

# REBEL Sensor

Real-time concrete monitoring without maturity curve



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Reilly Professor & Associate Dean of Faculty

College of Engineering, Purdue University



# Innovation: Technology Meets the Problem



**Curing time &  
Operational schedule**

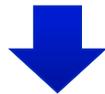


# The Problem

## Requirement for Determining In-situ Concrete Strength



- Open too early cause pre-mature failure and frequent patching



- Construction delay causing traffic jam



**Infrastructure scheduling → Construction and Maintenance**

# Conventional Strength Testing

## Current Methods

- Compression/ cylinder break
- Flexural/ beam break

## Disadvantages

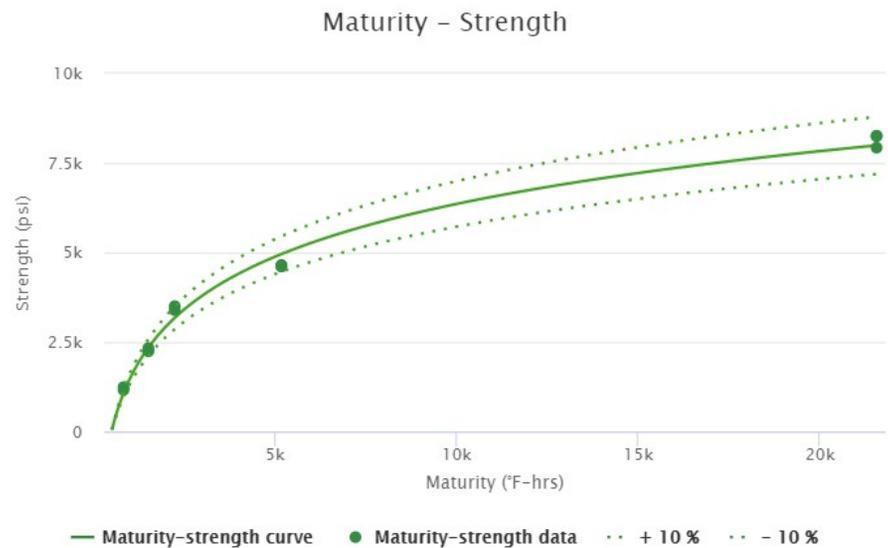
- Up to 50% error
- Time consuming
- Requires skilled labor
- **The actual in-place concrete is not being tested**



# Maturity Method

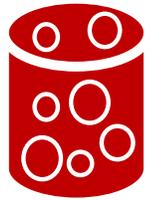
## Maturity testing (ASTM C-1074, IMT 402-15T)

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



[http://wikipave.org/index.php?title=Maturity\\_Testing](http://wikipave.org/index.php?title=Maturity_Testing)

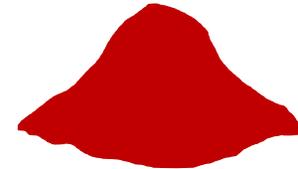
# The worldwide challenge



high % of false negatives  
("bad breaks")



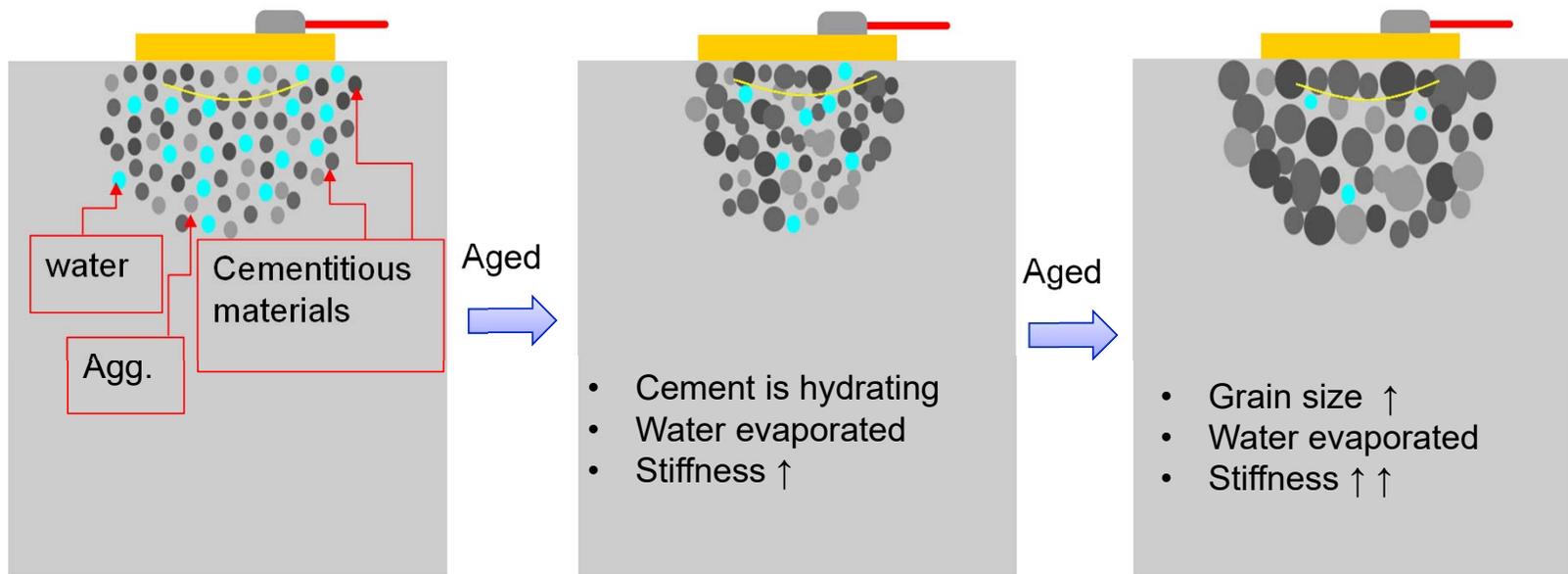
25% of schedule delays &  
increased costs



20% more cement added in  
concrete / ACI 318

# **Our Solution – Direct Mechanical Measurements Using Piezoelectric Sensor**

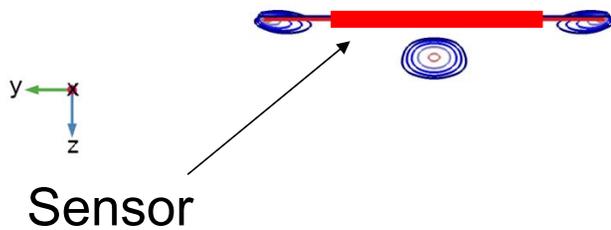
# Piezo-sensor for Concrete Strength Monitoring



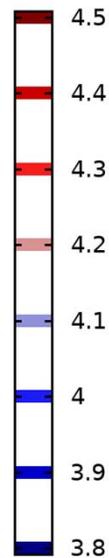
Using piezoelectric sensor to understand the concrete stiffness and strength through electromechanical coupling effect.

# Piezoelectric Resonance Sensor

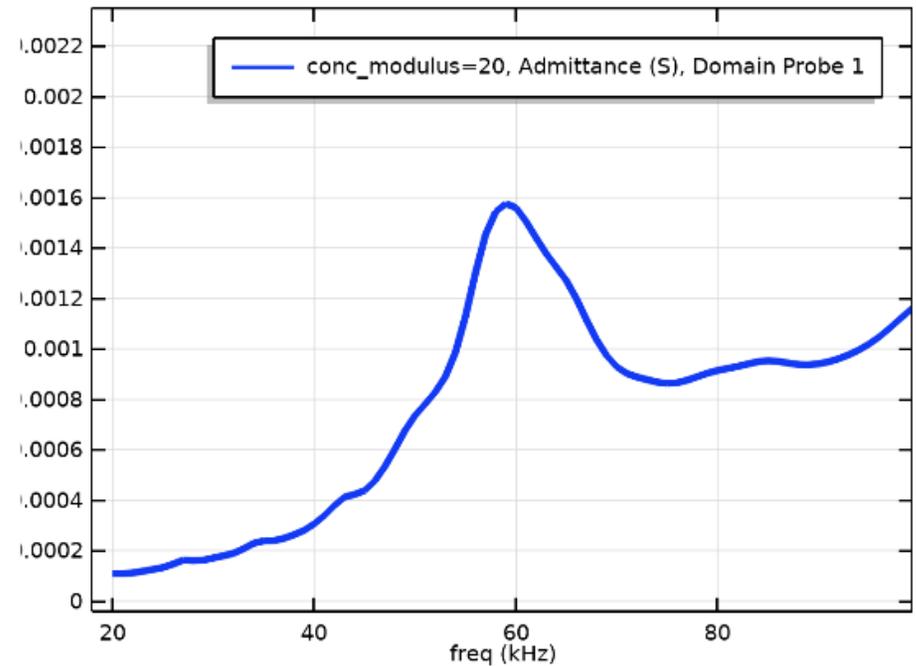
conc\_modulus(4)=20 GPa freq(1)=20 kHz Contour: log(solid.acc)



dB

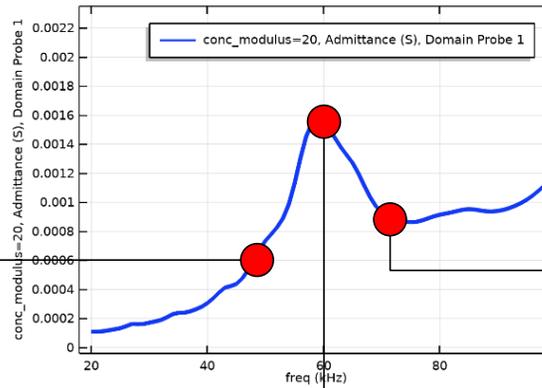


Dynamic modulus= 20 GPa



Wave field behavior vs. wave frequency emitted by the sensor

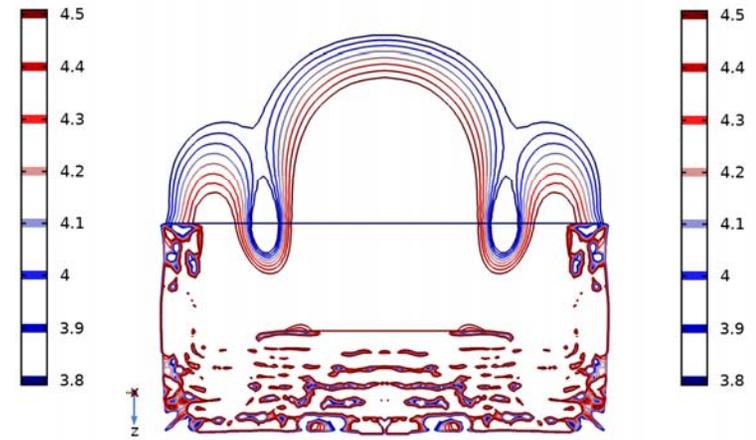
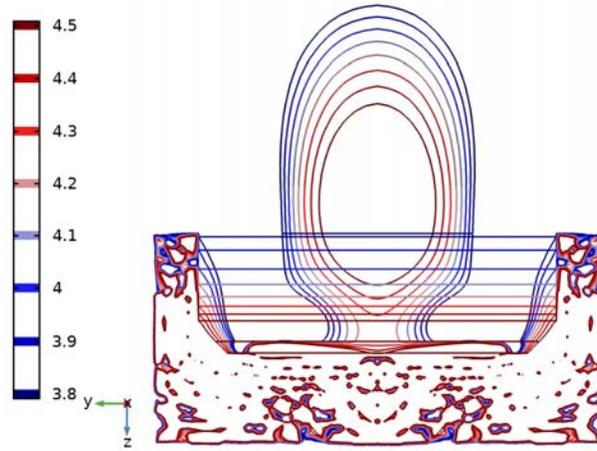
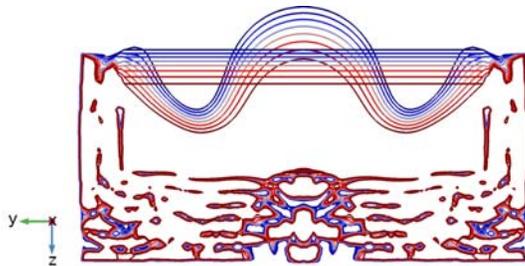
# Piezoelectric EMI-Resonance Sensor



