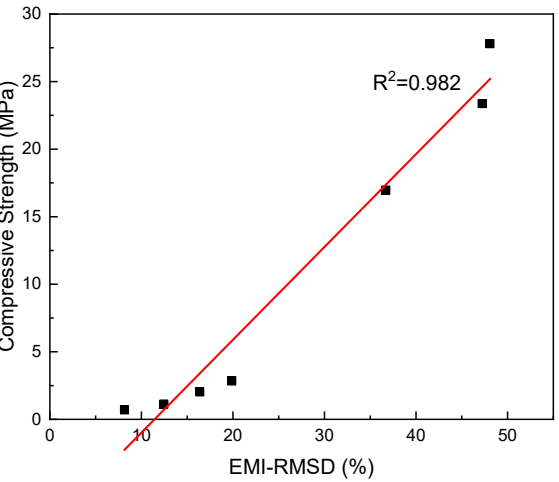
Testing Age

Very early age (4 – 8 hrs)

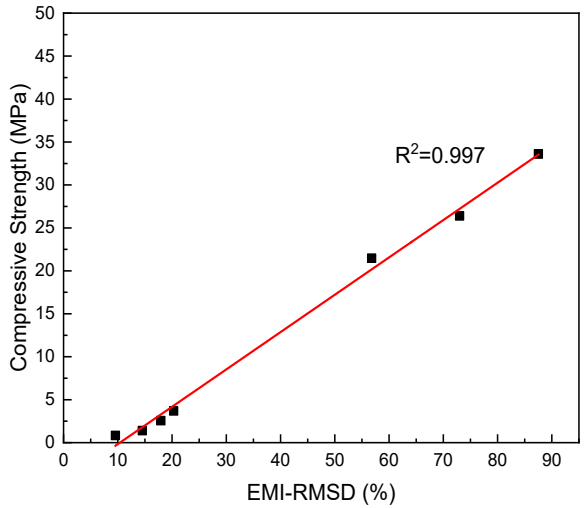
Early age (1,3,7 days)

Type I Cement with SCMs

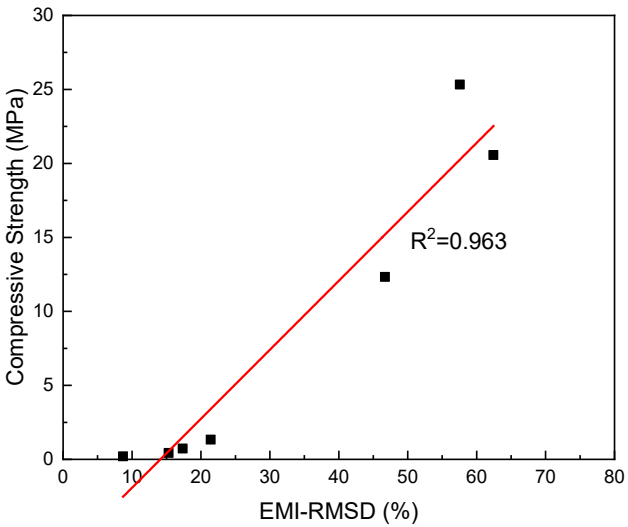
Slag 15%



Silica Fume 15%



Fly Ash 15%



R^2 value are above 0.96 , high accuracy

INDOT PCCP Mixtures

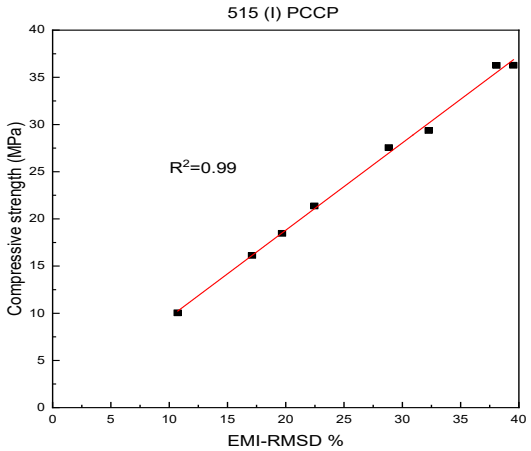
- EMI, Maturity test, Compressive test
- 4,6,8,10,12 hrs, 1,3,7,28 days
- Flexural test: 1,3,7,28 days

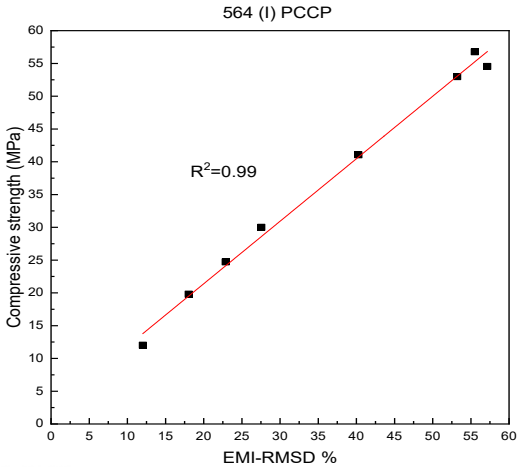
Mixes Design (lbs/cyds)

Cementitious				Aggregates			
Cement (Type) - SCMs	Fly Ash	Slag	W/C ratio	FA	CA	CA/FA ratio	SCMs Replaced %
515 (I)			0.42	1459	1773	1.22	0.0%
515 (III)			0.42	1459	1773	1.22	0.0%
564 (I)			0.42	1344	1800	1.34	0.0%
564 (III)			0.42	1344	1800	1.34	0.0%
564 (I)+10%CA			0.42	1344	1980	1.47	0.0%
564 (I)-10%CA			0.42	1344	1620	1.21	0.0%
440 (I) – FA	70		0.42	1455	1769	1.22	14%
350 (I) – SLAG		200	0.42	1310	1840	1.40	36%
480 (I) – FA	120		0.42	1277	1687	1.32	20%
480 (I) - SLAG		120	0.42	1277	1687	1.32	20%

Experimental Result

- Regression analysis: Compressive strength vs. EMI-RMSD
- The regression results exhibit satisfied high correlation between EMI-RMSD index and compressive strength of concrete.

