REBEL Sensor

- Real-time concrete monitoring without maturity curve

Luna Lu
ACPA Professor, Lyles School of Civil Engineering
Director, Center for Intelligent Infrastructure
Purdue University

PURDUE UNIVERSITY | Lyles School of Civil Engineering
CENTER FOR INTELLIGENT INFRASTRUCTURES

The Challenge

- Open too early cause pre-mature failure and frequent patching
- Construction delay causing traffic jam

Requirement for Determining In-place Concrete Strength

https://lacrossetribune.com/news/local/traffic-jam/

CENTER FOR INTELLIGENT INFRASTRUCTURES

Conventional Testing

Current Methods

- Compression/ cylinder break
- Flexural/ beam break

Disadvantages

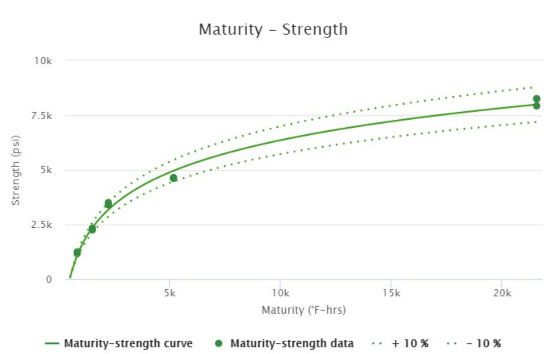
- Up to 50% error
- Typically have lower breaks
- Time consuming
- Requires skilled labor
- The actual in-place concrete is not being tested

CENTER FOR INTELLIGENT INFRASTRUCTURES

Maturity Method

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

Requires maturity curve, mix-dependent, 7-14 days, > $3000



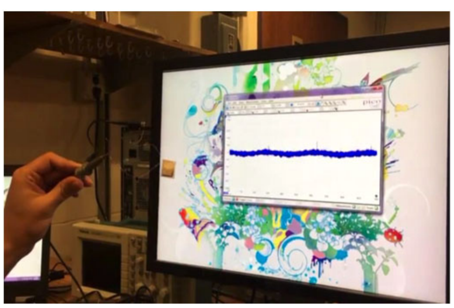
http://wikipave.org/index.php?title=Maturity_Testing

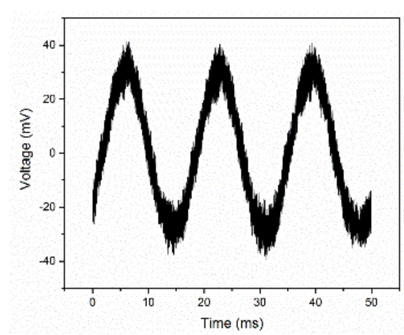
CENTER FOR INTELLIGENT INFRASTRUCTURES

Our Solution – Direct Mechanical Testing using piezoelectric sensor

CENTER FOR INTELLIGENT INFRASTRUCTURES

PVDF-GO Piezoelectric Nanogenerator





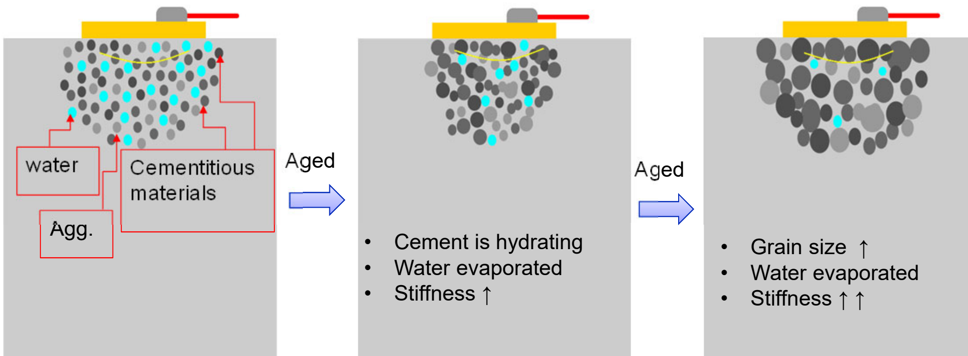
- Piezoelectric sensor – directly convert mechanical energy into electricity or vice versa.

E. Ghafari, N. Lu, et. al, Composites B: Engineering, 116, 40, 2017.
N. Lu , et. al, Advanced Composites & Hybrid Materials, 1:332-304, 2018
E. Ghafari, N. Lu, et. al, Composites B, 160, 1-9, 2019

How does this apply to Concrete sensing?

CENTER FOR INTELLIGENT INFRASTRUCTURES

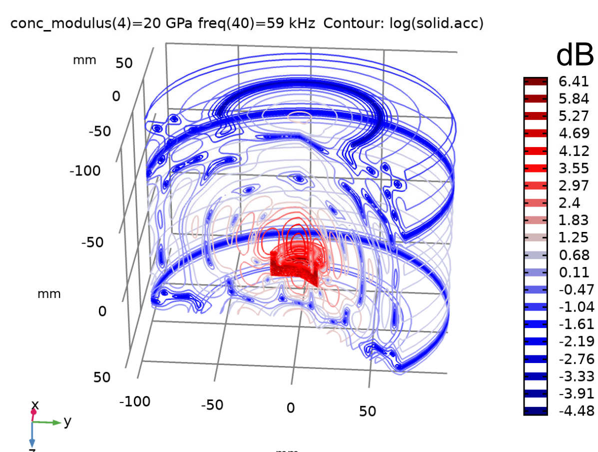
Piezo-sensor for Concrete Strength Monitoring



Using piezoelectric sensor to understand the concrete stiffness and strength through electromechanical coupling effect.