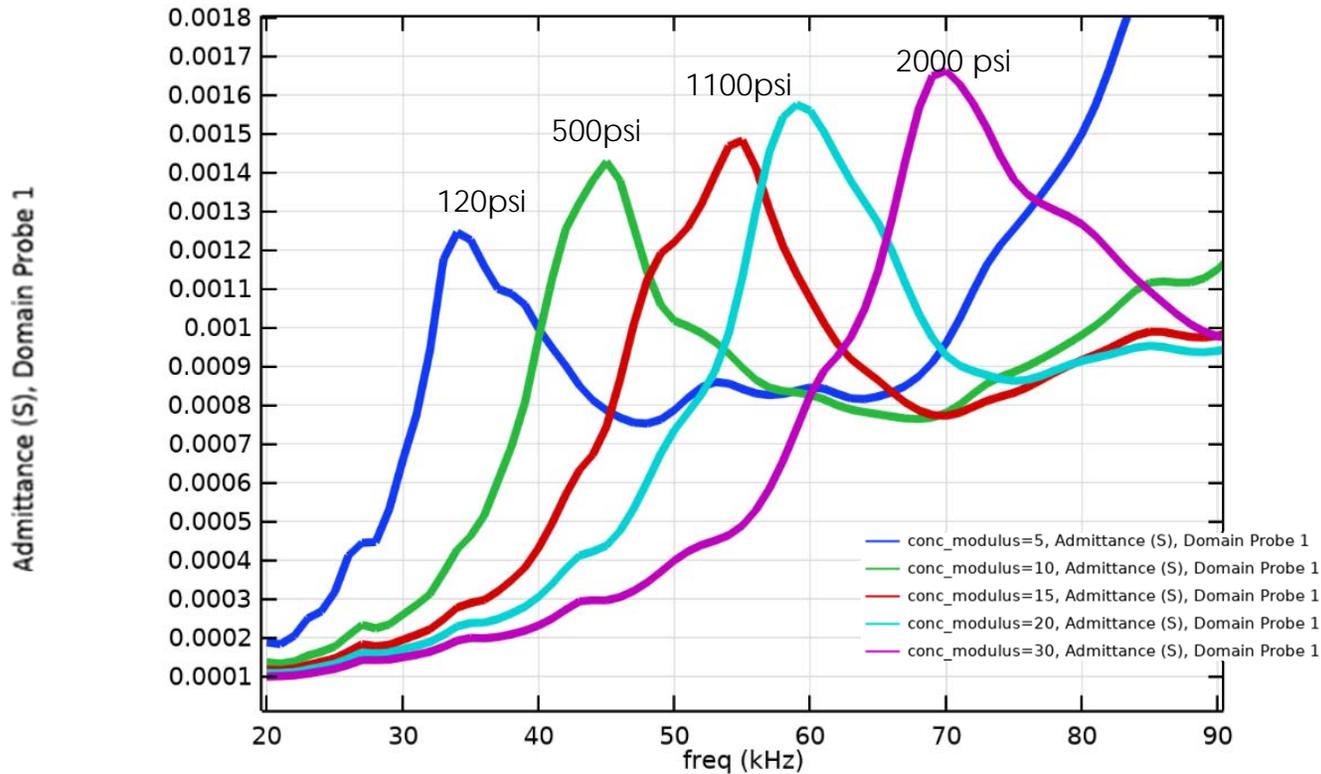
conc\_modulus(4)=20 GPa freq(31)=50 kHz Contour: log(solid.acc)

conc\_modulus(4)=20 GPa freq(41)=60 kHz Contour: log(solid.acc)

inc\_modulus(4)=20 GPa freq(51)=70 kHz Contour: log(solid.acc)



# Piezoelectric EMI-Resonance Sensor



Resonant peak of sensor vs. strength 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](https://doi.org/10.1061/(ASCE)AS.1943-5525.0001196).

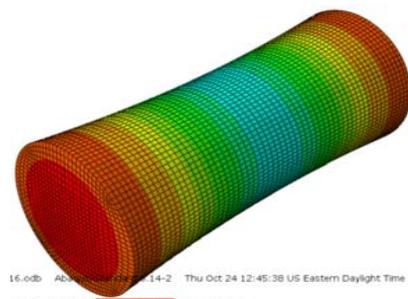
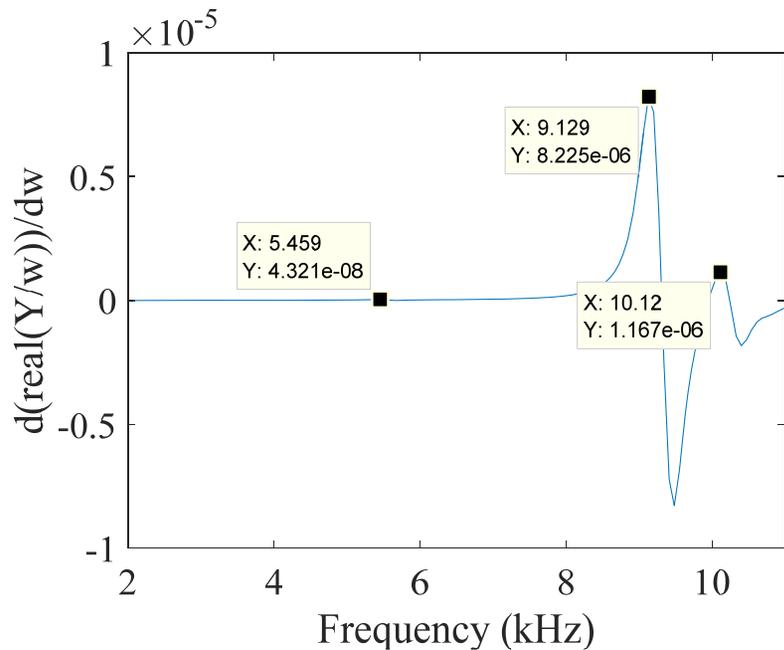
# Mathematical Principle of Sensing Methods

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

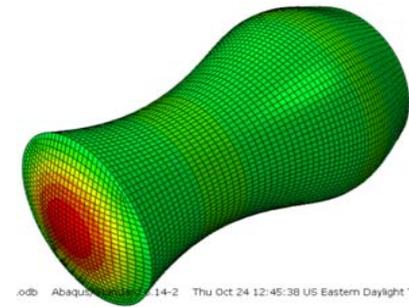
$$E_d = (f_r \cdot g)^2 \cdot \rho \cdot \frac{(1+\mu)(1-2\mu)}{1-\mu} \cdot 10^{-9}$$

$$E_s = 0.65 \cdot E_d^{1.04}$$

$$f_c' = \left( E_s \cdot \frac{10^3}{0.043 \cdot \rho^{1.5}} \right)^2$$



16 odb - Abaqus/Explicit - 14-2 Thu Oct 24 12:45:38 US Eastern Daylight Time 20  
1 = 1.21498E+09 [Freq = 5547.6 (cycles/time)]

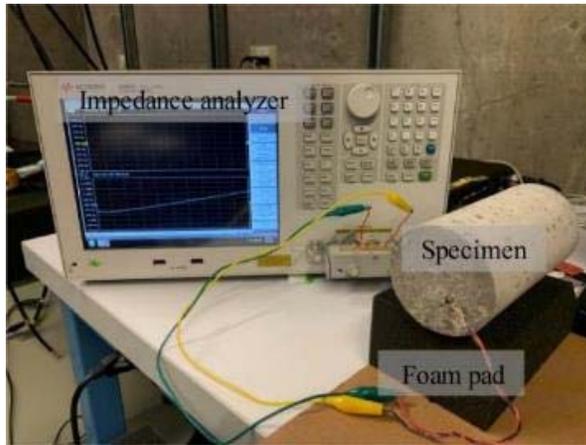


odb - Abaqus/Explicit - 14-2 Thu Oct 24 12:45:38 US Eastern Daylight Time  
1 = 4.06128E+09 [Freq = 10143 (cycles/time)]

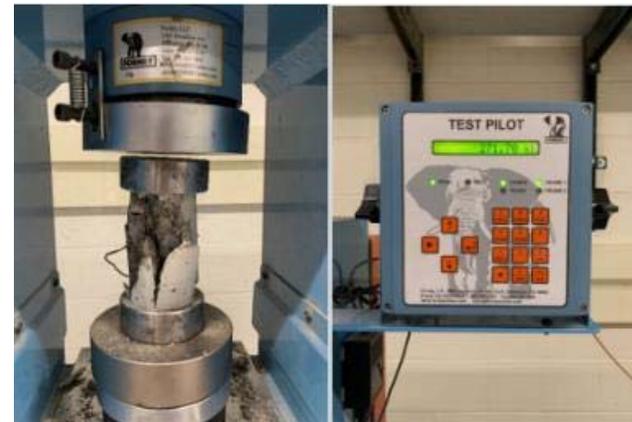
Z. Kong et. al *Journal of Aerospace Engineering*, 33, 04020079, 2020

# Compression Testing Comparison

No calibration is needed, direct measurement



**Sensed** strength 8847 psi



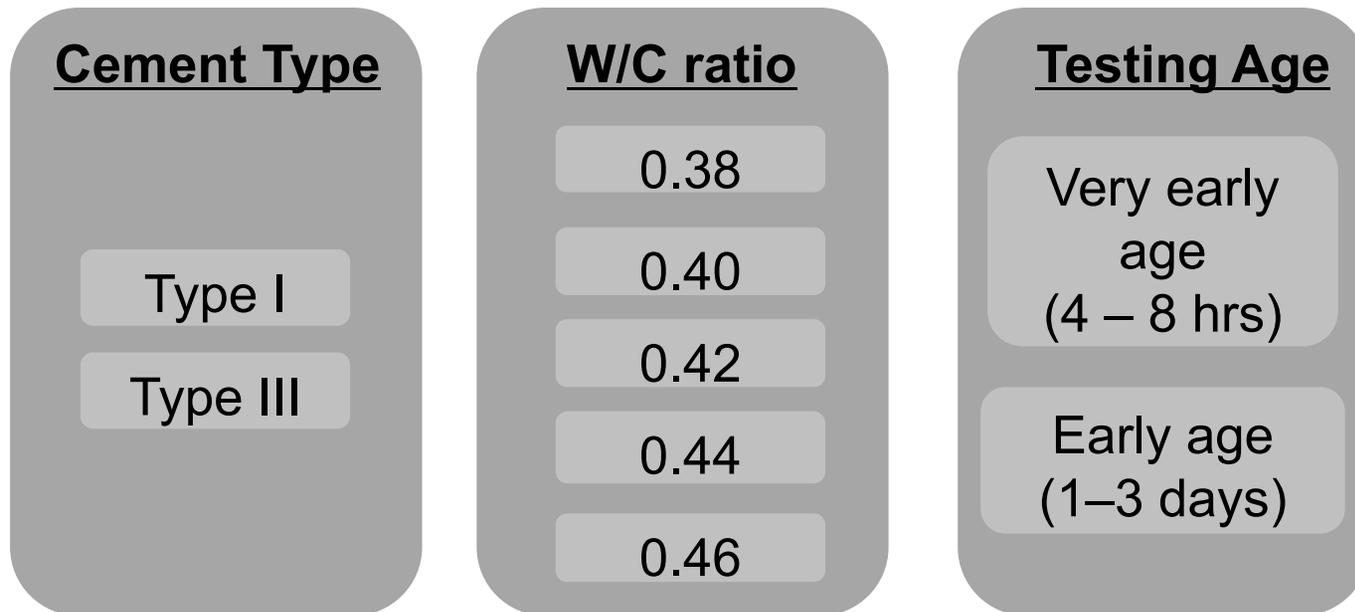
**Tested** strength 8784 psi

- 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*

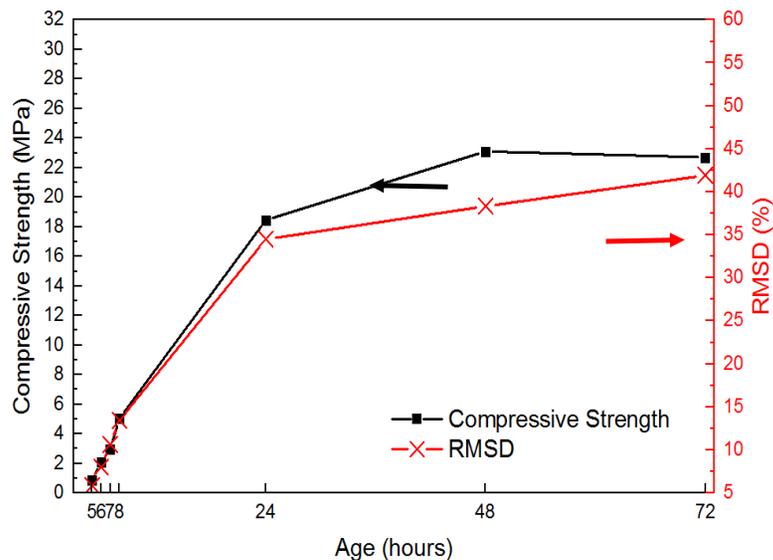
# Sensor Testing for Different W/C

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

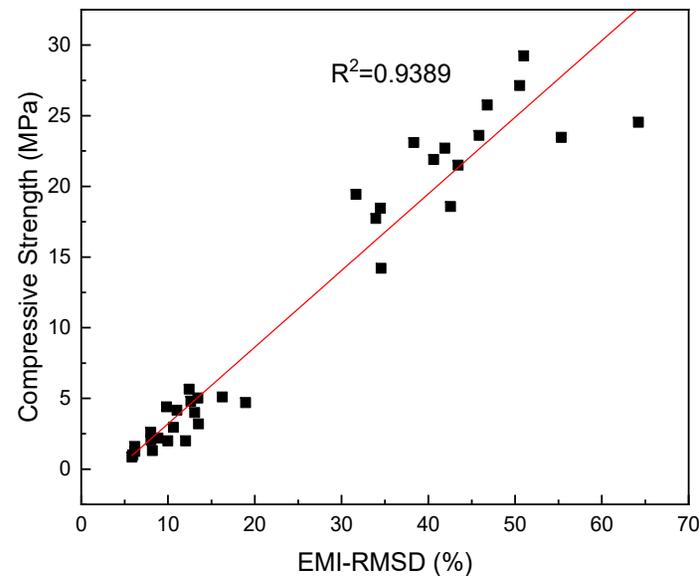


# Early-age Property

- 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



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



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

# 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%

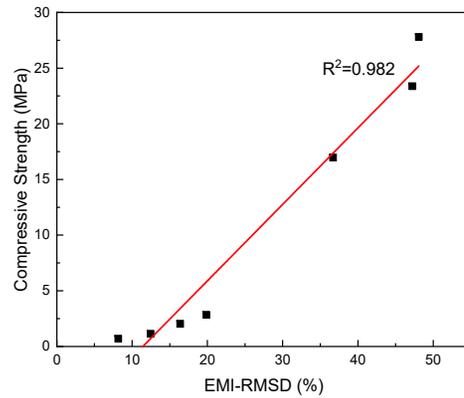
## Testing Age

Very early  
age  
(4 – 8 hrs)