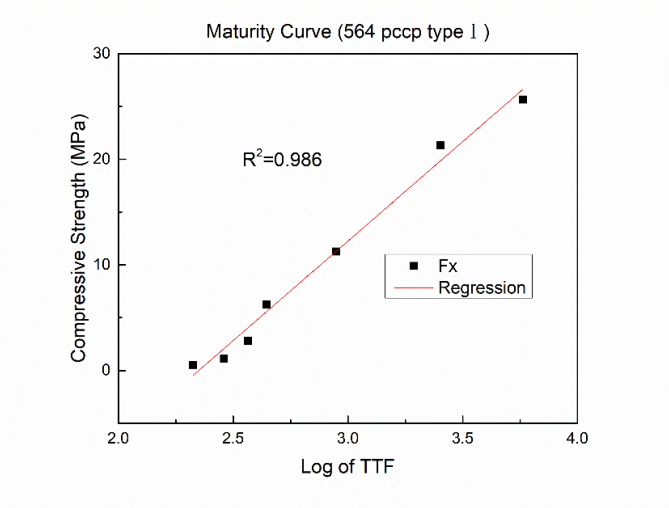


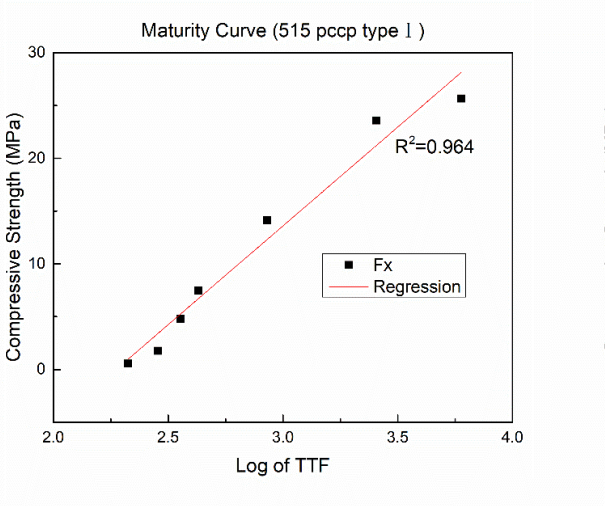


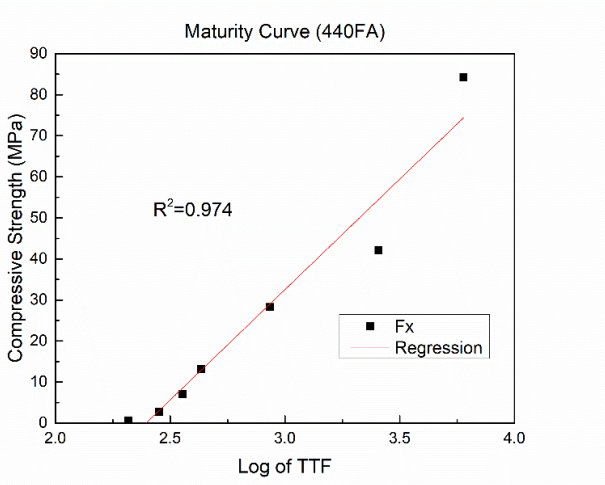
Mixes	EMI- R^2
515 (I)	0.99
515 (III)	0.98
564 (I)	0.99
564 (III)	0.92
564 (I)+10%CA	0.97
564 (I)-10%CA	0.93
440 (I) – FA	0.96
350 (I) – SLAG	0.87
480 (I) – FA	0.94
480 (I) - SLAG	0.93

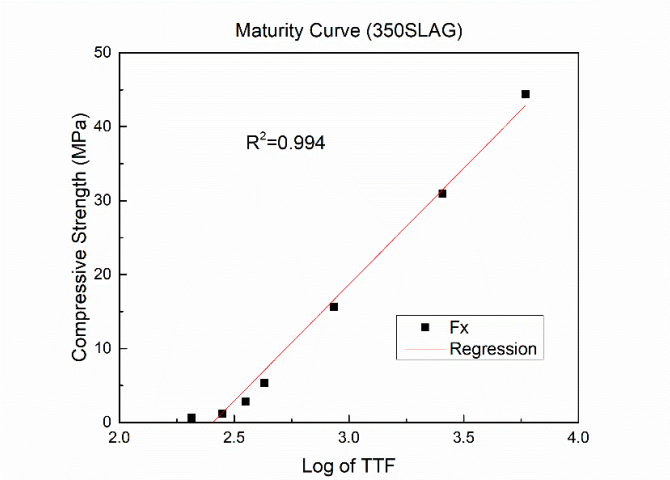
Experimental Results- Sensing vs Maturity Curve