CENTER FOR INTELLIGENT INFRASTRUCTURES

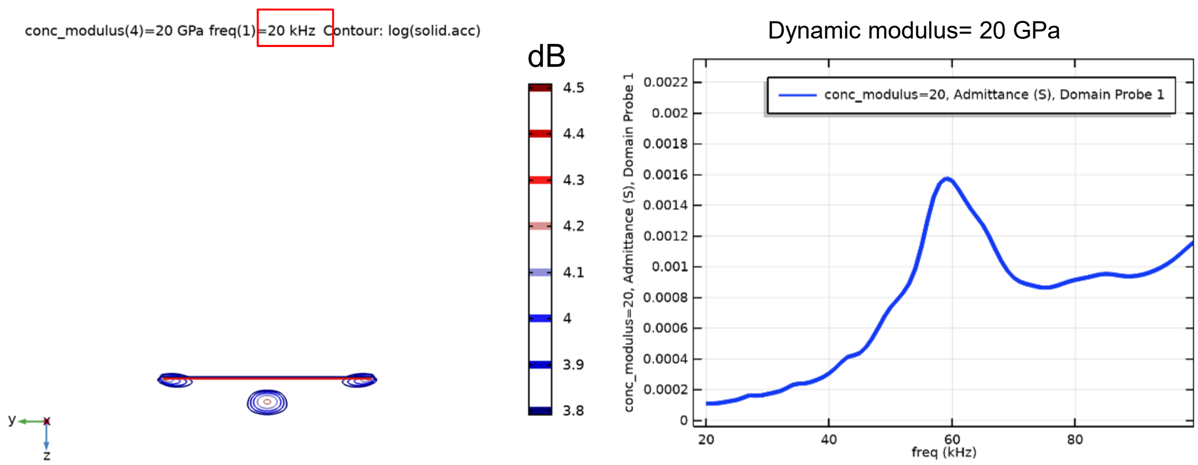
Piezoelectric EMI-Resonance Sensor



Directly measure the elastic modulus of concrete based on vibrational resonance

CENTER FOR INTELLIGENT INFRASTRUCTURES

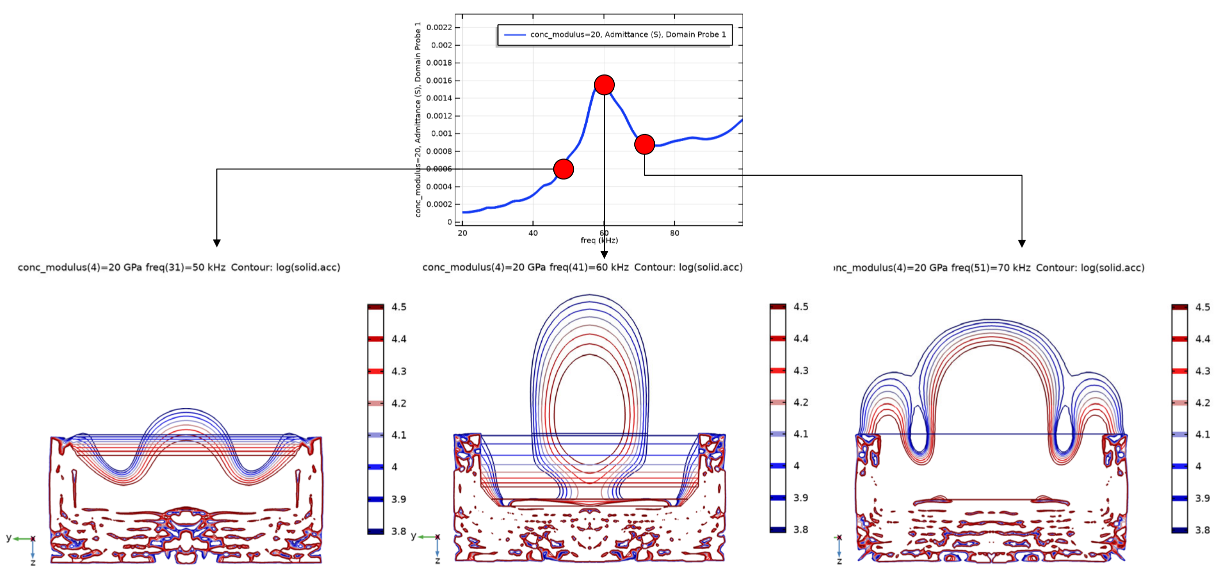
Piezoelectric EMI-Resonance Sensor



Wave field behavior vs. wave frequency emitted by the sensor

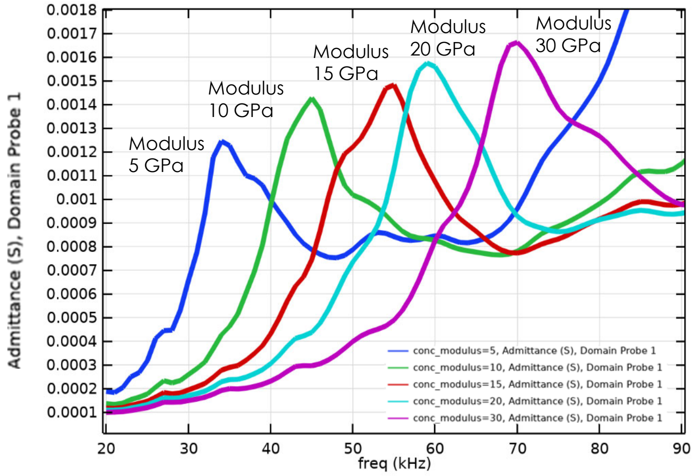
CENTER FOR INTELLIGENT INFRASTRUCTURES

Piezoelectric EMI-Resonance Sensor



CENTER FOR INTELLIGENT INFRASTRUCTURES

Piezoelectric EMI-Resonance Sensor



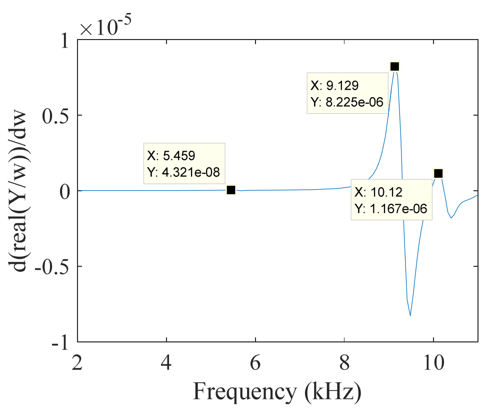
Resonant peak of sensor vs. dynamic modulus of concrete

Z. Kong, and N. Lu, *Journal of Aerospace Engineering* 33, no. 6 (November 2020): 04020079.
https://doi.org/10.1061/(ASCE)AS.1943-5525.0001196.