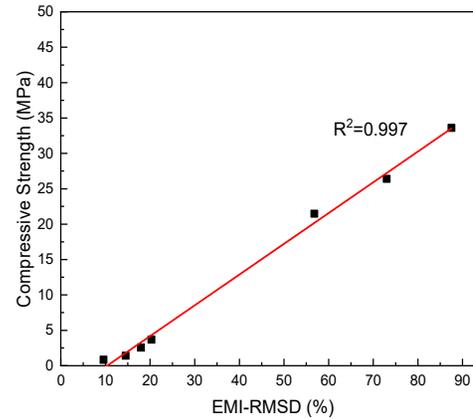
Early age  
(1,3,7 days)

# Sensor Performance with Various SCMs

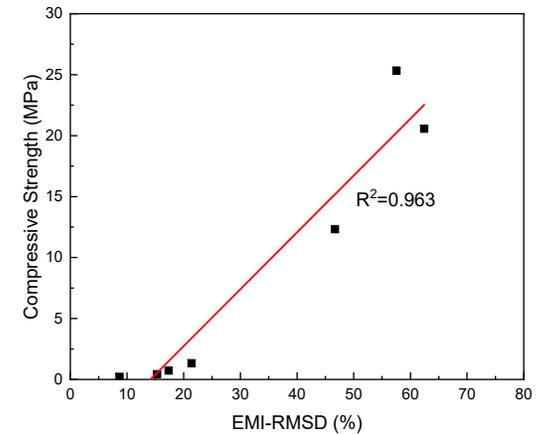
Slag 15%



Silica Fume 15%



Fly Ash 15%



R<sup>2</sup> value are above **0.96** , high accuracy

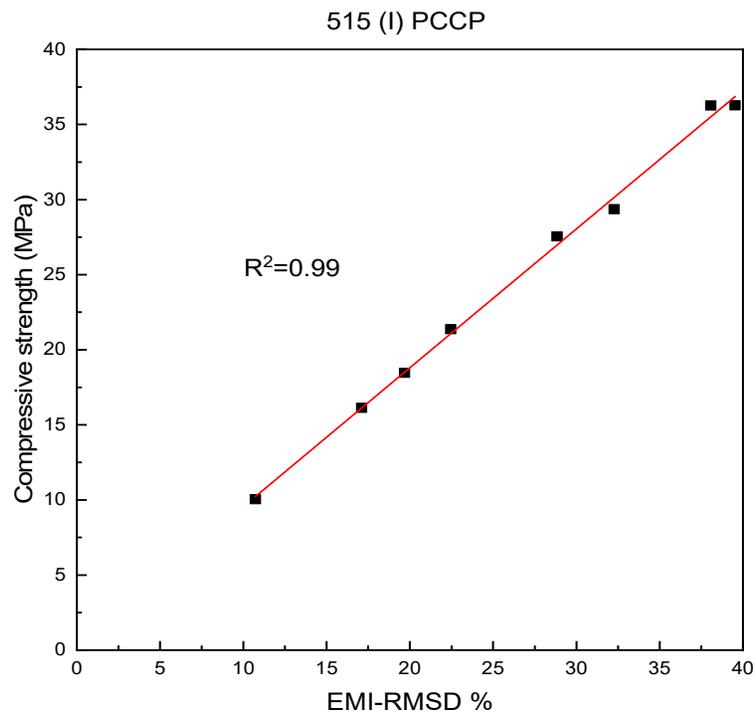
# INDOT PCCP with different mixes

## 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%

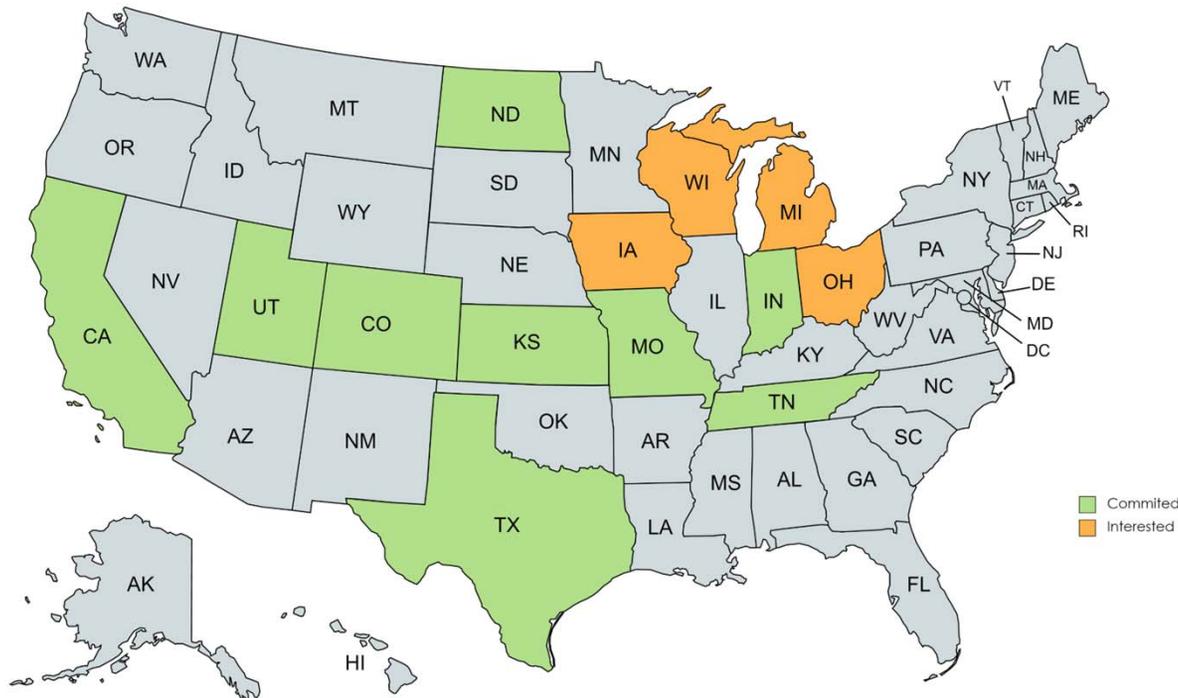
# Testing Result for 10 Different PCCP Mixes

- Sensing and cylinder testing are highly correlated



Mixes	EMI- R <sup>2</sup>
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

# FHWA Pooled Fund Study – 1499

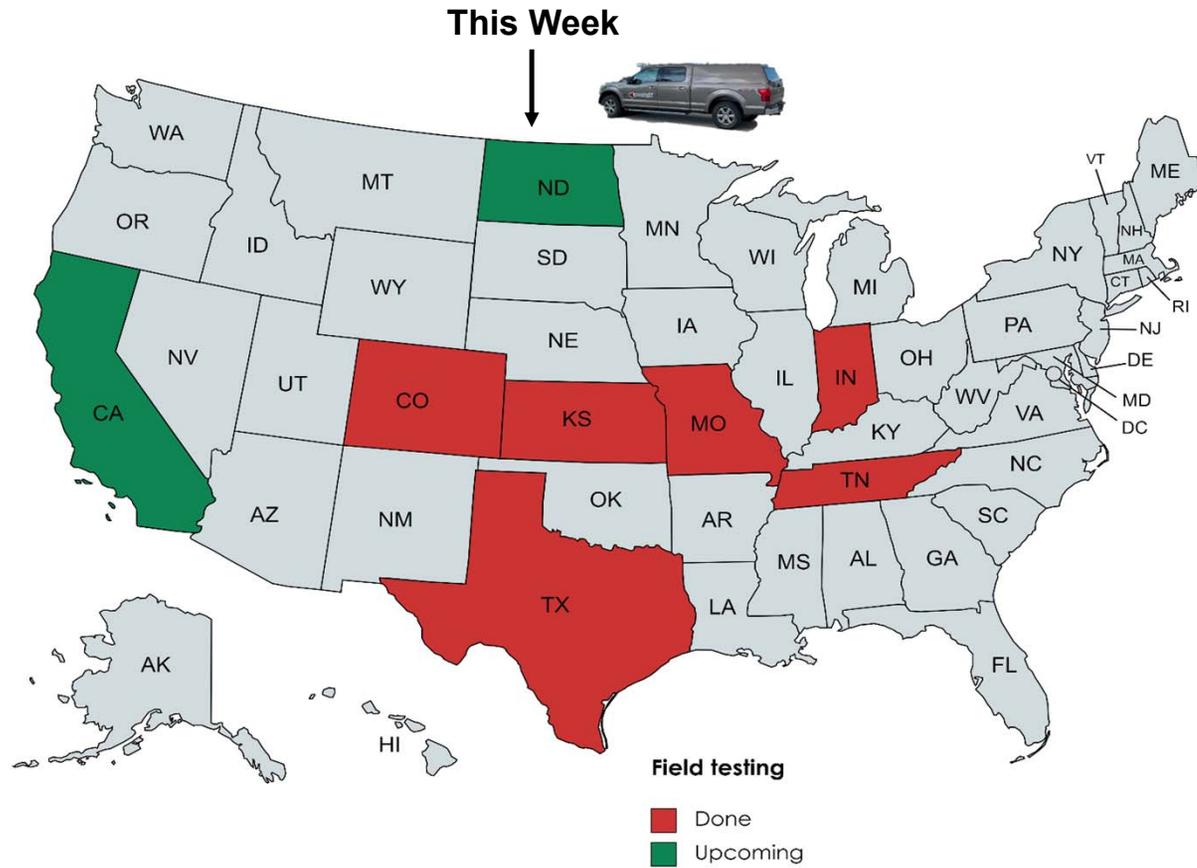


## ■ Committed states

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

## ■ New AASHTO Standard

# Nationwide field testing



# Nationwide Field Testing



Garrett, IN



Tennessee



Missouri



Indy



Kansas



Colorado

# Full Depth Paving – Fort Wayne



Contractor: Primco Construction, Sept-02-2021

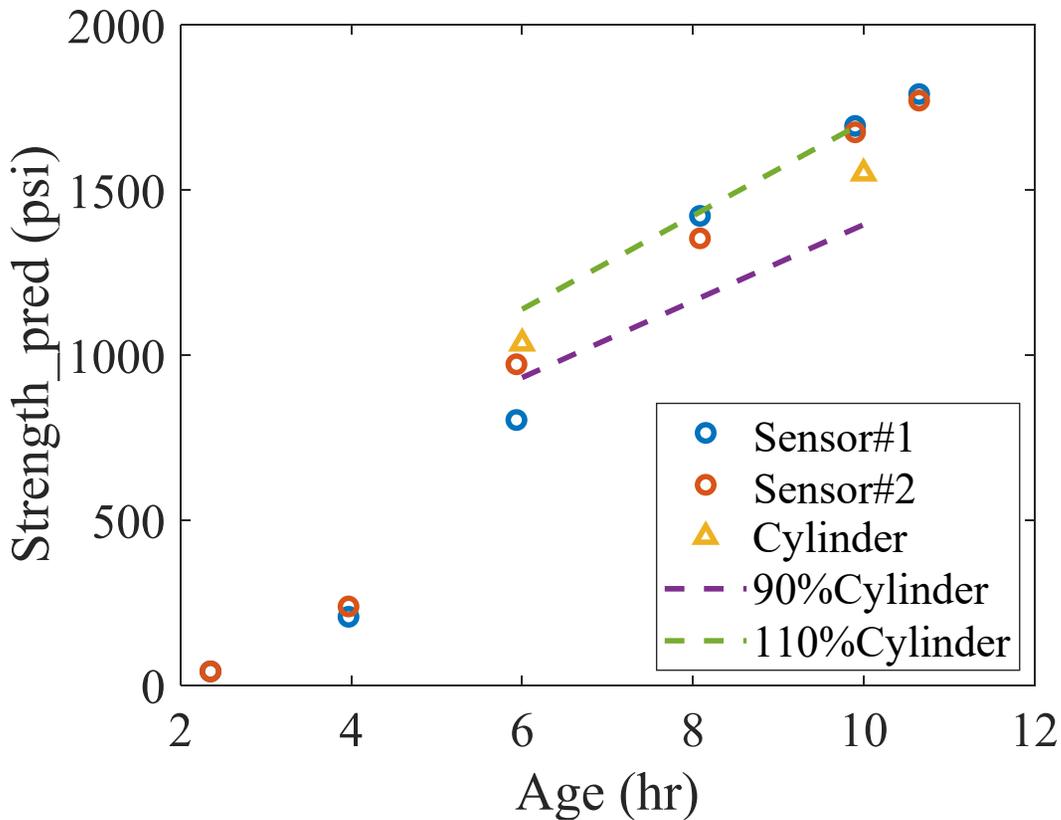
Slab Thickness: 12"