- Experimental results of maturity test







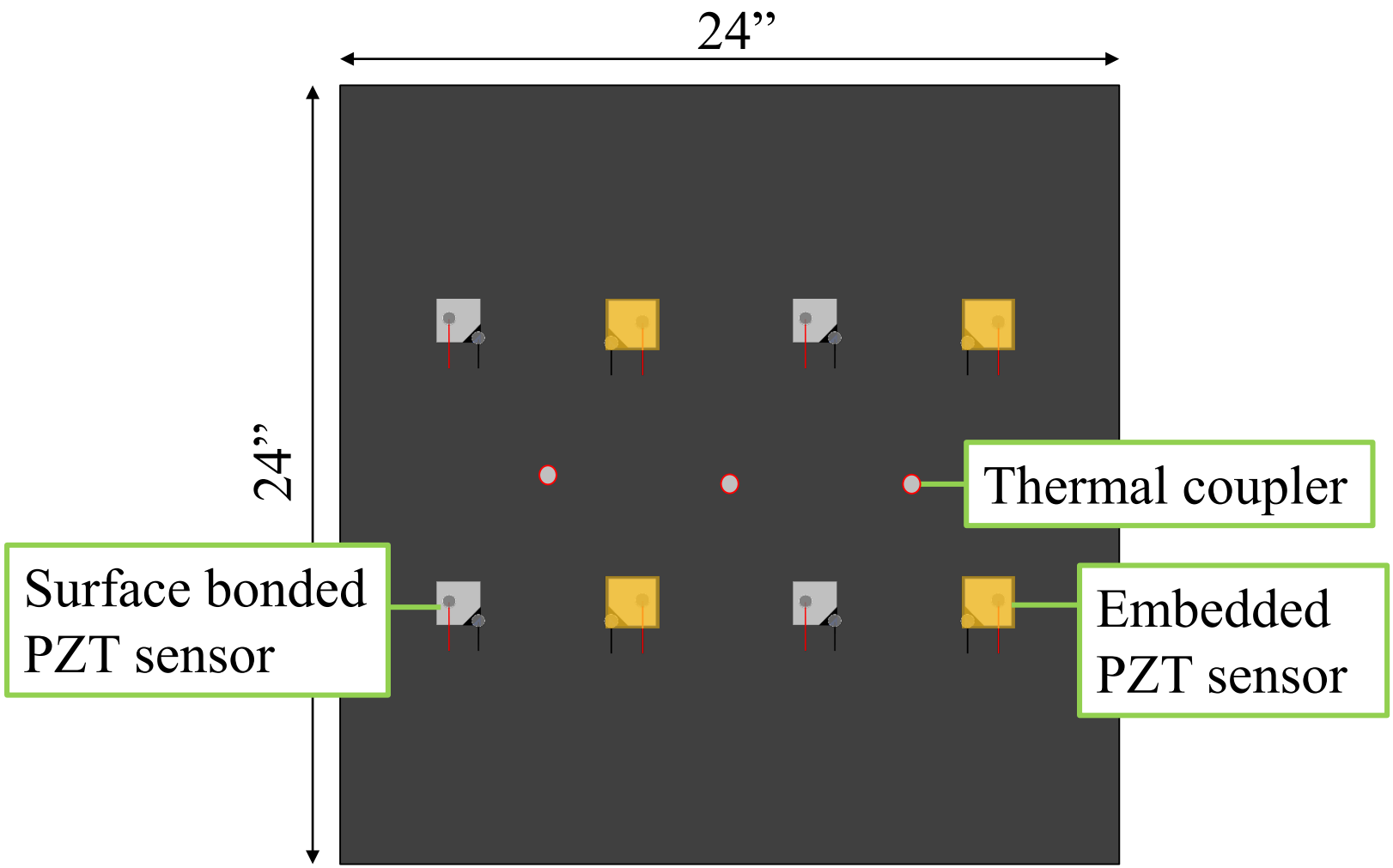


- **EMI method can reach the same accuracy with maturity test**

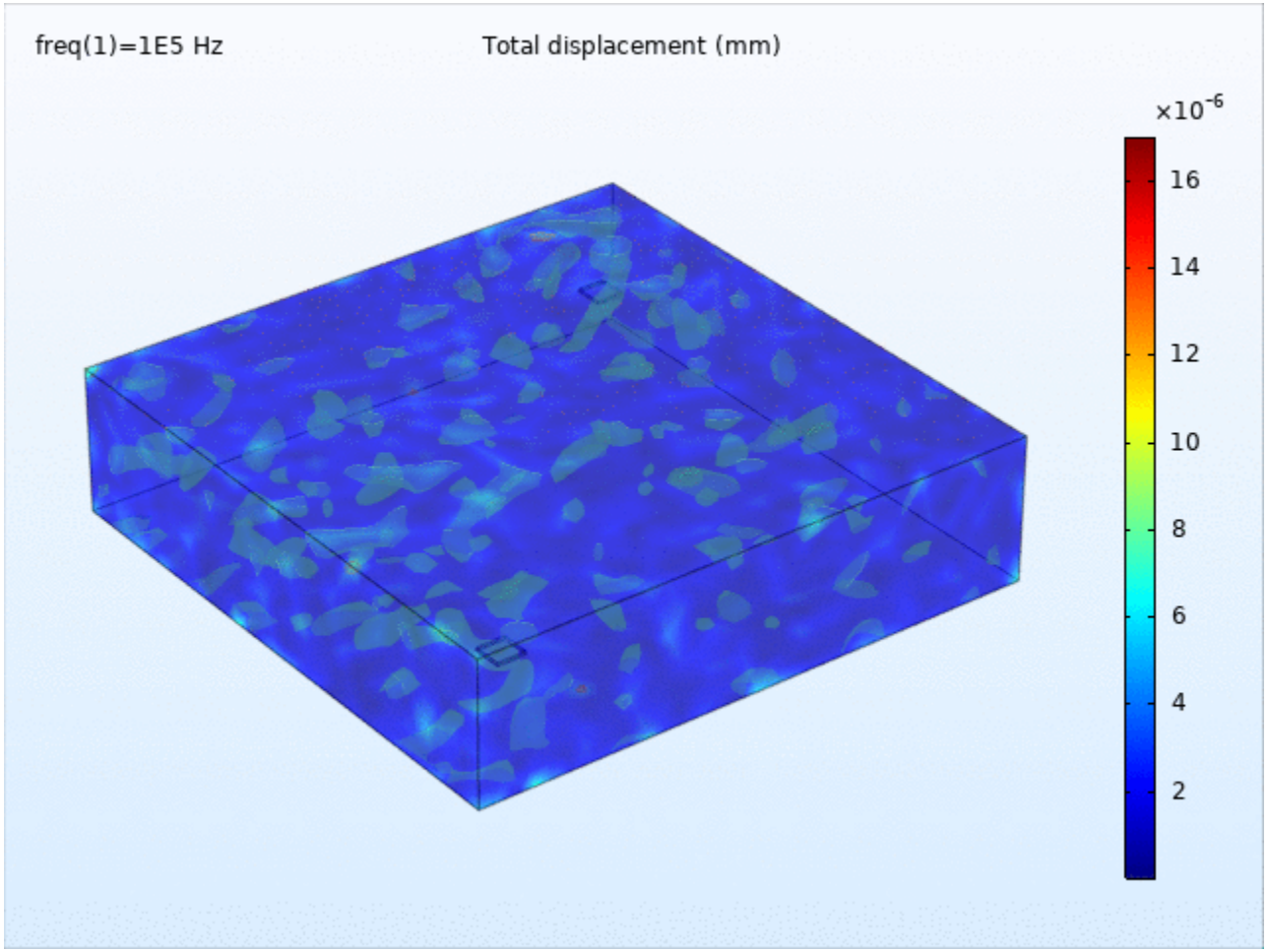
In-place Sensing for Large Concrete Slab

