REBEL Sensor

Real-time concrete monitoring without maturity curve

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I-65: When should we open to traffic?

strength determines construction schedule and payment

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

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California study on cylinder consistency

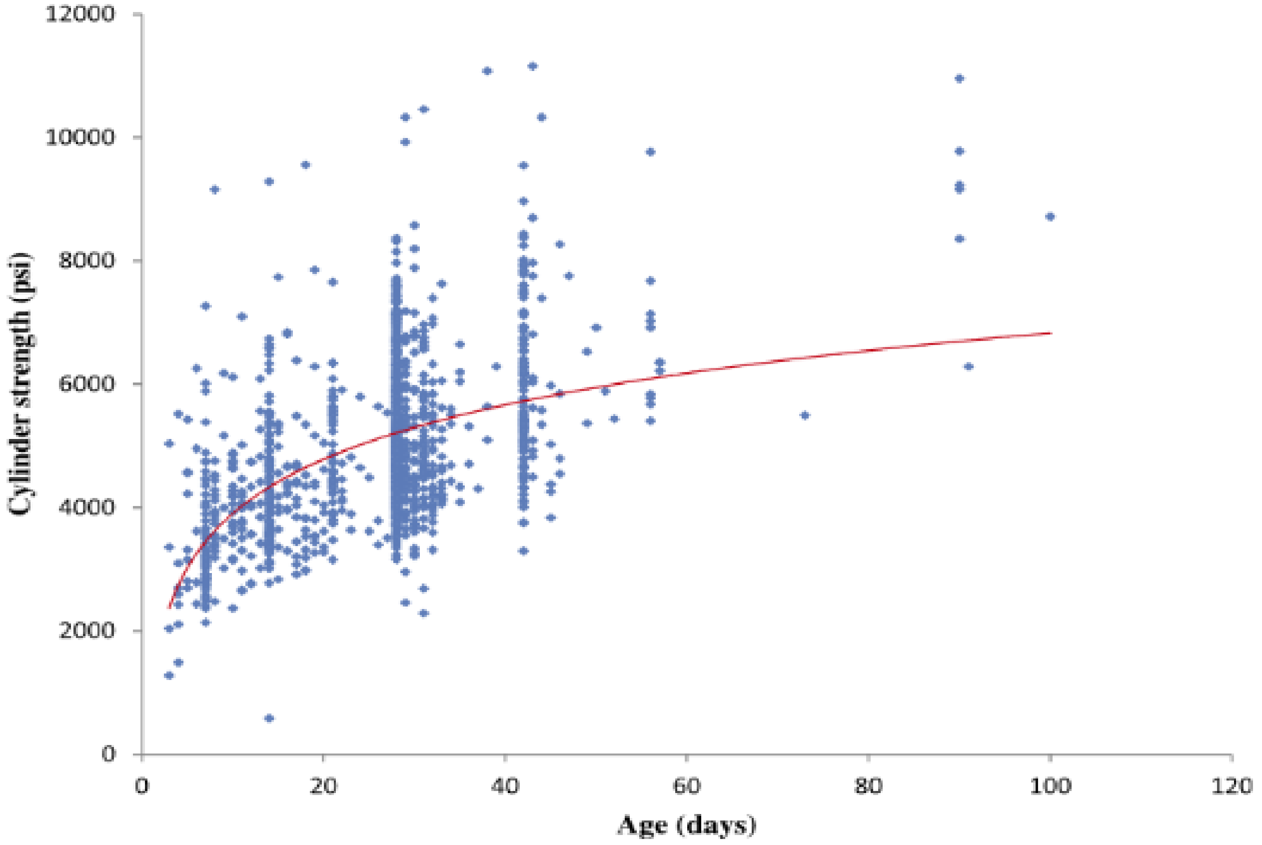

Fig. 1. Variation of concrete strength with age for $f_c' = 25$ MPa (3,600 psi) (note: 1 psi = 6.894757 kPa)

- No surprise to anyone
- Critical decisions at the wrong time
- Or delays in production schedules
- Or worse problems with payment
- Causing industry to over cement by as much as 20%
  - Resulting in higher cost (+ $10/CY)
  - Higher carbon footprint
  - Weaker concrete

Unanwa, Christian, and Mark Mahan. “Statistical Analysis of Concrete Compressive Strengths for California Highway Bridges.” *Journal of Performance of Constructed Facilities* 28, no. 1 (February 2014): 157–67. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000404.