Mix: w/c= 0.42, 6 oz E5 nano-silica incorporation

# Testing Setup



# Testing Results

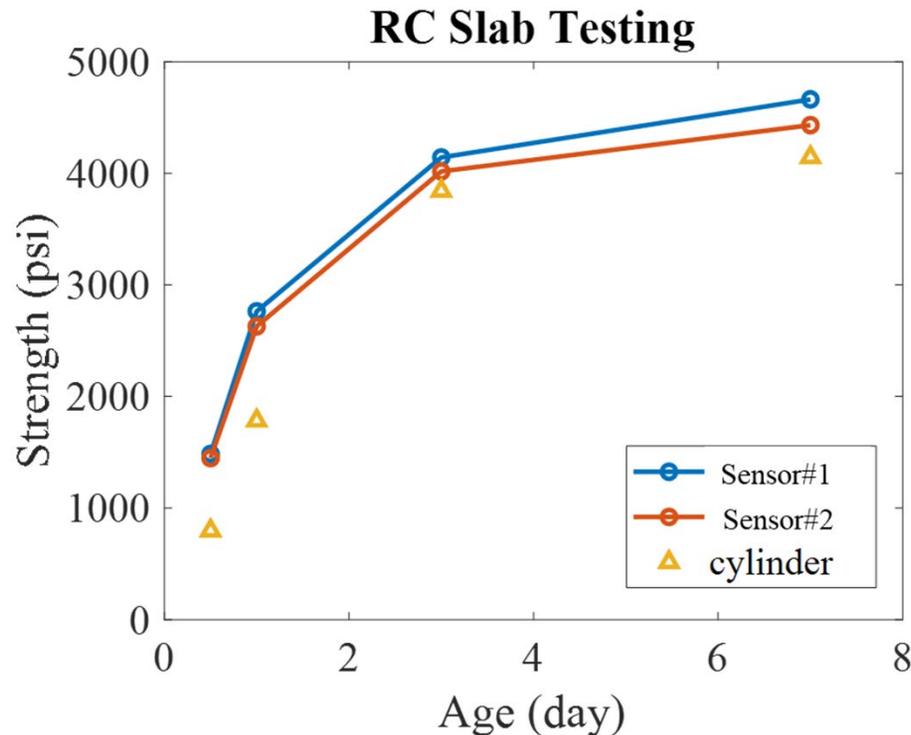


- Strength information can be obtained after 2 hrs concrete are poured, strength was around 300psi
- Different sensors' reading are very consistent
- Over 8hrs, sensors show higher strength value than the data obtained from the cylinder testing

# I-469 Bridge Deck Full Depth Paving



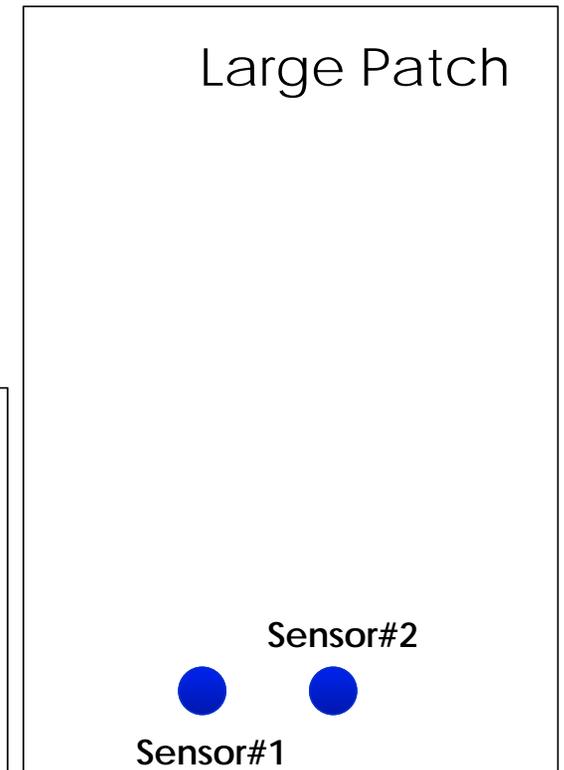
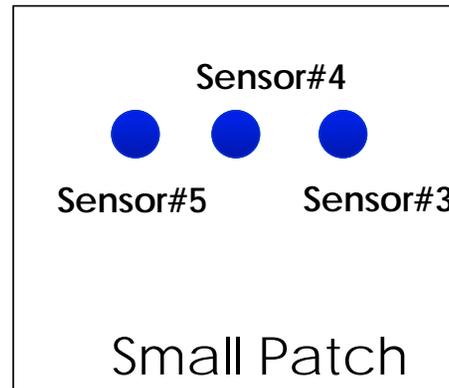
# I-469 Bridge Deck Full Depth Paving



Data from two sensors in RC deck

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

# Indianapolis International Airport Project



Concrete Contractor: Milestone Construction; Sept-10-2021

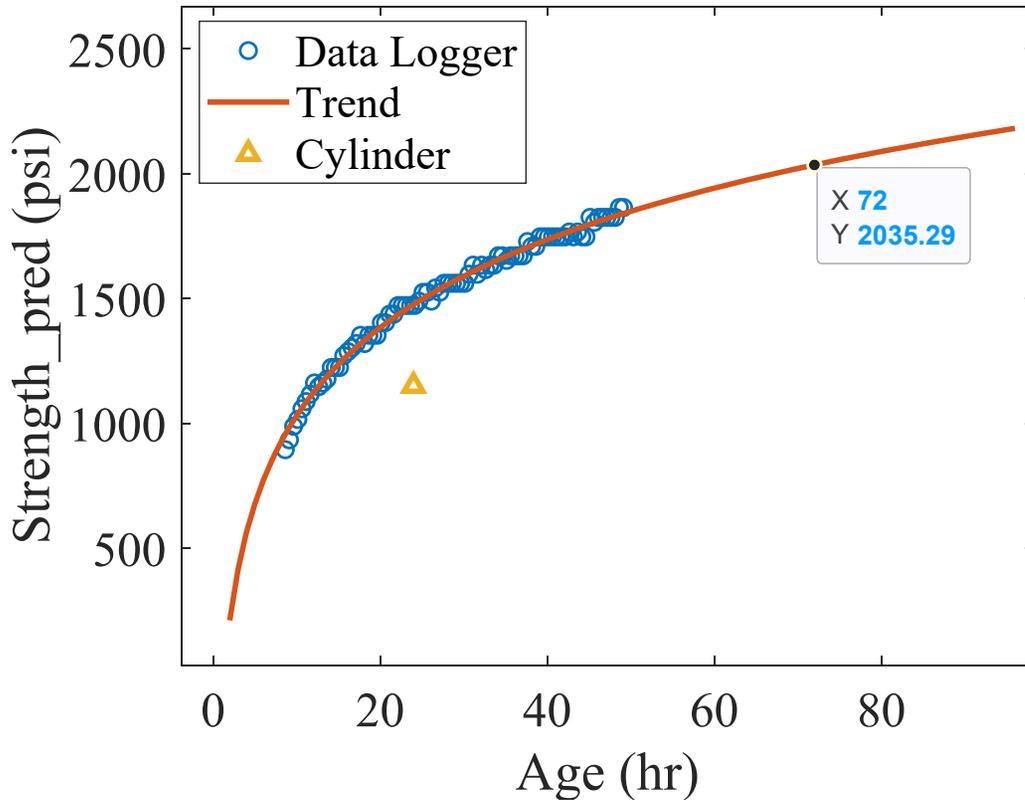
Slab Thickness: 18"