Plan view of concrete slab experiment

- 2’ x 2’ x 1’ (L x W x t) slab sample

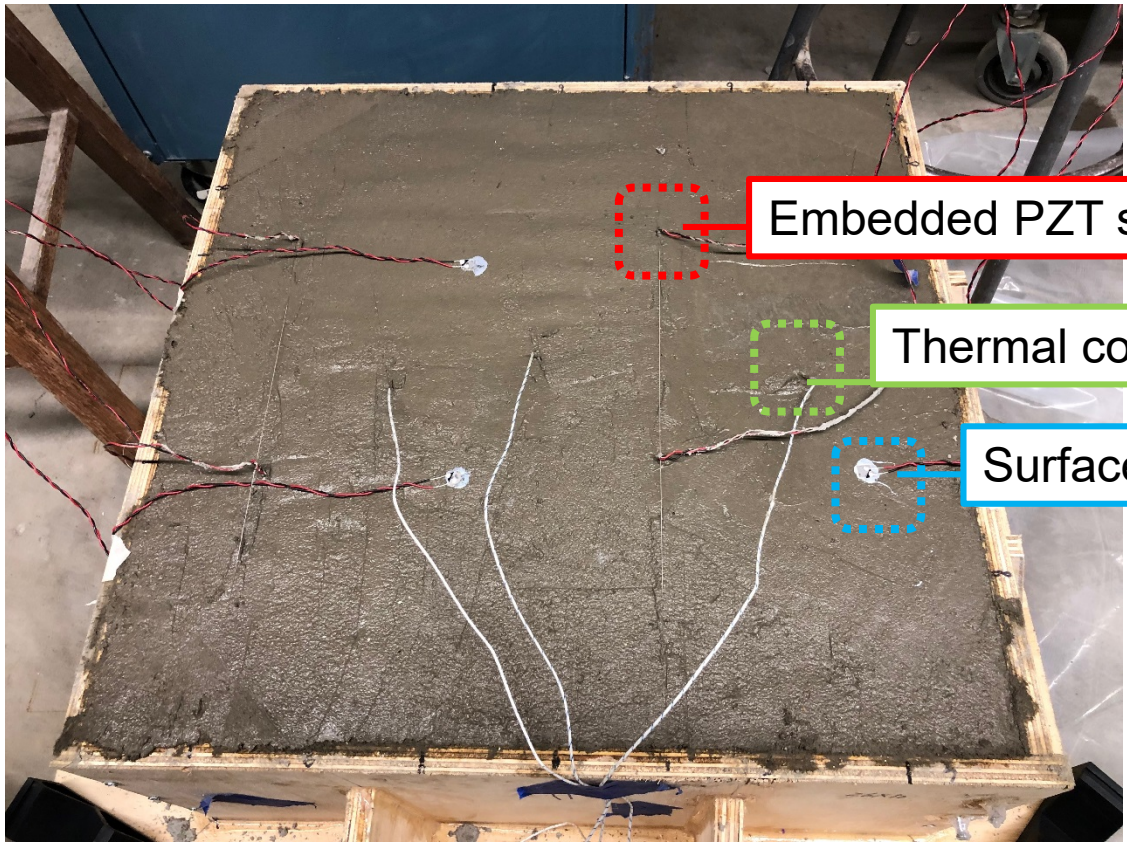


3-D Demonstration for Sensor in Slab

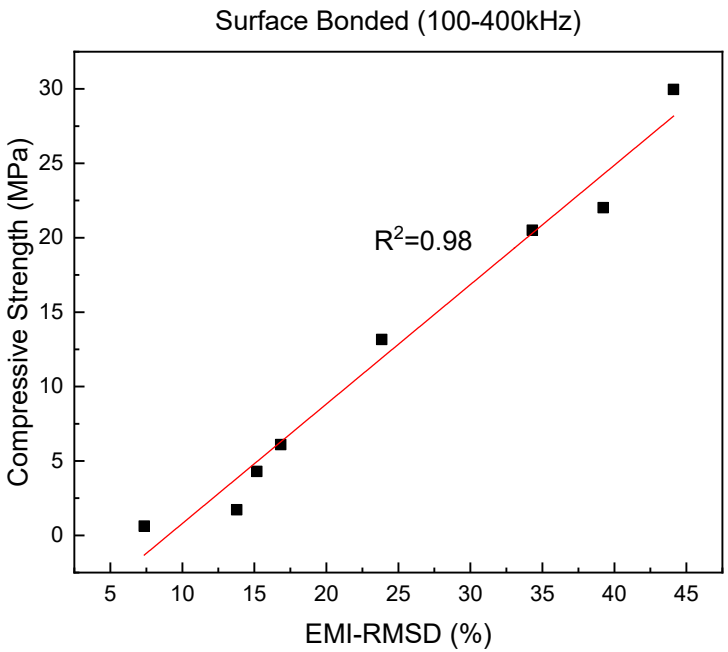


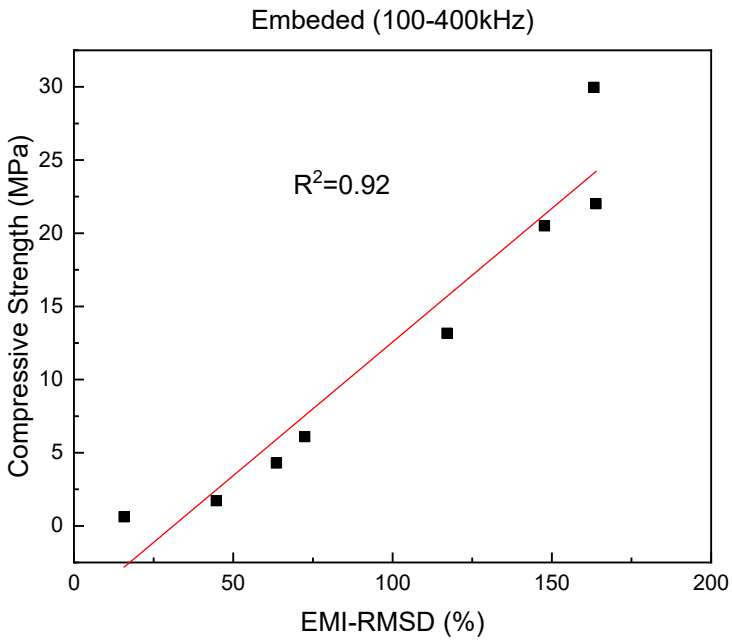
Sensor Deployment

- Four embedded sensors, four surface bonded sensors, three thermal couples