CENTER FOR INTELLIGENT INFRASTRUCTURES

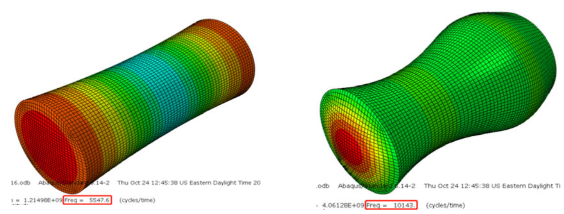
Mathematical Principle of Sensing Methods

A mathematical computation of mechanical properties of concrete using piezoelectric sensors and vibration resonance



Coupled electric admittance of the PZT patch

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



Z. Kong et. al Journal of Aerospace Engineering, 33, 04020079, 2020

CENTER FOR INTELLIGENT INFRASTRUCTURES

Mathematical Principle of Sensing Methods

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

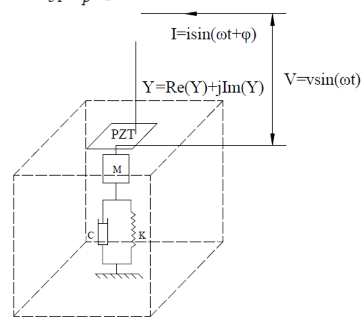
Coupled electric admittance of the PZT patch

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

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

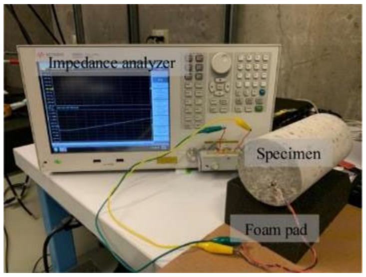
CENTER FOR INTELLIGENT INFRASTRUCTURES

Laboratory Testing and Validation

CENTER FOR INTELLIGENT INFRASTRUCTURES

Compression Testing Comparison

No pre-developed database is needed, direct measurement



Modulus	6024 psi	Modulus	5981psi
Strength	8847 psi	Strength	8784 psi

- Sensing and compressive testing conducted on the exactly same cylinder
- Modulus and Strength results are identical

Z. Kong et. al Journal of Aerospace Engineering, 33, 04020079, 2020

CENTER FOR INTELLIGENT INFRASTRUCTURES

Compression Testing Comparison

Overall, the sensed strength value has accuracy > 95% compared to traditional mechanical compression test.

Specimen Name	Strength by Compression (MPa)	Strength by EMI-R (MPa)	Error (relative to compression test)
GH-1	69.03	65.45	-5.2%
GH-2	71.87	71.68	-0.3%
GH-3	81.87	79.82	-2.5%
GH-4	78.57	76.07	-3.2%

Z. Kong et. al Journal of Aerospace Engineering, 33, 04020079, 2020

CENTER FOR INTELLIGENT INFRASTRUCTURES

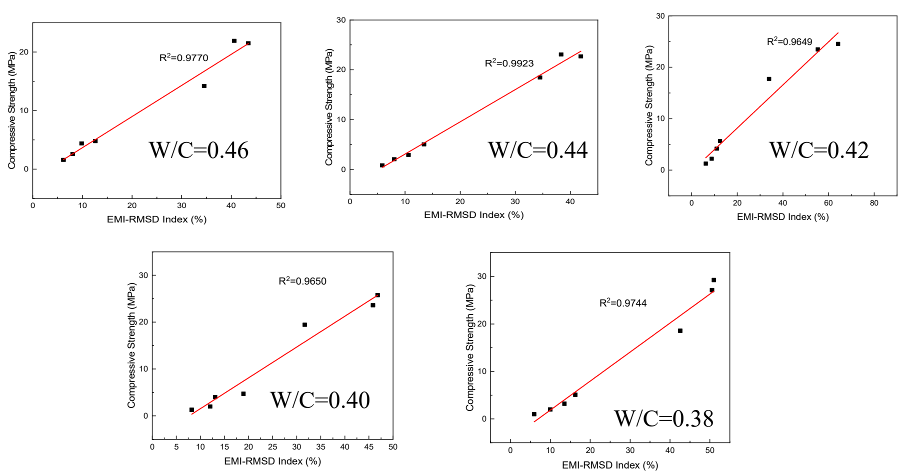
Sensor Testing for Different W/C

- Mortar experiments
- Sensing vs 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	