Mix design: w/c= 0.43 with 40% slag for ASR

# Sensor Installation

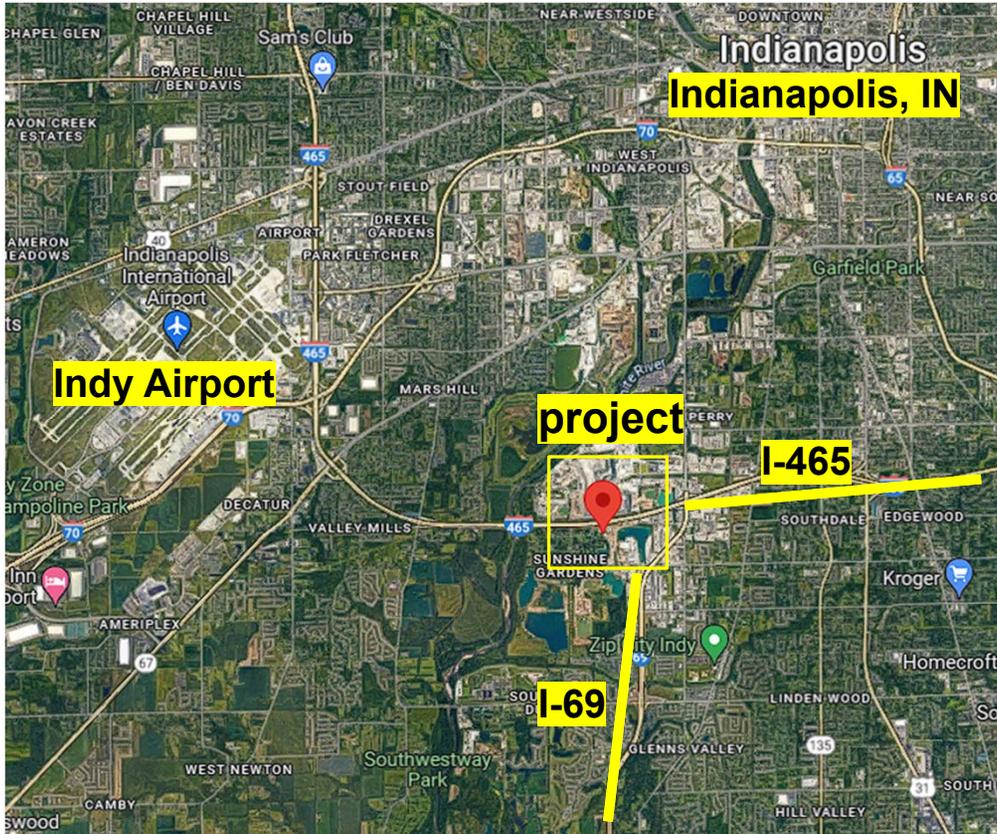


# Testing Data



- 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

# Indiana I-69 Paving



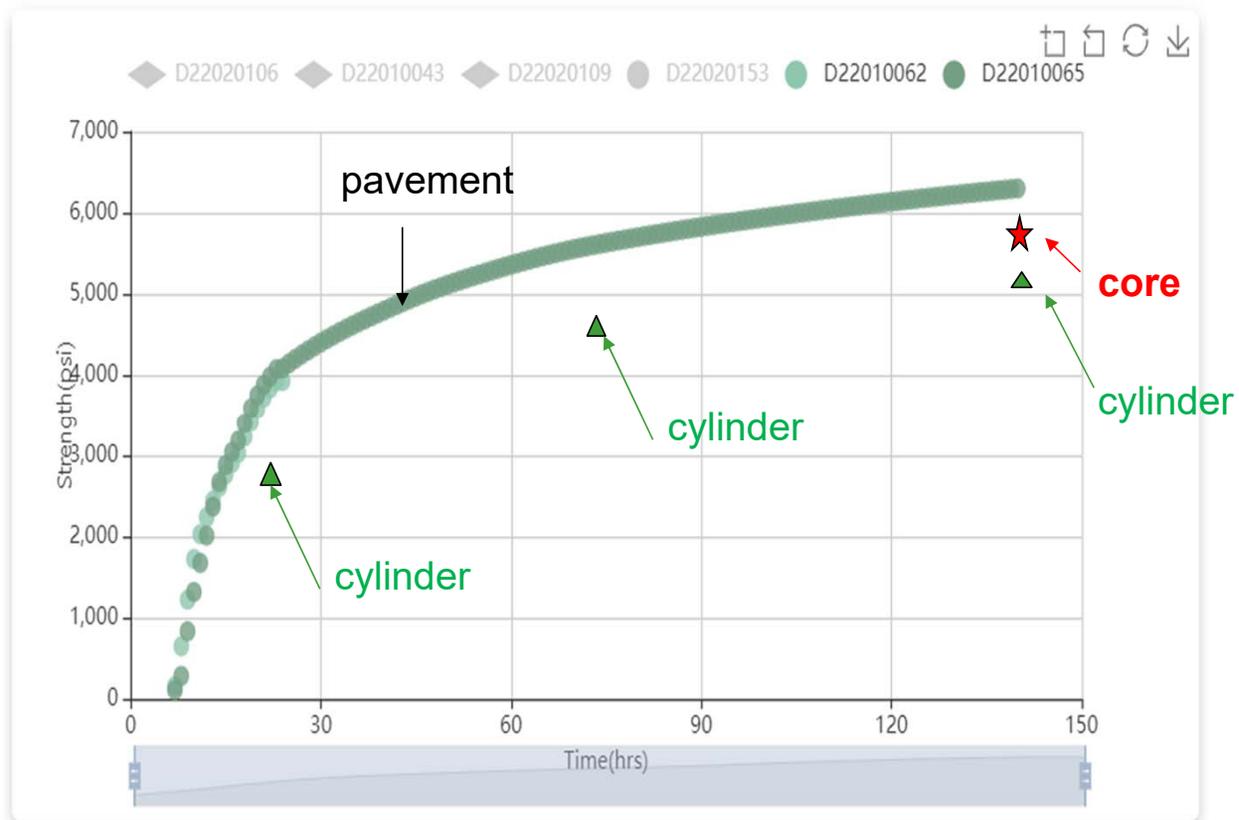
<b>Date</b>	2023-7-25
<b>Location</b>	Indianapolis, IN
<b>Coordinate</b>	39.691282, -86.204355
<b>Pavement Thickness</b>	11"
<b>Rebar</b>	#6 (0.75")
<b>Ingredients</b>	<b>Amount (/yd<sup>3</sup>)</b>
Fine Agg.	1268 lbs
Coarse Agg.	1830 lbs
Type II	425 lbs
Slag	145 lbs
Water	233.7 lbs
W-C-Ratio	0.410

# Indiana I-69 Paving

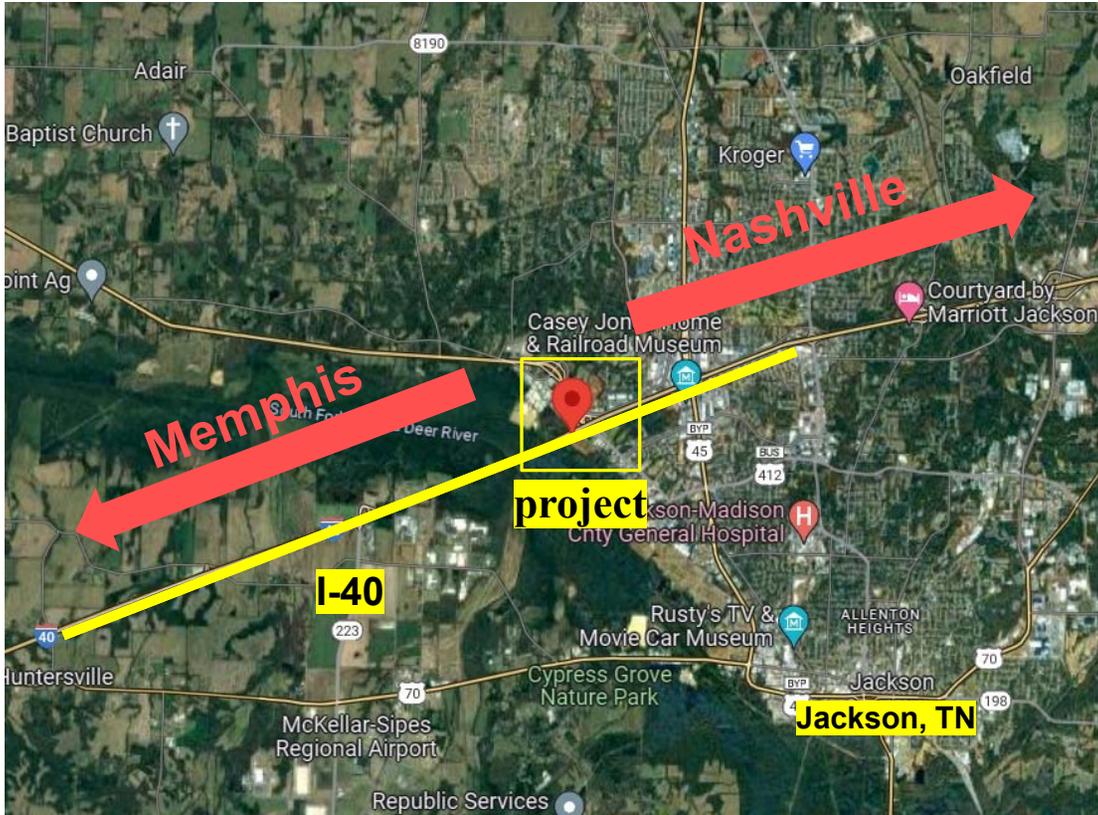


# Indiana I-69 Paving

## Sensing Results vs Cylinder Results



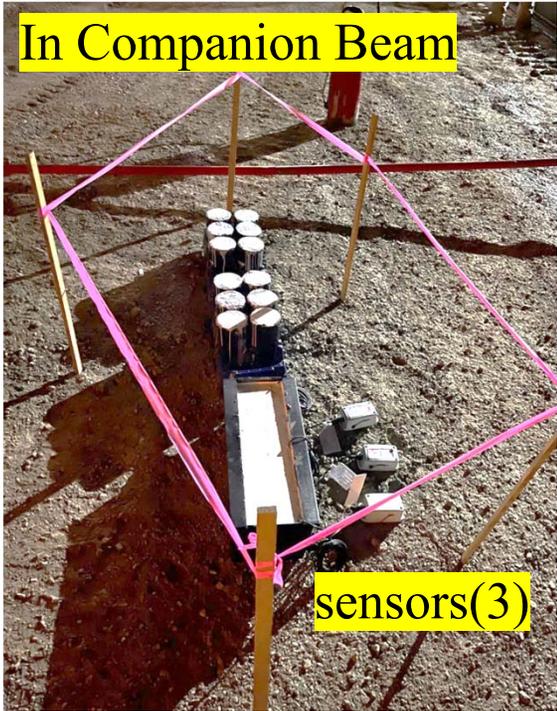
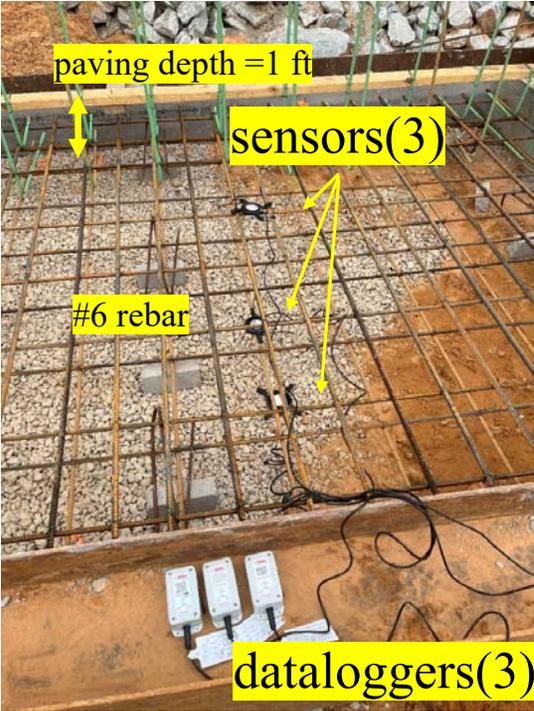
# Tennessee I-40 Bridge Pavement & Parapet Wall



Date	7-12-2023
Location	Jackson, TN
Coordinate	35°39'20.2"N 88°52'40.9"W
Wall Depth	4.5 ft

Mixture	Amount (/yd <sup>3</sup> )
Fine Agg.	1214 lbs
Coarse Agg.	1800 lbs
Cement	423 lbs
Fly Ash	141 lbs
Water	254.5 lbs
W-C-Ratio	0.430