Regression Result

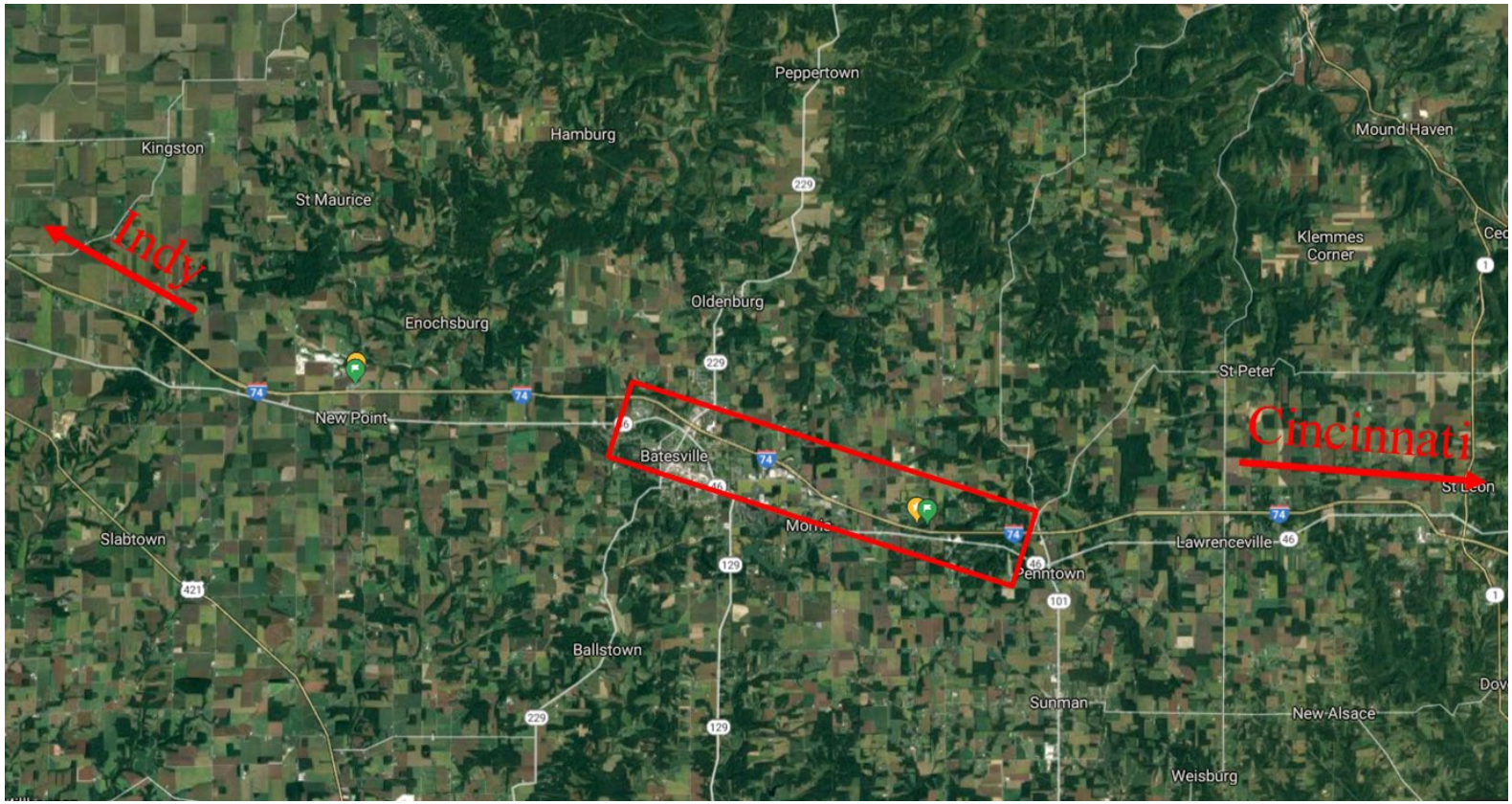




- Both two method can get a high correlation coefficient.

Implementation in Full Depth Paving

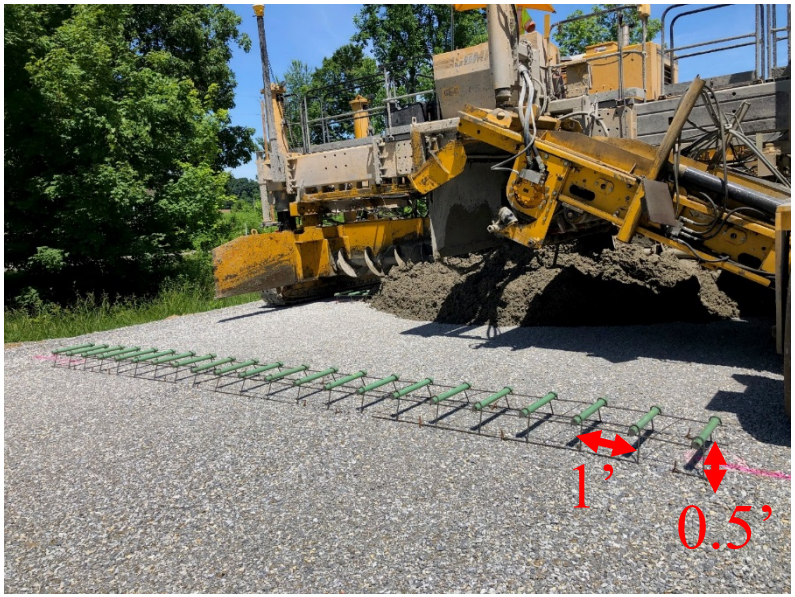
Job Site on Interstate 74



- I-74 (Batesville)
- Visited job site twice, 19 sensors was placed;