CENTER FOR INTELLIGENT INFRASTRUCTURES

Type I cement

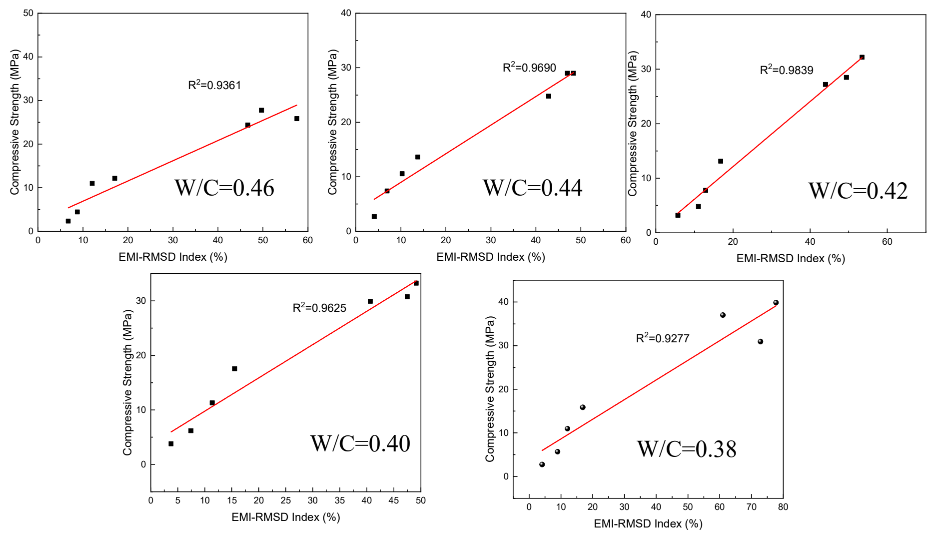


R^2 values are above 0.95, indicating good linear correlation

CENTER FOR INTELLIGENT INFRASTRUCTURES

yfarnam@purdue.edu

Type III cement



Y. Su et. al., Construction and Building Materials, 259, 119848, 2020

CENTER FOR INTELLIGENT INFRASTRUCTURES

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

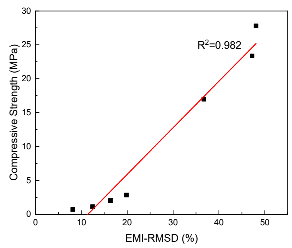
Very early age (4 – 8 hrs)

Early age (1,3,7 days)

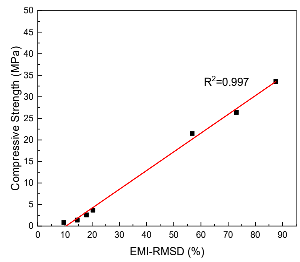
CENTER FOR INTELLIGENT INFRASTRUCTURES

Sensor Performance with Various SCMs

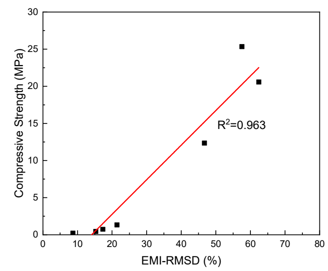
Slag 15%



Silica Fume 15%



Fly Ash 15%



R^2 value are above 0.96 , high accuracy

CENTER FOR INTELLIGENT INFRASTRUCTURES

INDOT PCCP with different mixes

- 4,6,8,10,12 hrs, 1,3,7,28 days
- Testing age : 1,3,7,28 days

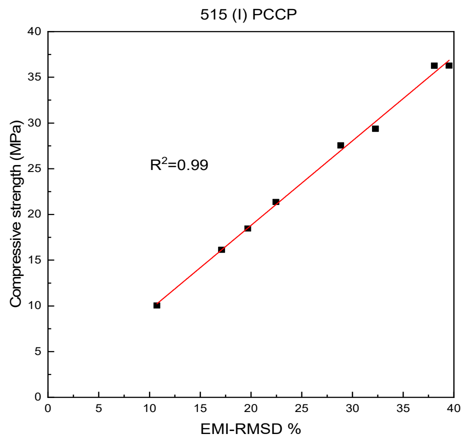
Mixes Design (lbs/cyds)

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%

CENTER FOR INTELLIGENT INFRASTRUCTURES

Testing Result for 10 Different PCCP Mixes

- Sensing and cylinder testing are highly correlated



Mixes	EMI- R^2
515 (I)	0.99
515 (III)	0.98
564 (I)	0.99
564 (III)	0.94
564 (I)+10%CA	0.97
564 (I)-10%CA	0.95
440 (I) – FA	0.96
350 (I) – SLAG	0.97
480 (I) – FA	0.94
480 (I) - SLAG	0.94