# Tennessee I-40 Paving



# Tennessee I-40 Paving

## Sensing Results vs Cylinder Results

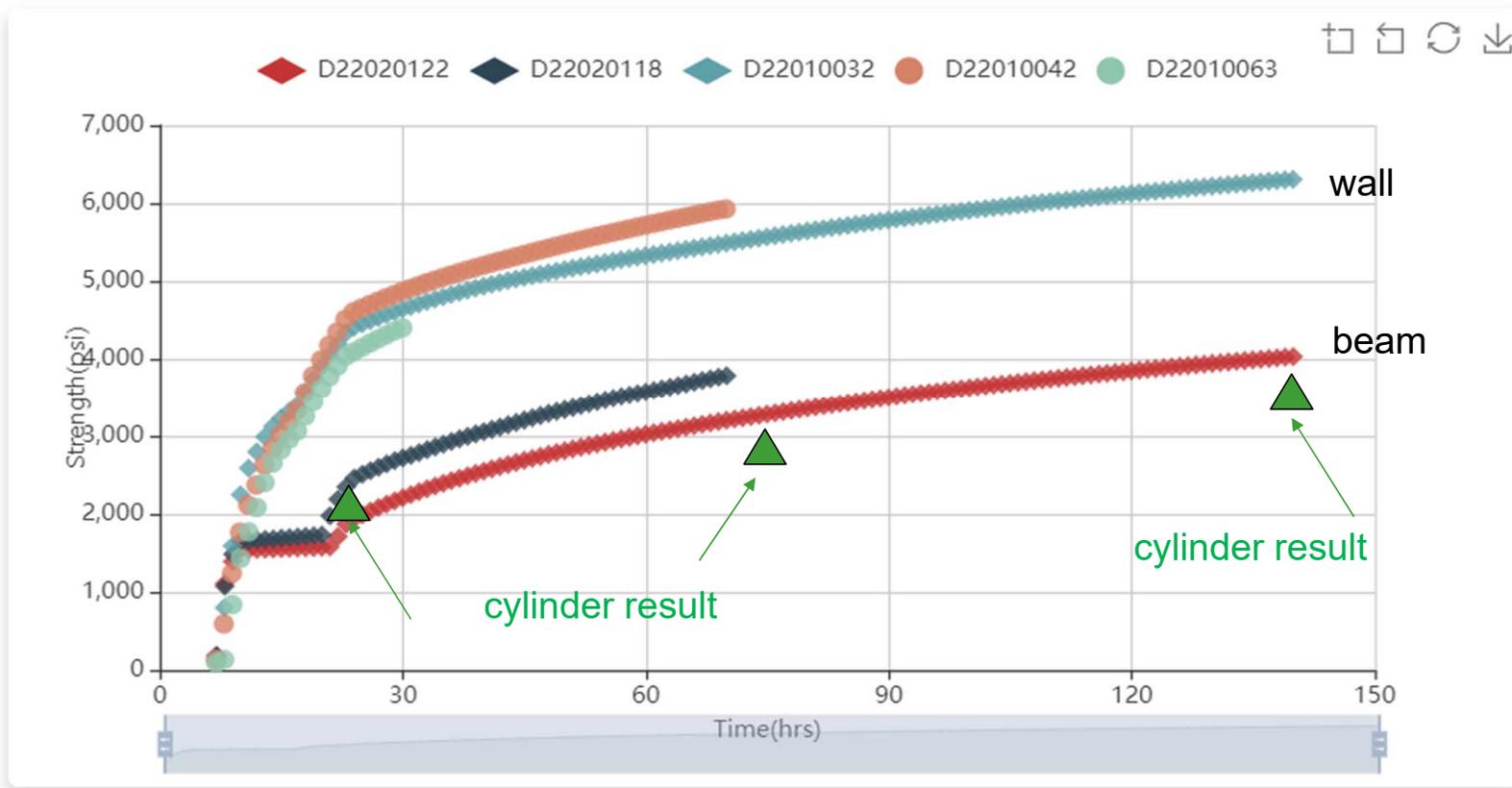


# Tennessee I-40 Bridge Parapet Wall

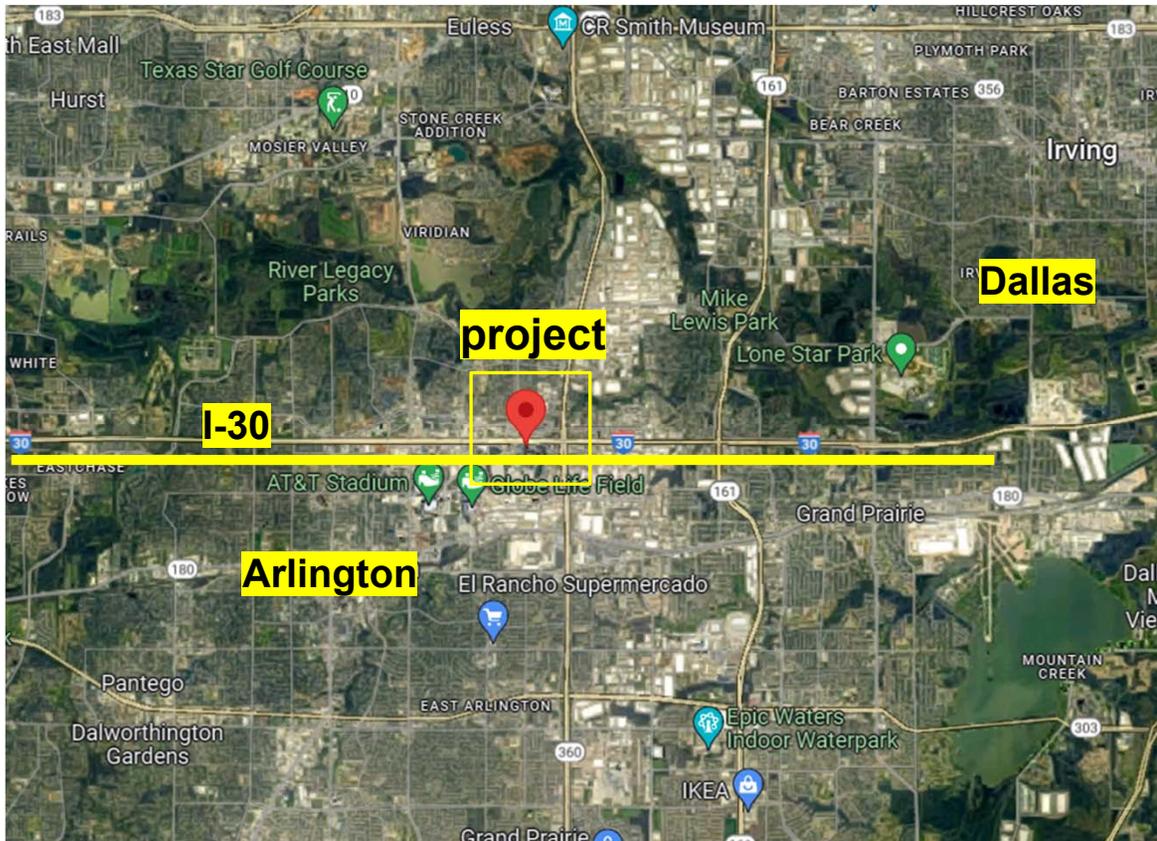


# Tennessee I-40 Bridge Parapet Wall

## Sensing Results vs Cylinder Results

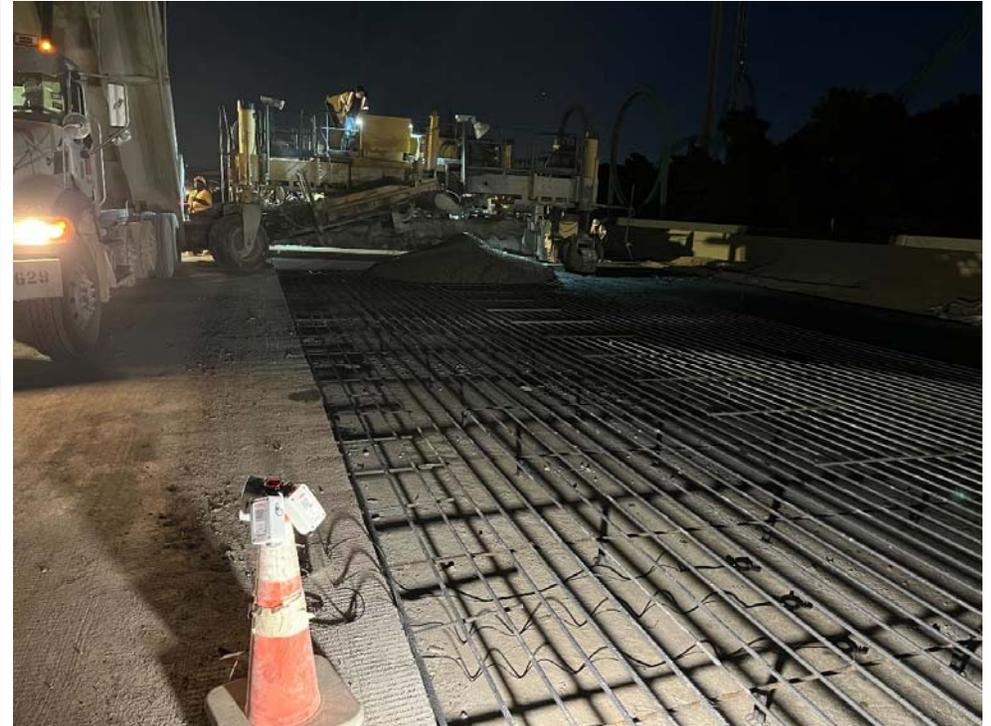


# Texas I-30 Bridge



<b>Date</b>	2023-8-16
<b>Location</b>	Arlington, TX
<b>Coordinate</b>	32°45'34.7"N 97°04'19.0"W
<b>Pavement Thickness</b>	14"
<b>Rebar</b>	8" interval, 7" high
<b>Ingredients</b>	<b>Amount (lbs/yd<sup>3</sup>)</b>
Fine Agg.	1432
Coarse Agg.	1752
Cement	354
Fly Ash	191
Water	237
W-C-Ratio	0.44

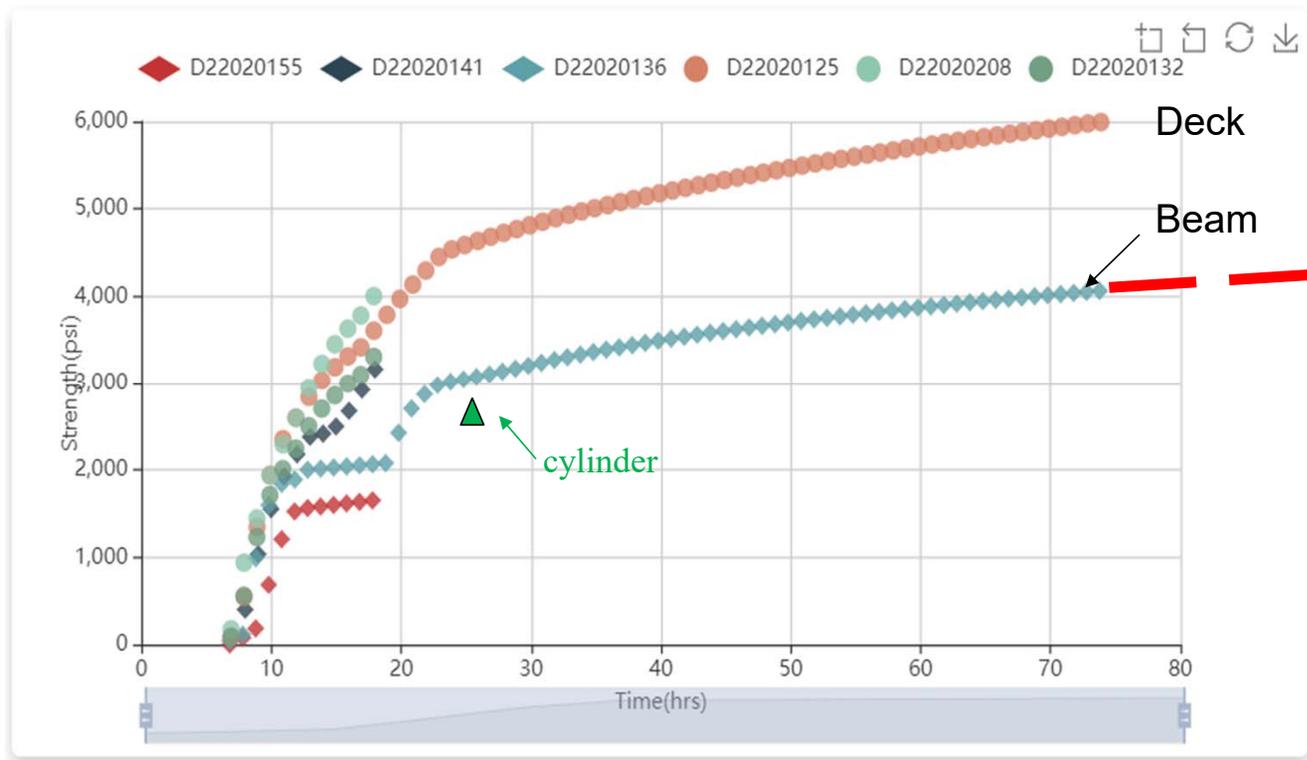
# Texas I-30 Bridge



# Texas I-30 Bridge



# Texas I-30 Bridge

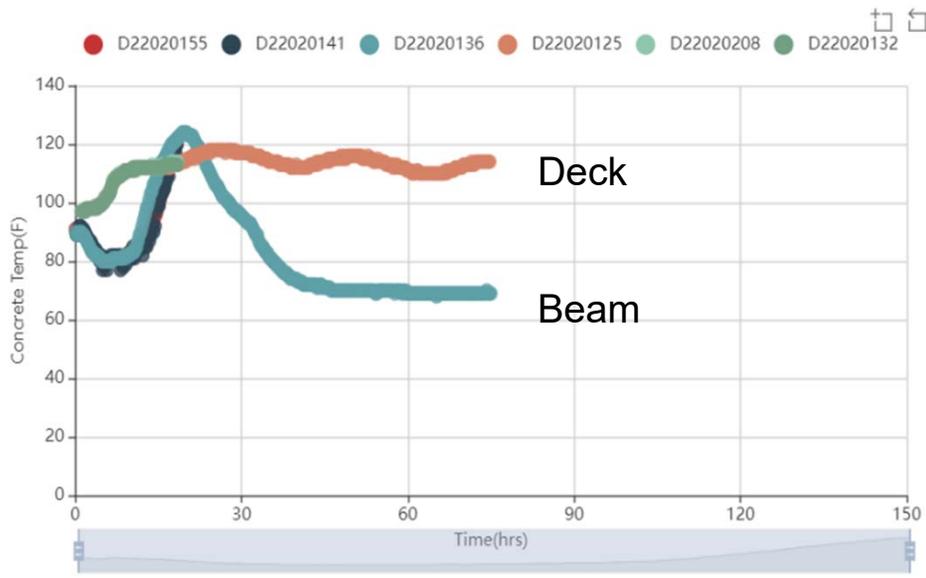


projected

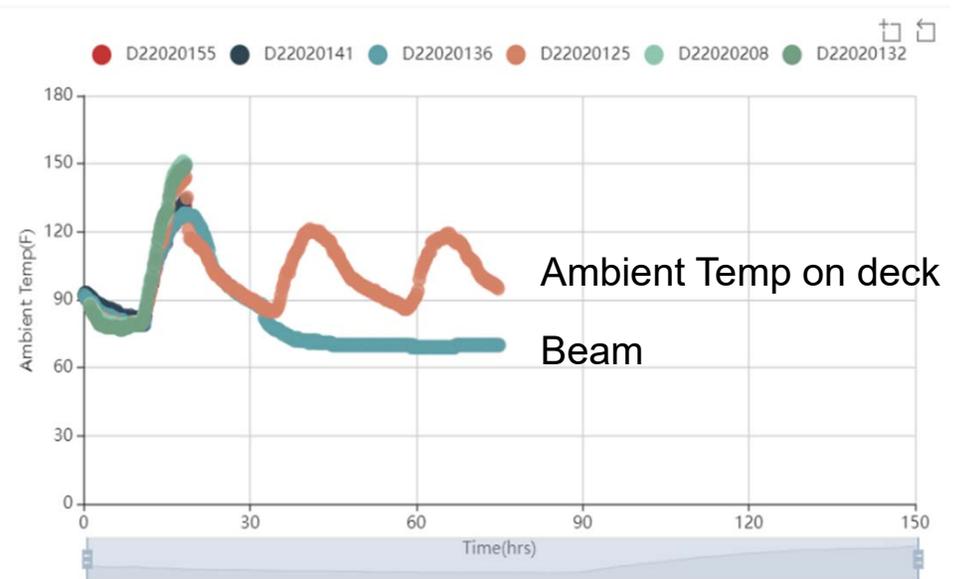
cylinder(5day, 3890 psi)