Full Depth Paving

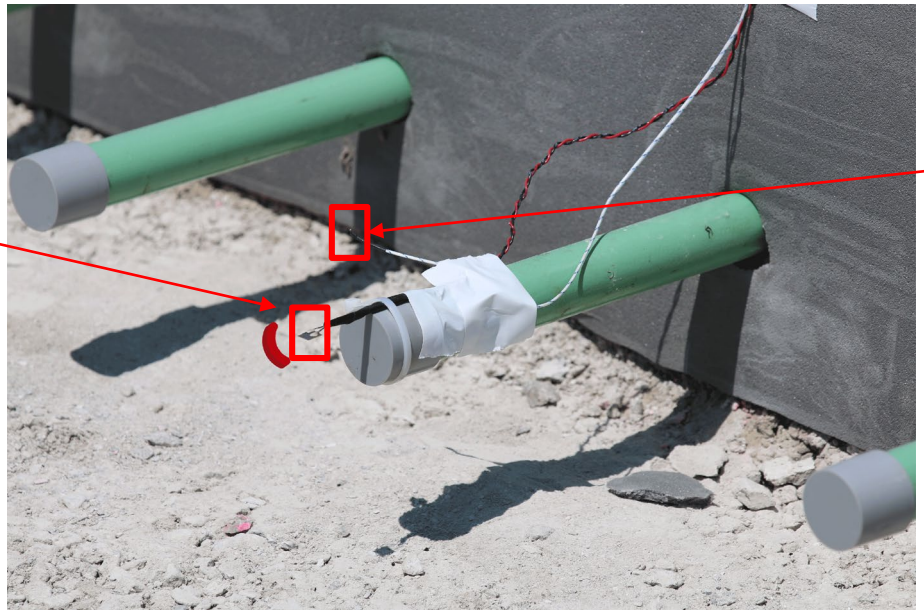
- The full depth paving 23” Width x 1’Depth x 15’ Length
- Curing for three days
- Dowel basket at every 15’



Sensor Deployment

Bond the sensor before casting → Concrete pouring and casting → Prepare cylinder samples → Sensing at 1st to 8th hour → Sensing & cylinder test at 1st day

PZT sensor



Thermocouple

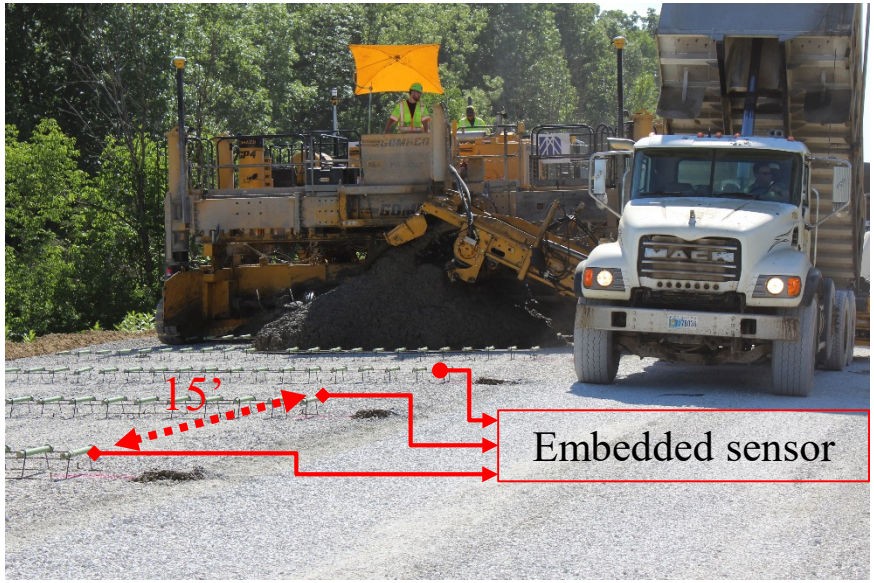
Embedded Sensor

Locate the sensor

Embedded the wire protection tube

Paving

- Three embedded sensor are tie on the dowel bar
- The span of each sensor is 15’



Locate the sensor

Concrete paving

Bonding Sensor

- Install the thermal couple right after paving
- Surface bond the sensor at 4th hour after casting

Install thermal couple

Bonding sensor

Surface bonded sensor

Experimental Photo

Testing Results

Age	Sensing	Cylinder Testing
1 Day	18 MPa (2610 psi)	15 MPa (2175 psi)

- Sensing results of first day sample are higher than the cylinder testing result.
- The exothermic hydration reactions of mass concrete is higher than the cylinder sample

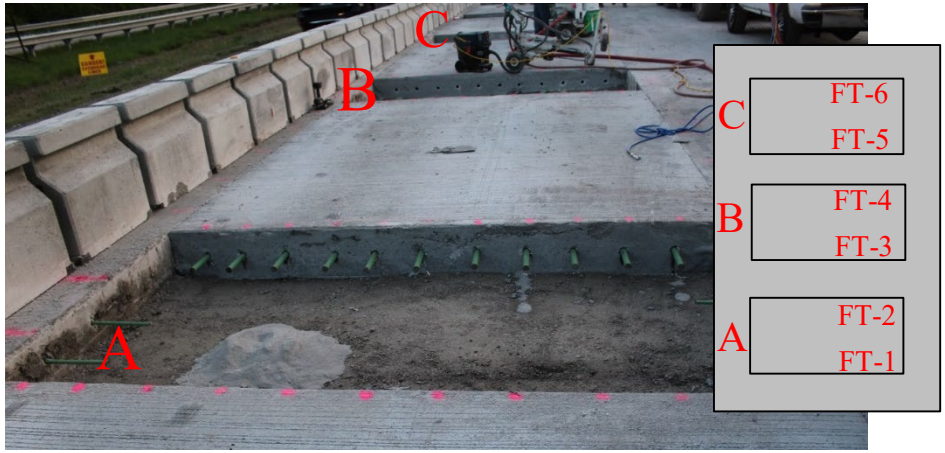
Field Implementations (Patching job)

Job Site

- I-70 West (Plainfield)

Field Test

- Date: 05/15/2019
- Casting at 05/15/2019 9:30pm
- EMI measuring start from 05/15/2019 10:30 pm to 05/16/2019 6:30am
- Measurement interval: 1 hours