G. Han et. al., Journal of Intelligent Systems and Materials , 32(10), 1128,2021

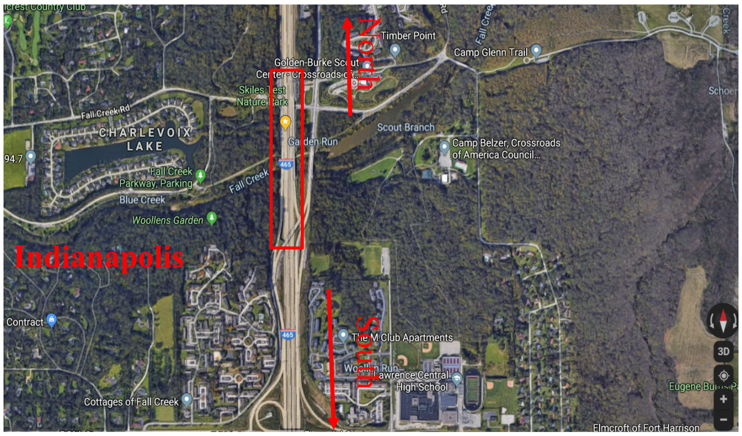
CENTER FOR INTELLIGENT INFRASTRUCTURES

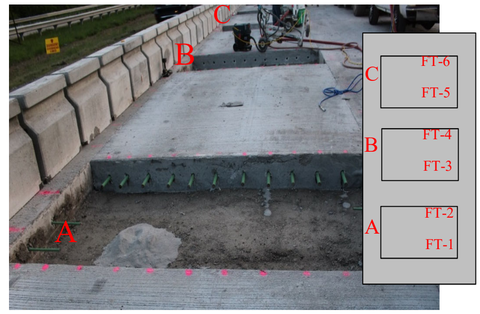
Field Study in 2019

CENTER FOR INTELLIGENT INFRASTRUCTURES

Pilot Testing in I-465

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





Hole (6' x 12') preparation

Testing Results

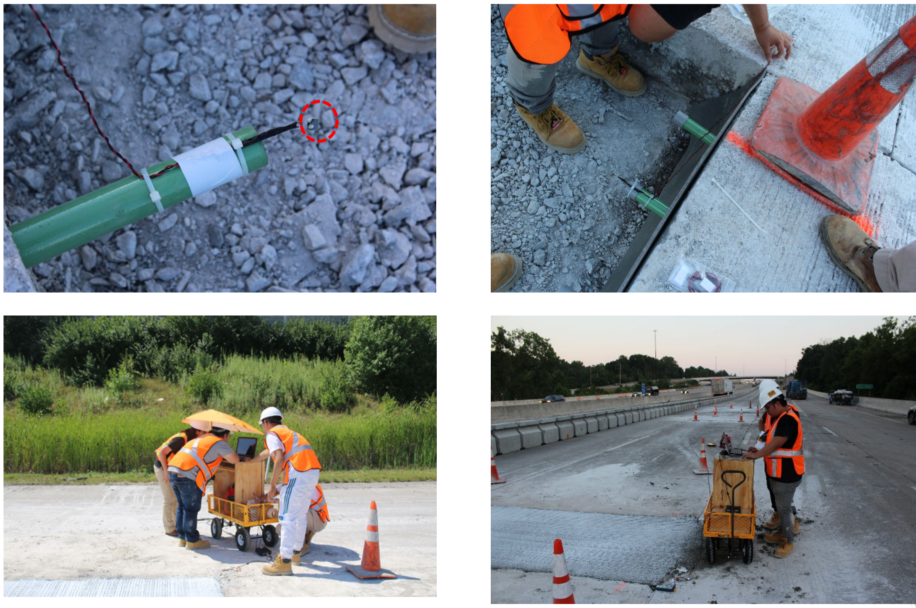
- Reference Compressive strength of 1 day sample

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 of the in-place concrete is higher than that of cylinder testing

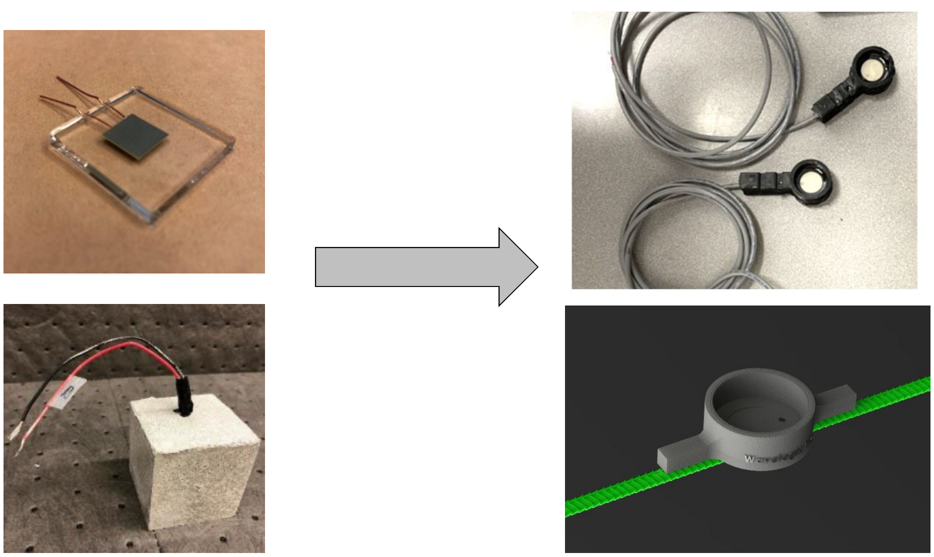
Y. Su et. al., ACI Materials Journal, 118(1), 147, 2021

Pilot Testing in I-465



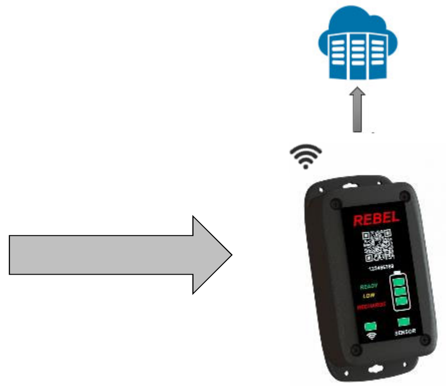
CENTER FOR INTELLIGENT INFRASTRUCTURES

Developed Robust Sensors



CENTER FOR INTELLIGENT INFRASTRUCTURES

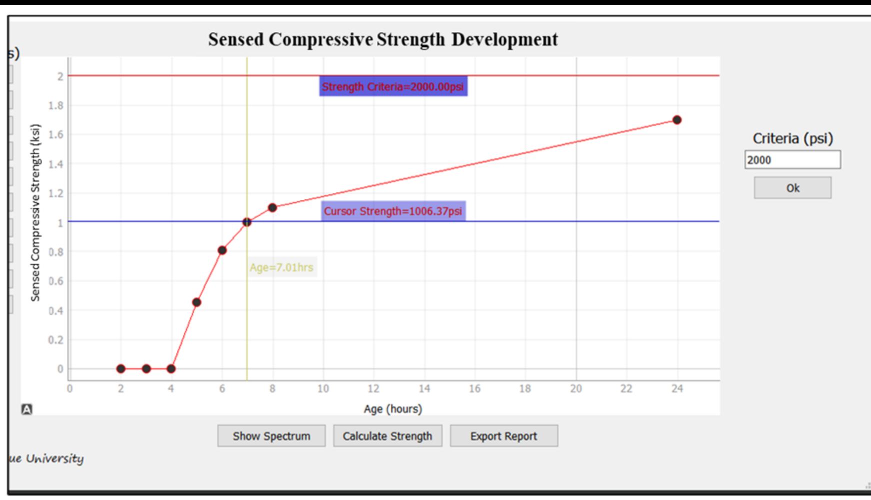
Data Acquisition and Wireless Communication