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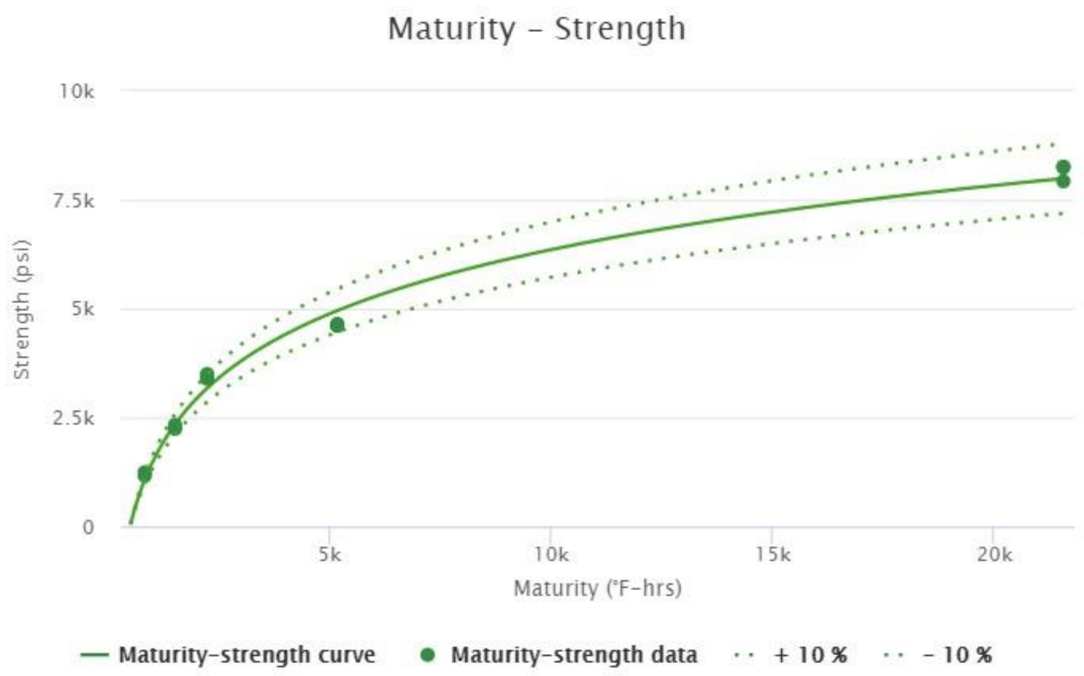
Maturity Testing