# Texas I-30 Bridge Curing Temperature

## Concrete Temperature



## Ambient Temperature

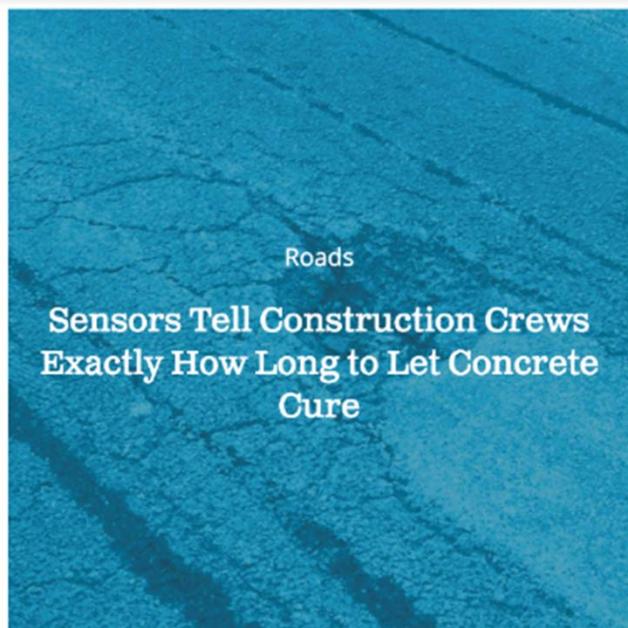


## 3 Patents & 7 Journal Publications

- E. Ghafari, et. Al.. “Evaluating the Compressive Strength of the Cement Paste Blended with Supplementary Cementitious Materials Using a Piezoelectric Based Sensor”. Construction and Building Materials, 171, 504-510, 2018.
- W. Dong, et. al. “Piezoresistive behaviors of cement-based sensor with carbon black subjected to various temperature and water content.” Composites Part B: Engineering, 178, 107488, 2019.
- YF. Su, et. al. “Embeddable Piezoelectric Sensors for Strength Gain Monitoring of Cementitious Materials: The Influence of Coating Materials”. Engineered Science, 11, 66-75, 2020.
- Z. Kong, and N. Lu. “Improved Method to Determine Young’s Modulus for Concrete Cylinder Using Electromechanical Spectrum: Principle and Validation”. Journal of Aerospace Engineering, 33 (6), 04020079, 2020.
- YF. Su, et. al. “Trial Field Implementation of Piezoelectric Sensing Technique for In-place Concrete Evaluation”. ACI Materials Journal. 118-M14, 2021.
- G. Han, et. al. “Mechanism for Using Piezoelectric Sensor to Monitor Strength Gain Process of Cementitious Materials with Temperature Effect”. Journal of Intelligent Material Systems and Structures, 32(10), 1128-1139, 2021.
- G. Han, et. al. “In Situ Rheological Properties Monitoring of Cementitious Materials Through the Piezoelectric Based Electromechanical Impedance (EMI) Approach”. Engineered Science, 16, 259-268. 2021.

# Recognitions and Awards

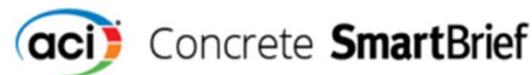
## 2021 REPORT CARD FOR AMERICA'S INFRASTRUCTURE



### Science to reveal how long highway construction should actually take

Ever wonder why your commute or vacation route has a lane closed down for days or even months at a time? It could be because a construction project wrapped up before the concrete was ready to take on heavy truck traffic, causing the pavement to fail too soon and need repairs more frequently throughout the year. Indiana, the "Crossroads of America," is doing something about it: Asking researchers to find out exactly how long it takes for concrete to mature on a highway.

August 29, 2019



News for and about concrete professionals

SIGN UP · FORWARD

### 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.

[EurekaAlert/Purdue University](#) (8/29)



Nation

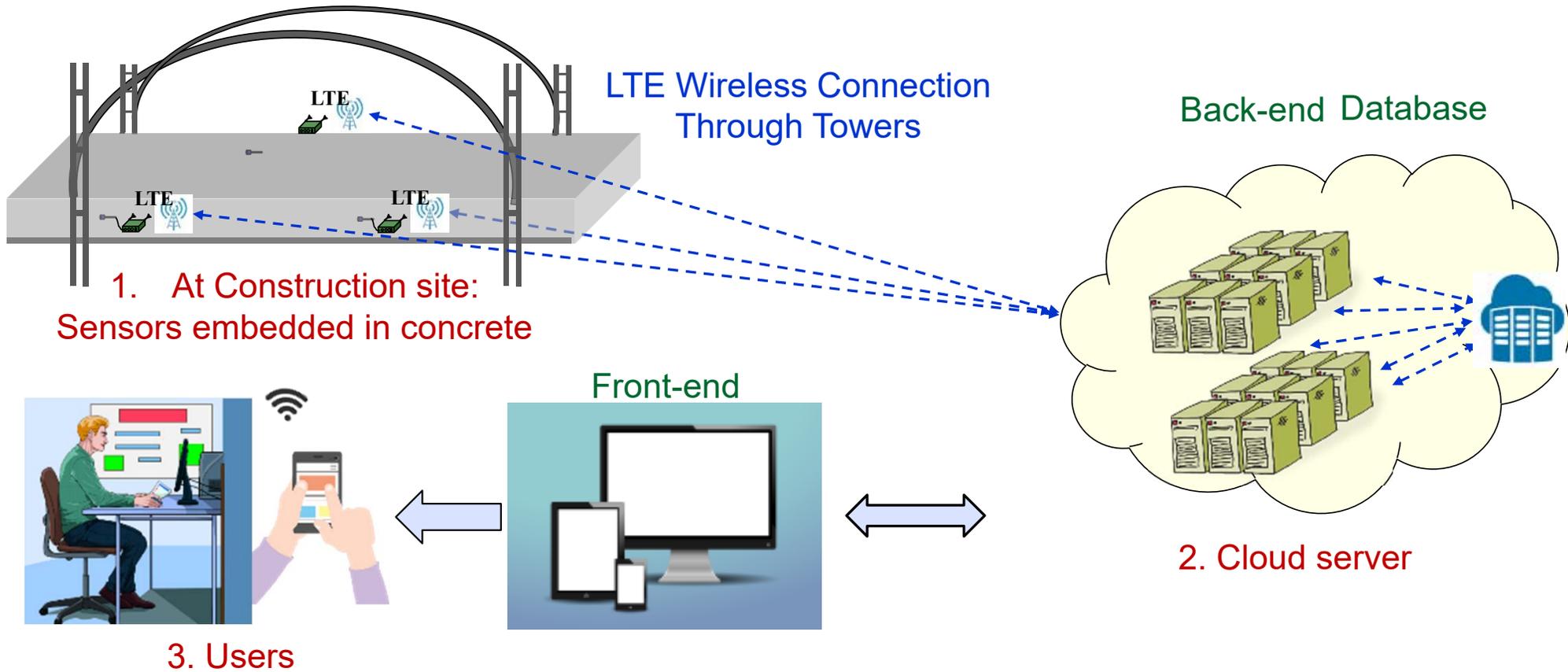
Project Uses Highway Sensors To Track Lifecycle Of Concrete

[editor@aashto.org](#) September 8, 2019 0 COMMENTS

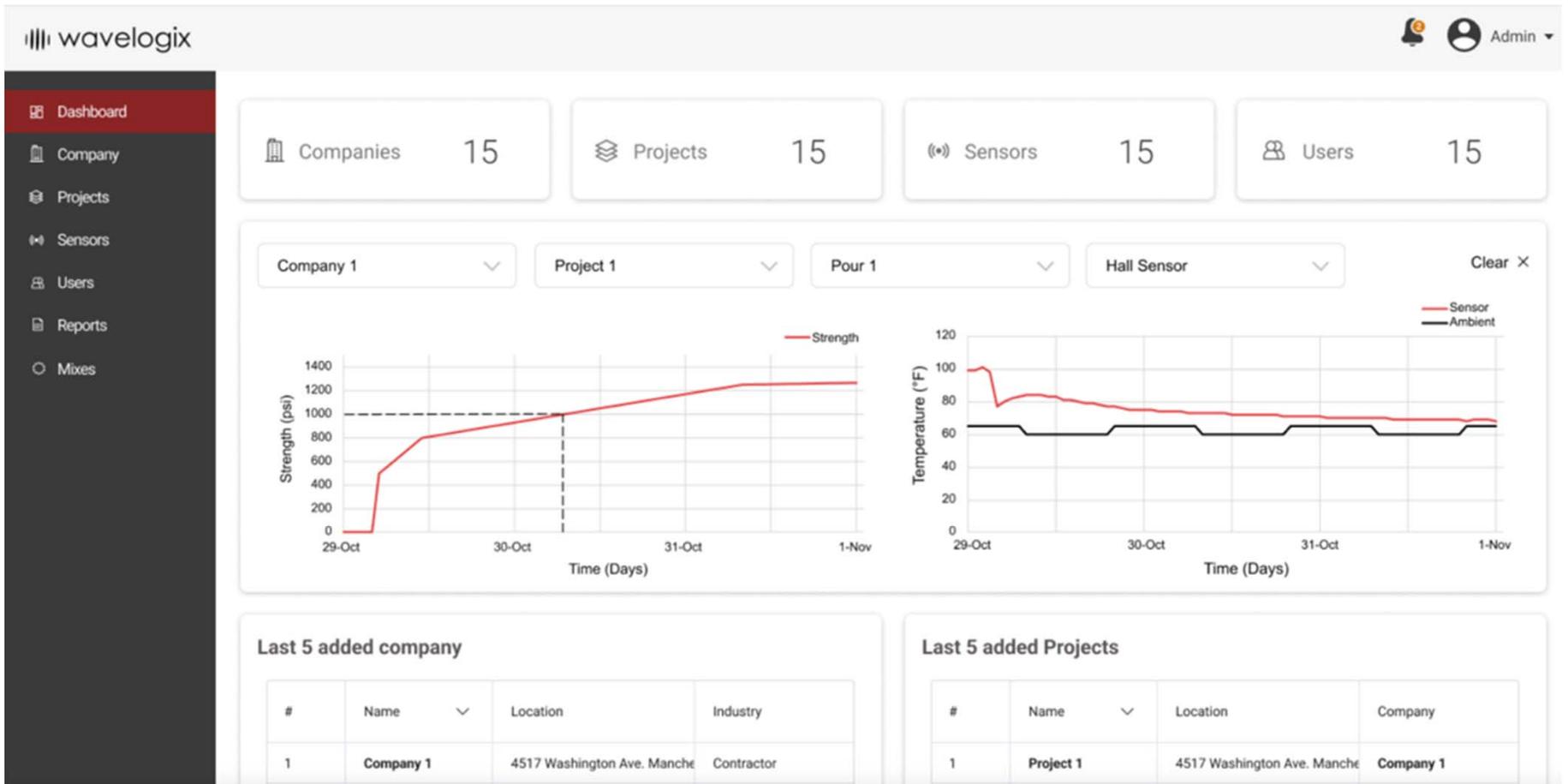
2021 ASCE GameChanger  
2022 ASCE Alfred Noble Prize



# Rebel Sensor IoT Platform



# Dashboard and User Interface



# Learn More



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SMART INFRASTRUCTURE SOLUTIONS

Improving the quality and safety of the world's infrastructure while optimizing the performance and efficiency of those who build it.