- Portable, fully automated data logger
- On chip data collection, analysis
- Wireless data transmission

CENTER FOR INTELLIGENT INFRASTRUCTURES

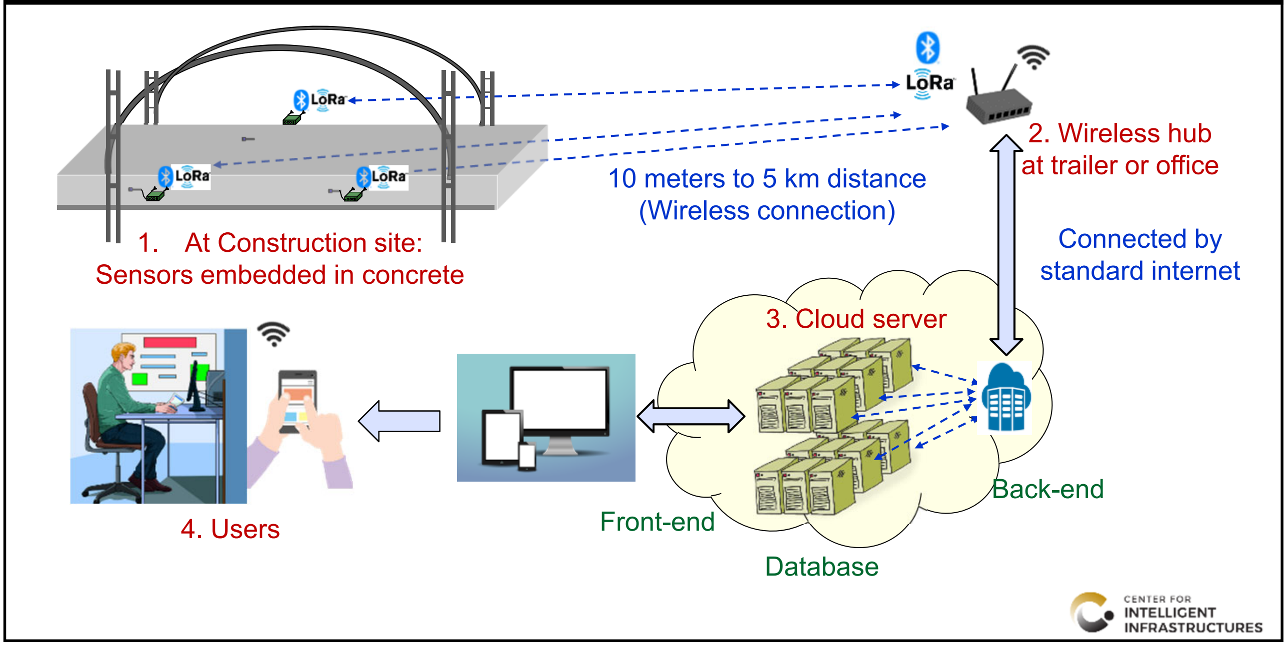
Hardware and Software



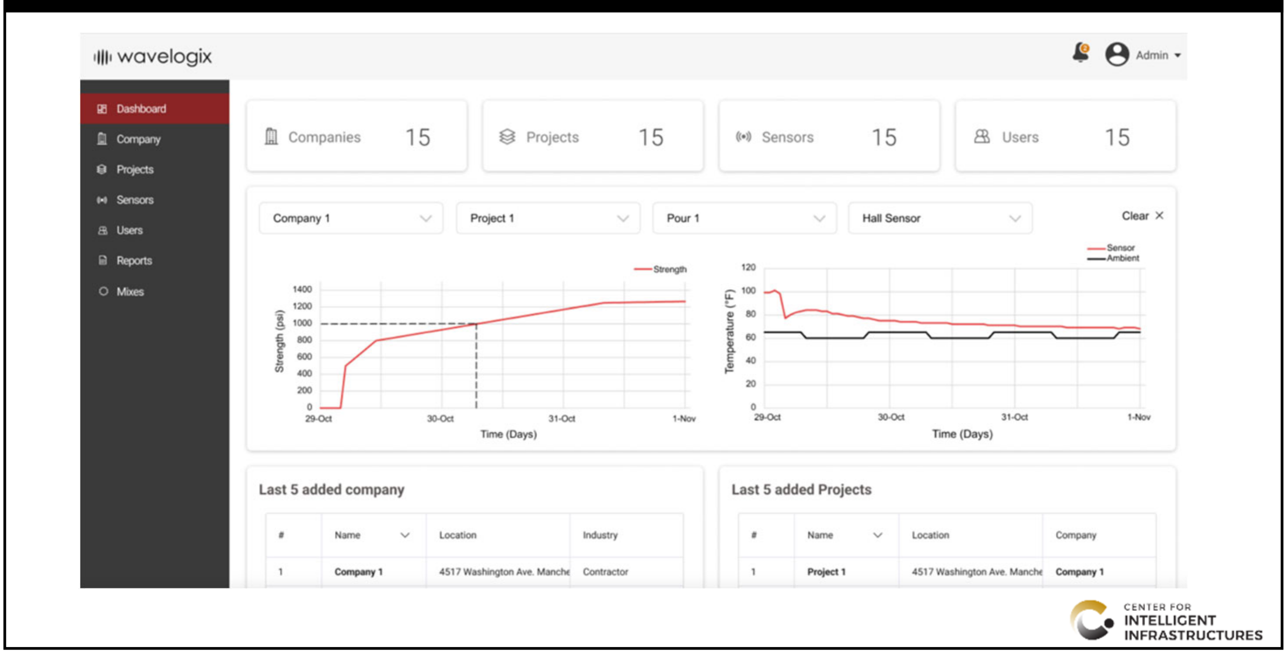
- Customized graphic user interface (GUI) for data report
- Easy to print the report in excel format