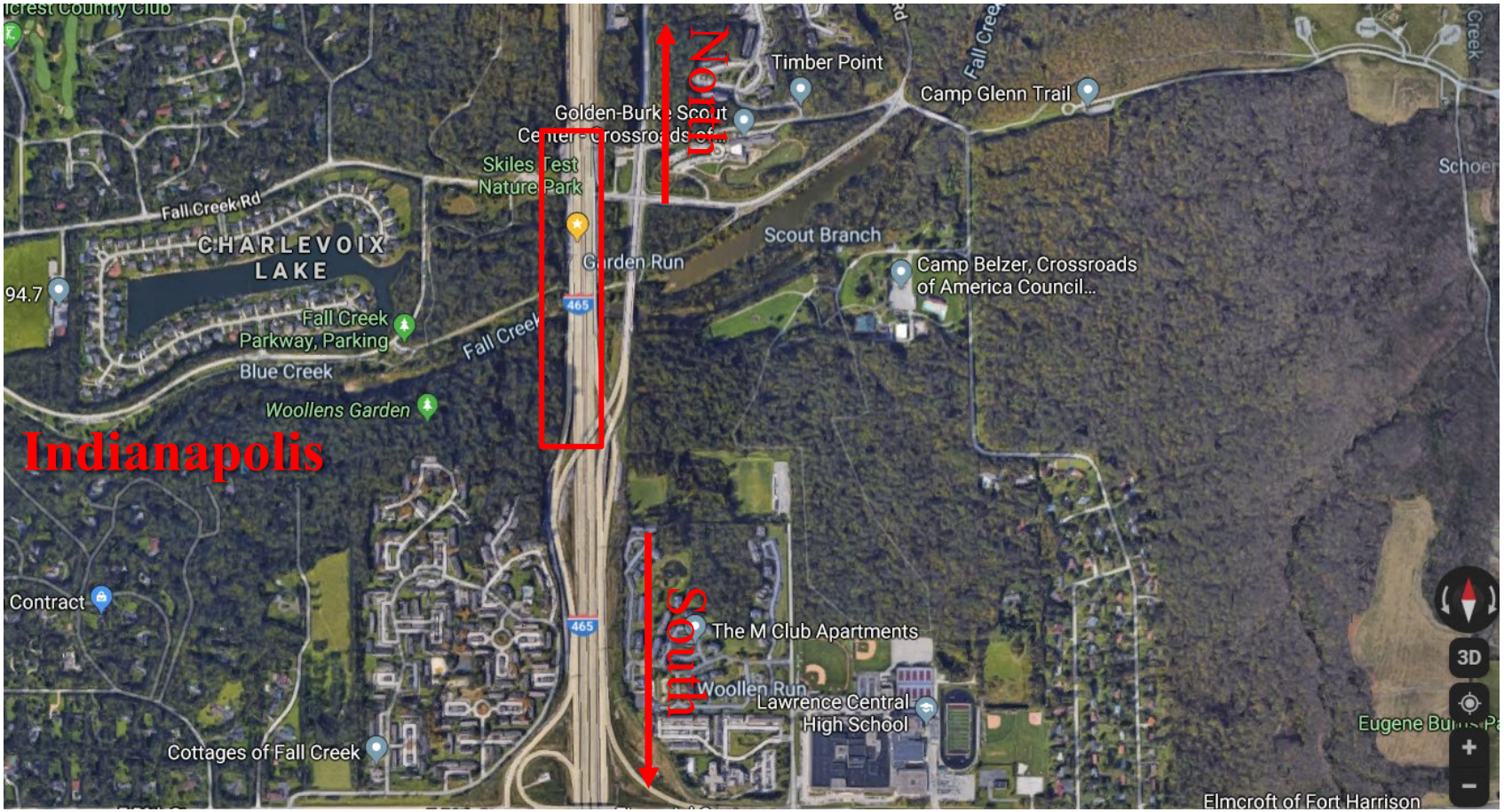
Hole (6’ x 12’) preparation

Tie the sensor on the second dowel

Patching Job

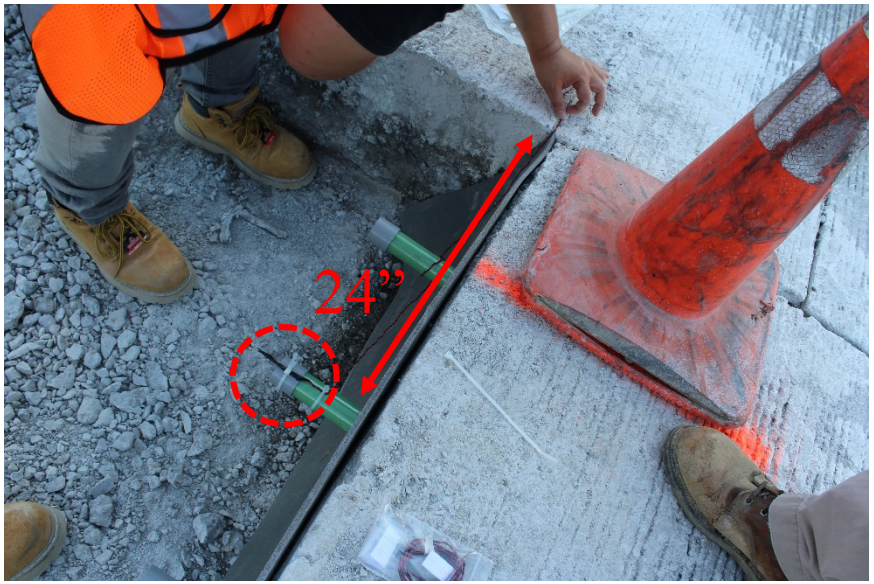
I-465 Job Site

- I-465 (Indy, 38.55MM-41MM)