An **ASCE**  
GameChanger

WINNER OF 2021  
**ASCE**  
AMERICAN SOCIETY OF CIVIL ENGINEERS  
#GAMECHANGERS

[www.wavelogix.tech](http://www.wavelogix.tech)



# REBEL Sensor

Real-time concrete monitoring without maturity curve



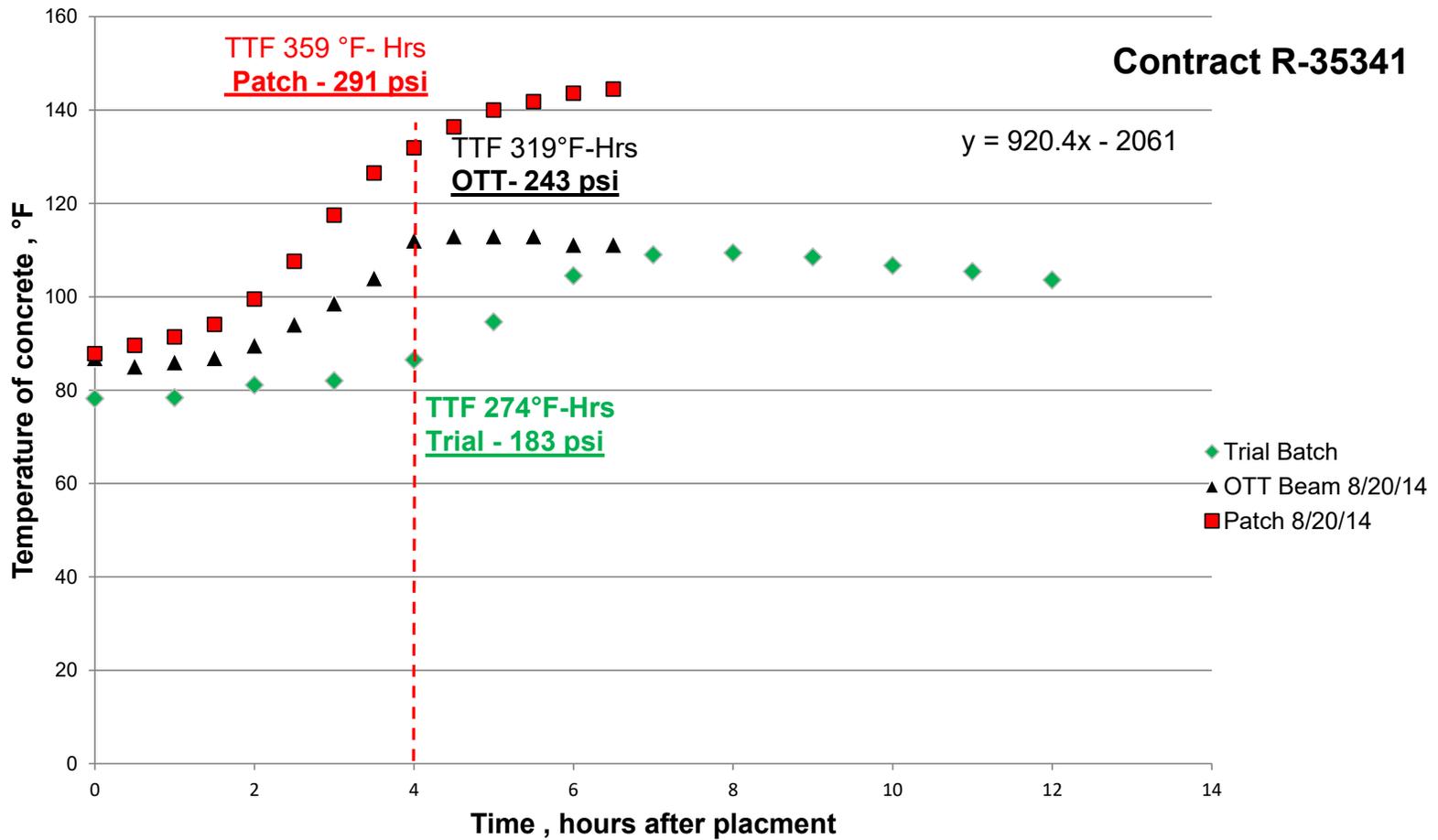
Luna Lu

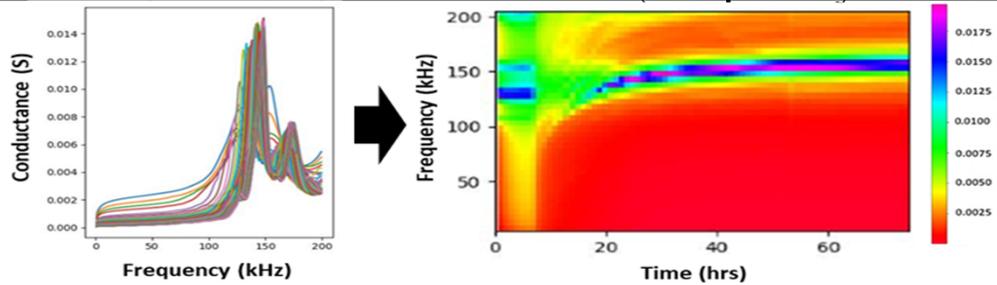
Founder & CEO of Wavelogix, Inc.

Reilly Professor of Civil Engineering, Purdue University

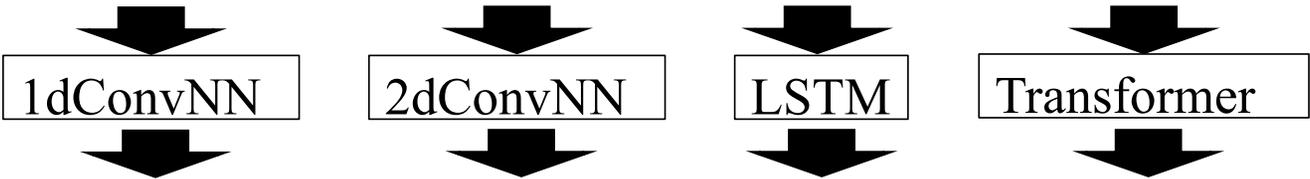


# INDOT Experience with Maturity

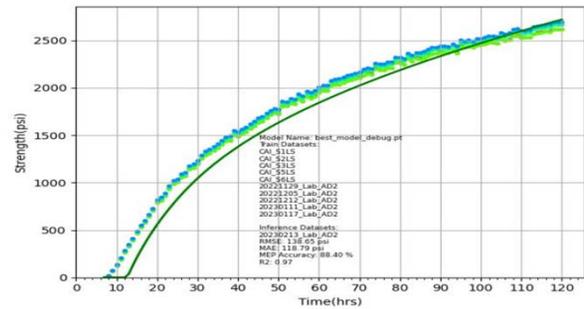




Machine Learning Models



Concrete Strength Prediction



# Compression Testing Comparison

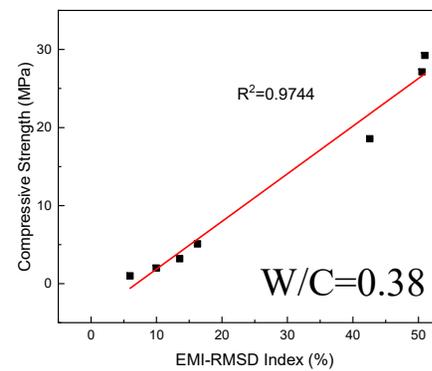
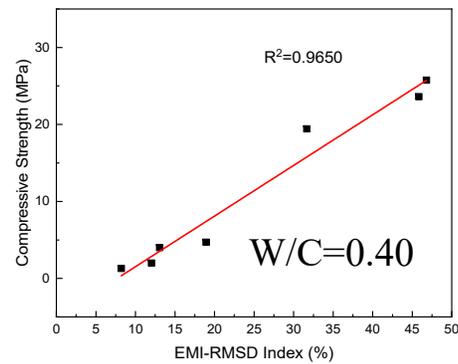
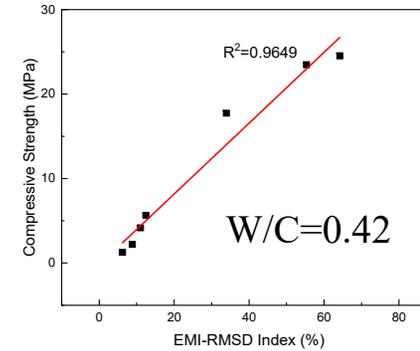
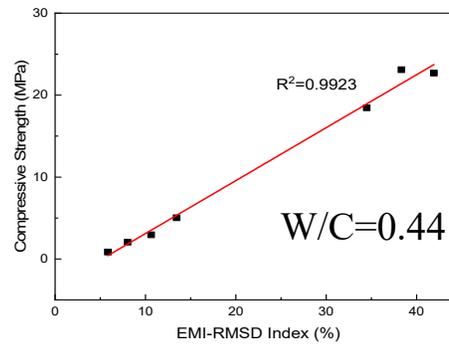
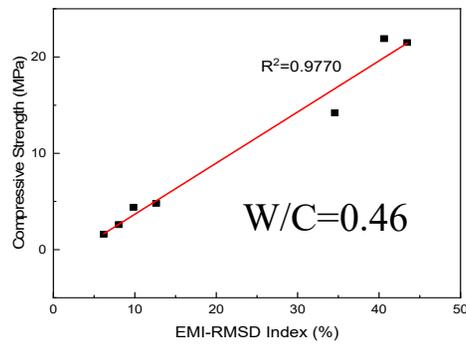
Overall, the sensed strength value has 95% accuracy compared to traditional mechanical compression test.



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%

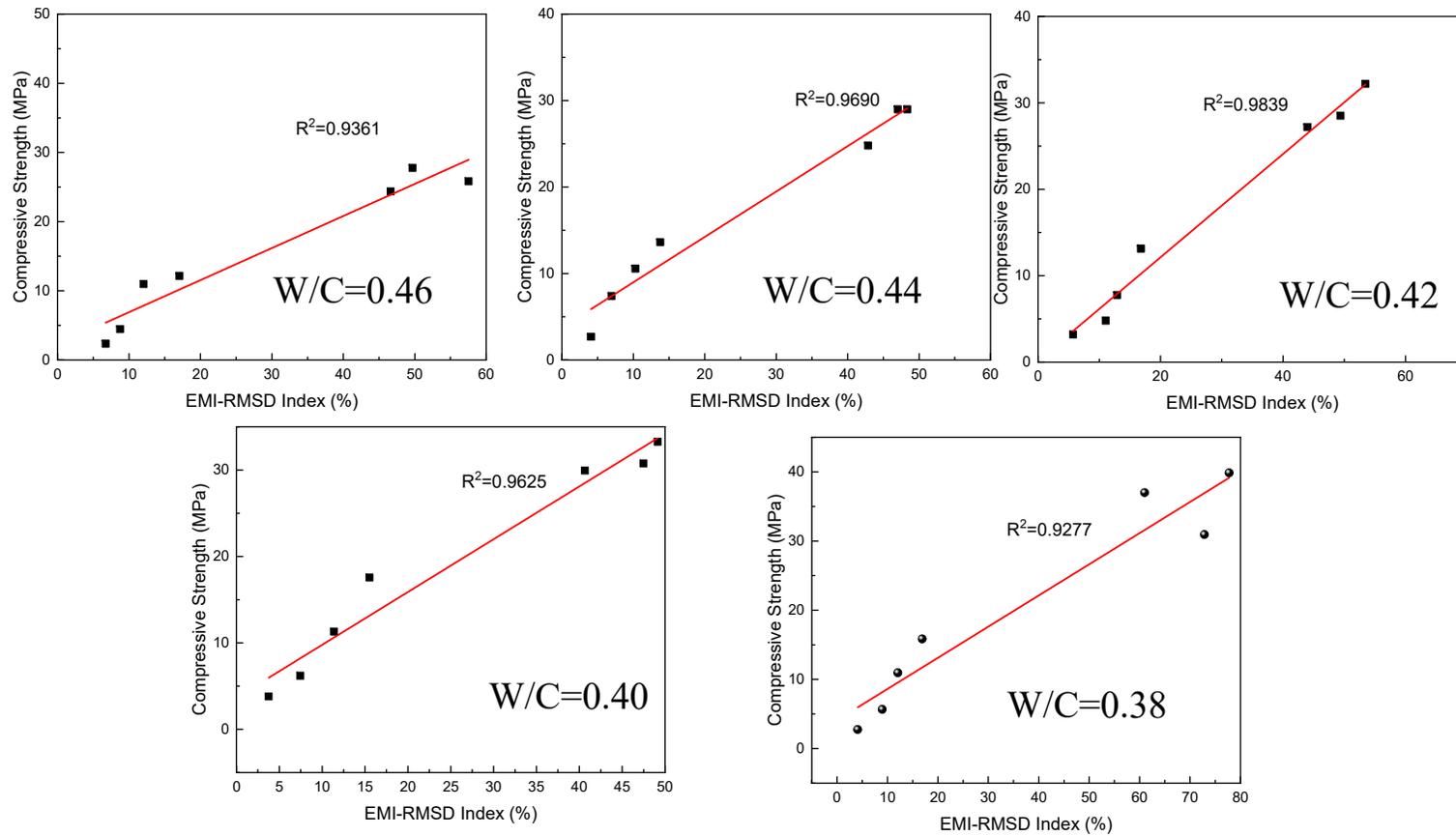
Z. Kong et. al *Journal of Aerospace Engineering*, 33, 04020079, 2020

# Type I cement



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

# Type III cement



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