CENTER FOR INTELLIGENT INFRASTRUCTURES

IoT sensing Platform



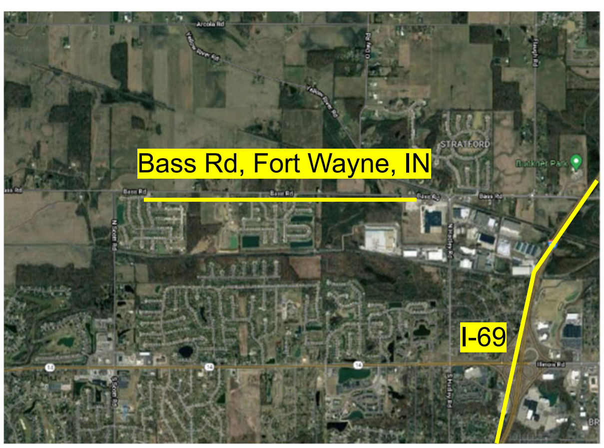
Dashboard and User Interface



2021 Field Testing and Validation

CENTER FOR INTELLIGENT INFRASTRUCTURES

Full Depth Paving – Fort Wayne



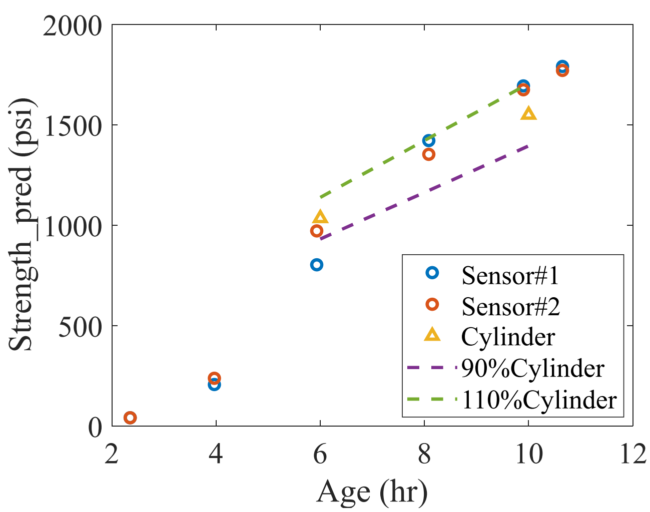
Contractor: Primco Construction, Sept-02-2021
Slab Thickness: 12”
Mix: w/c= 0.42, nano-silica incorporation

CENTER FOR INTELLIGENT INFRASTRUCTURES

Testing Setup

CENTER FOR INTELLIGENT INFRASTRUCTURES

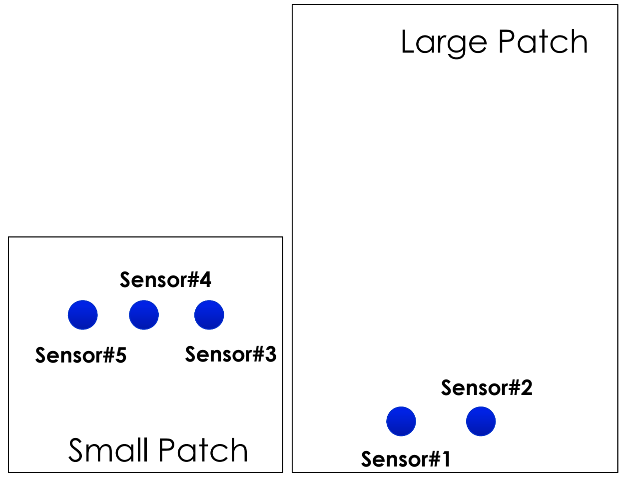
Testing Results



- Strength information can be obtained after 2 hrs concrete are poured, strength was around 300psi
- Different sensors' reading are very consistent
- Over 8hrs, sensors show higher strength value than the data obtained from the cylinder testing

CENTER FOR INTELLIGENT INFRASTRUCTURES

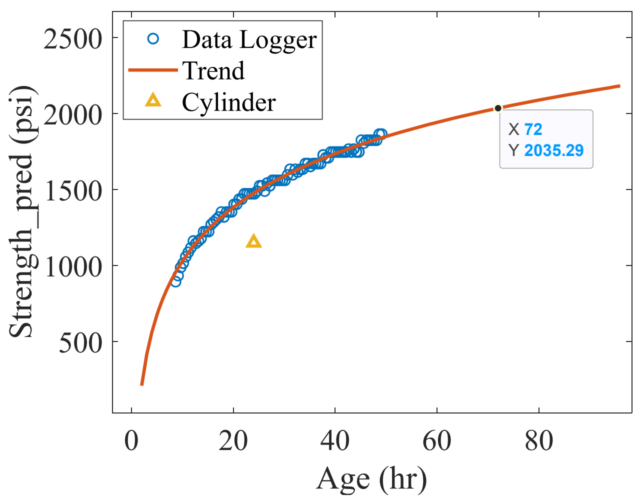
Indianapolis International Airport Project



Concrete Contractor: Milestone Construction; Sept-10-2021
Slab Thickness: 18”
Mix design: w/c= 0.43 with 40% slag for ASR

Sensor Installation

Testing Data



- Continuous monitoring of strength has been achieved
- Sensor reading is very consistent
- Cylinder reading is discrete
- Sensor reading is higher than cylinder results as expected