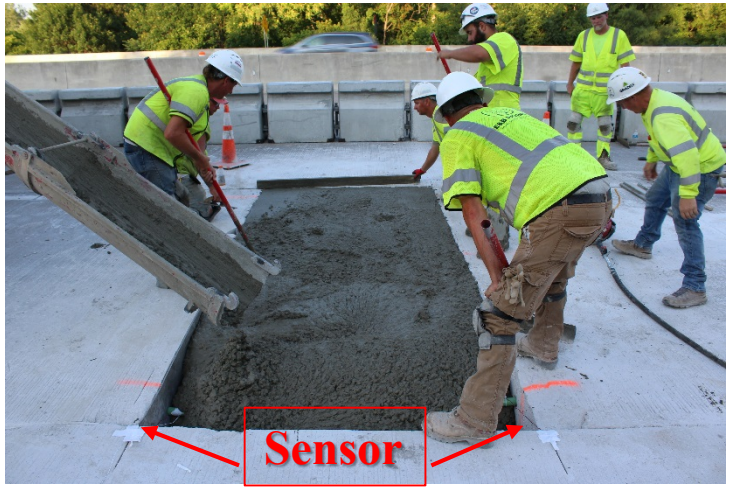
Field Test – Sensor Deployment

The sensor is 2” from the dowel bar



Tie the sensor on the 2nd dowel bar

Field Test – Concrete Patching



Concrete casting

Spray curing compound

Perform EMI measurement

Testing Results

- Reference Compressive strength of 1 day sample

Hole 1	Hole 2	Hole 3	Sensing Data	Cylinder Testing
18.5 MPa	16.7 MPa	18.0 MPa	17.8 MPa (2581psi)	11.4 MPa (1653psi)

- Due to the high internal temperature of mass concrete, the strength using sensing method are higher than the one from cylinder test

Media Report

August 29, 2019

aci Concrete SmartBrief

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INDUSTRY NEWS

Purdue engineers collecting data on concrete maturity for INDOT

Engineers at Purdue University have designed sensors that are being used to monitor real-time concrete strength development through factors such as hydration, stiffness and compressive strength. The Indiana Department of Transportation plans to adopt the sensors on highways to keep contractors informed on concrete distress.

EurekAlert!/Purdue University (8/29)

#purdue #purdueengineering #concreterepair
Piezoelectric Sensor for Measuring Concrete Strength

https://www.youtube.com/watch?v=LS0zXtIa2PA

PurdueTODAY 150 YEARS OF GIANT LEAPS

August 29, 2019 Current web edition

IN THE SPOTLIGHT

EurekAlert! AAAS

HOME NEWS RELEASES MULTIMEDIA MEETINGS PORTALS ABOUT

NEWS RELEASE 29-AUG-2019

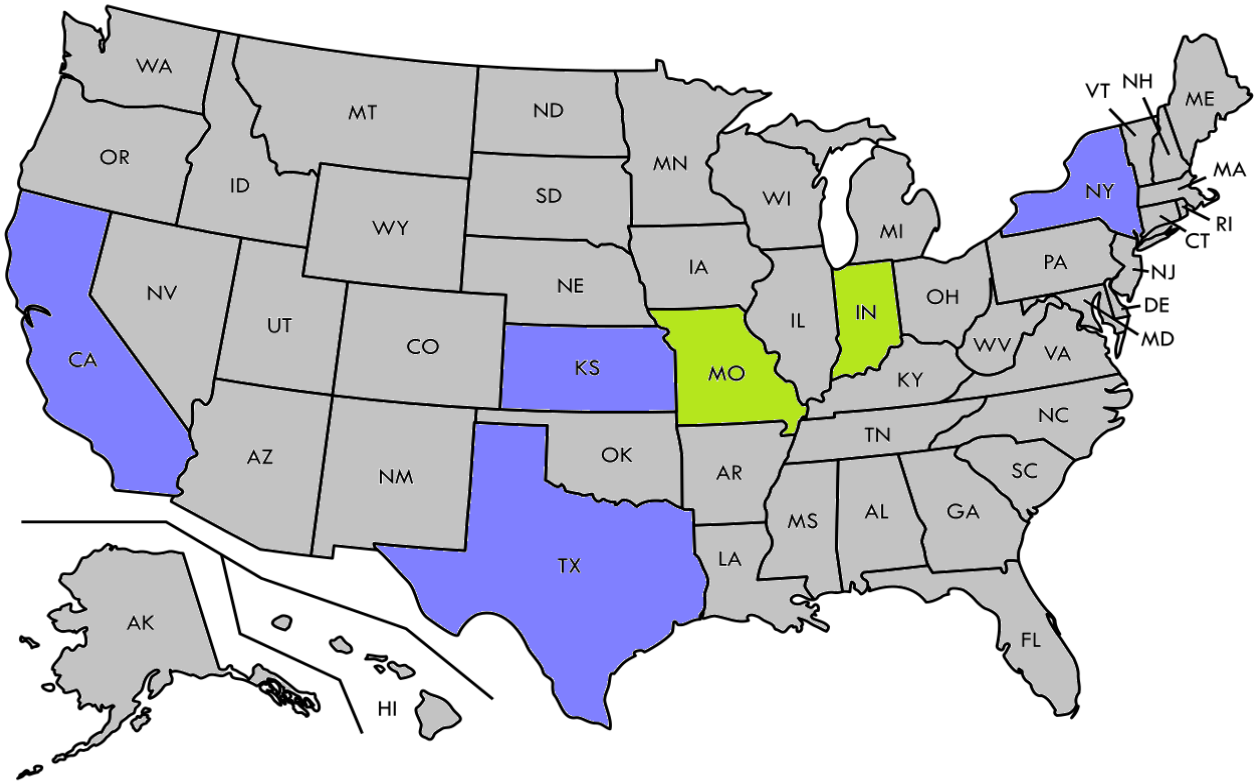
Science to reveal how long highway construction should actually take

PURDUE UNIVERSITY

SHARE PRINT E-MAIL

Pooled Fund Study – 1499

- Each measurement takes less than 5 minutes
- < $10 per sensor, commercially available
- No Calibration is needed
- High accuracy level (> 92% correlation)



Acknowledgements

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Project Advisors:

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Mix design

I-74 PCCP Mix (lbs/cyd)

Cement-I	Fly ash	Sand- INDOT #23	Stone- INDOT #8	QA 3 stone	Water	AEA (oz/Cyd)	WRDA 82 (oz/CWT)	W/C
350	150	1390	1270	514	210	6.5	4	0.42

I-465 PCCP Mix (lbs/cyd)

Cement-I	Sand- INDOT #23	Stone- INDOT #8	Water	AEA (oz/Cyd)	Recover (oz/ Cyd)	W/C
752	1115	1650	299.5	2.5	3	0.398

I-70 PCCP Water to cement ratio

W/C
0.415