CENTER FOR INTELLIGENT INFRASTRUCTURES

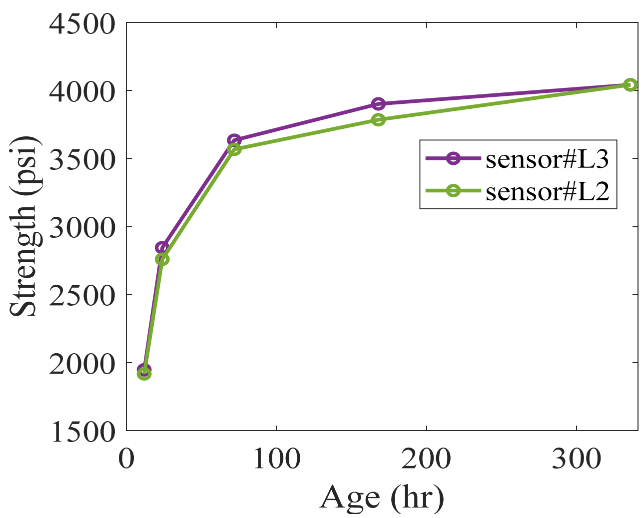
I-469 Bridge Deck Full Depth Paving

CENTER FOR INTELLIGENT INFRASTRUCTURES

I-469 Bridge Deck Full Depth Paving

CENTER FOR INTELLIGENT INFRASTRUCTURES

I-469 Bridge Deck Full Depth Paving



Data from two sensors in RC deck

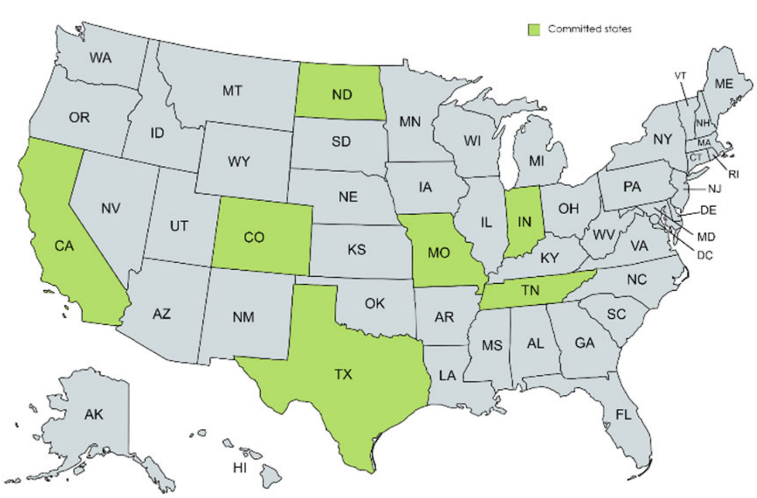
- Continuous monitoring of strength has been achieved
- Sensor readings are very consistent

CENTER FOR INTELLIGENT INFRASTRUCTURES

2021 ASCE GameChanger

CENTER FOR INTELLIGENT INFRASTRUCTURES

FHWA Pooled Fund Study – 1499



Committed states

- Caltrans
- Colorado DOT
- Indiana DOT
- North Dakota DOT
- Missouri DOT
- Texas DOT
- Tennessee DOT

New AASHTO Standard

CENTER FOR INTELLIGENT INFRASTRUCTURES

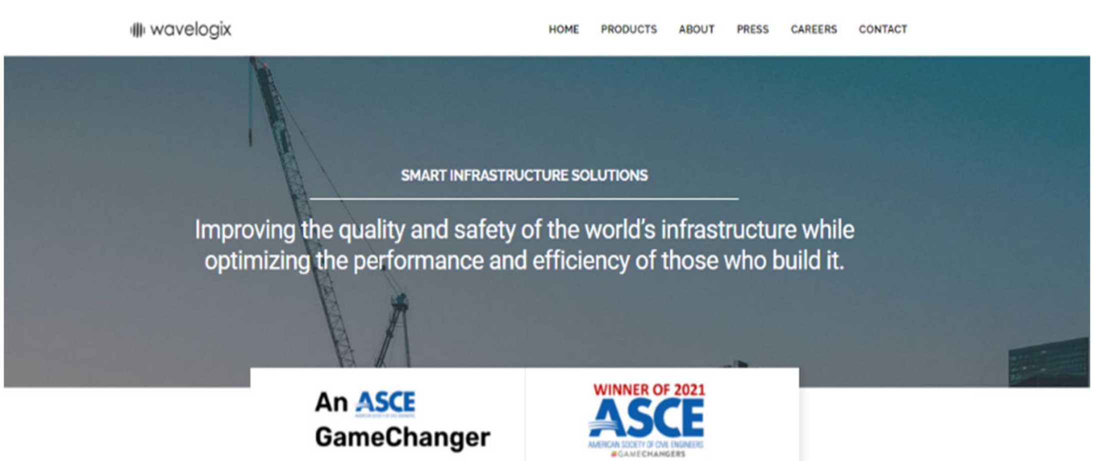
From Lab to Market Timeline

Ideation/Science →	Lab Testing →	Prototyping →	Field Testing →	Formation/Licensing →	Mfg/Release
2017	2018	2019	2020	2021	2022

CENTER FOR INTELLIGENT INFRASTRUCTURES

Learn More

Jennifer Rhodes Jennifer@wavelogix.tech



www.wavelogix.tech

CENTER FOR INTELLIGENT INFRASTRUCTURES


Acknowledgements
ACPA
INDIANA CHAPTER
AMERICAN CONCRETE PAVEMENT ASSOCIATION
INDIANA DEPARTMENT OF TRANSPORTATION
INDOT
R.L. McCOY
INC.
COLUMBIA CITY, IN.
Milestone
PRIMCO INC.
ROAD
BRIDGE
PURDUE UNIVERSITY
Lyles School of Civil Engineering
CENTER FOR
INTELLIGENT
INFRASTRUCTURES