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

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



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

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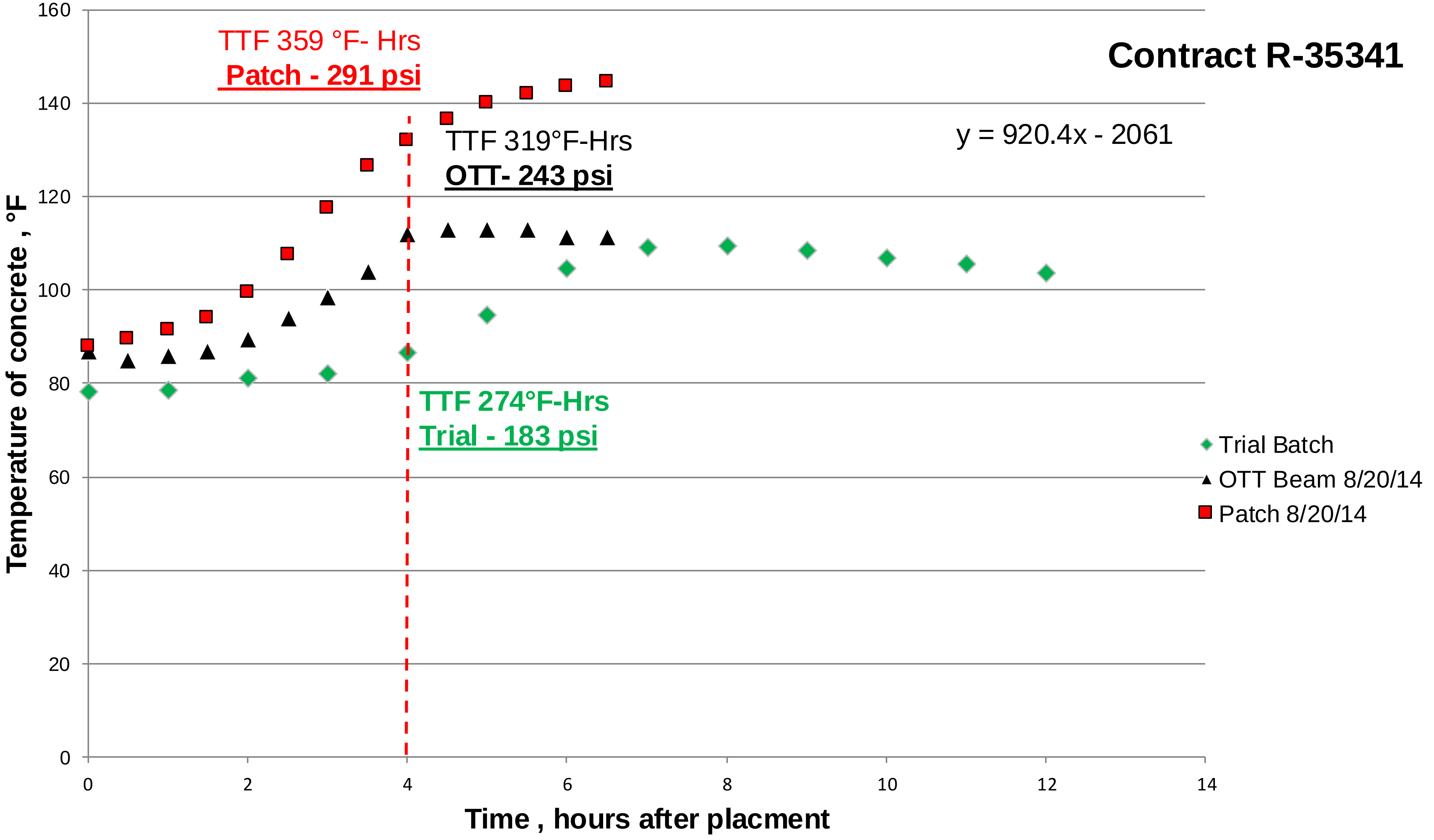
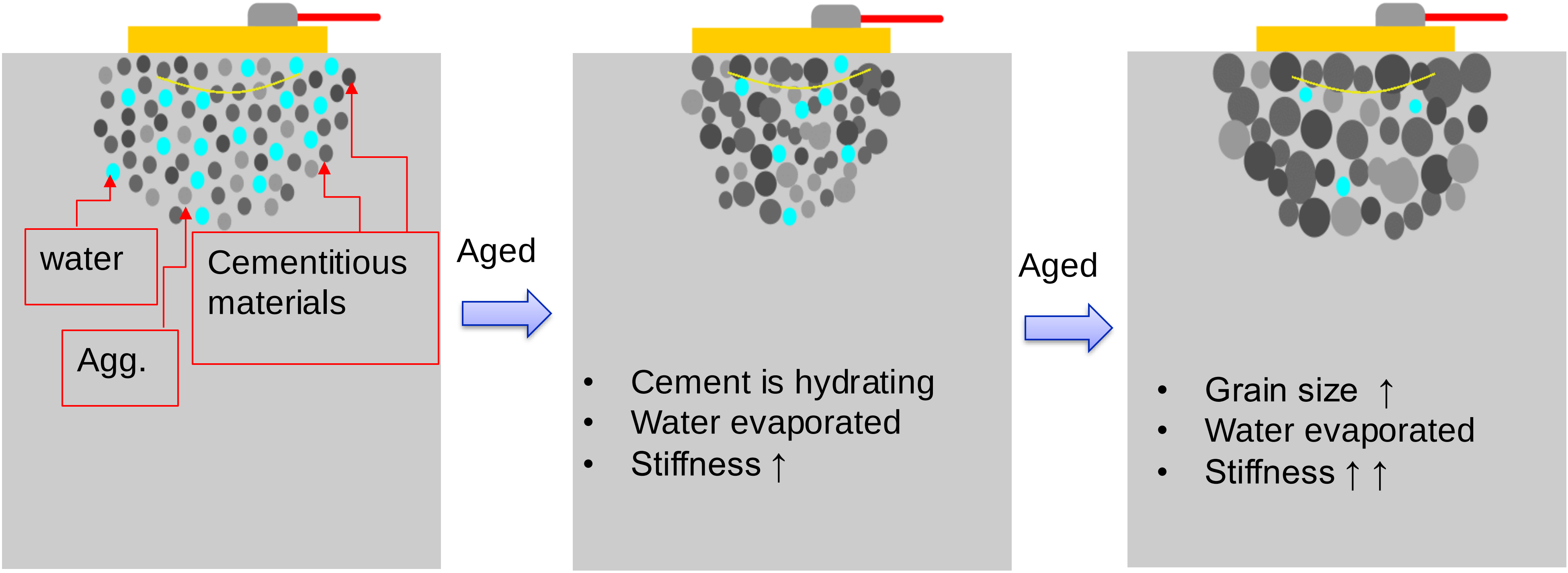
INDOT Experience with Maturity



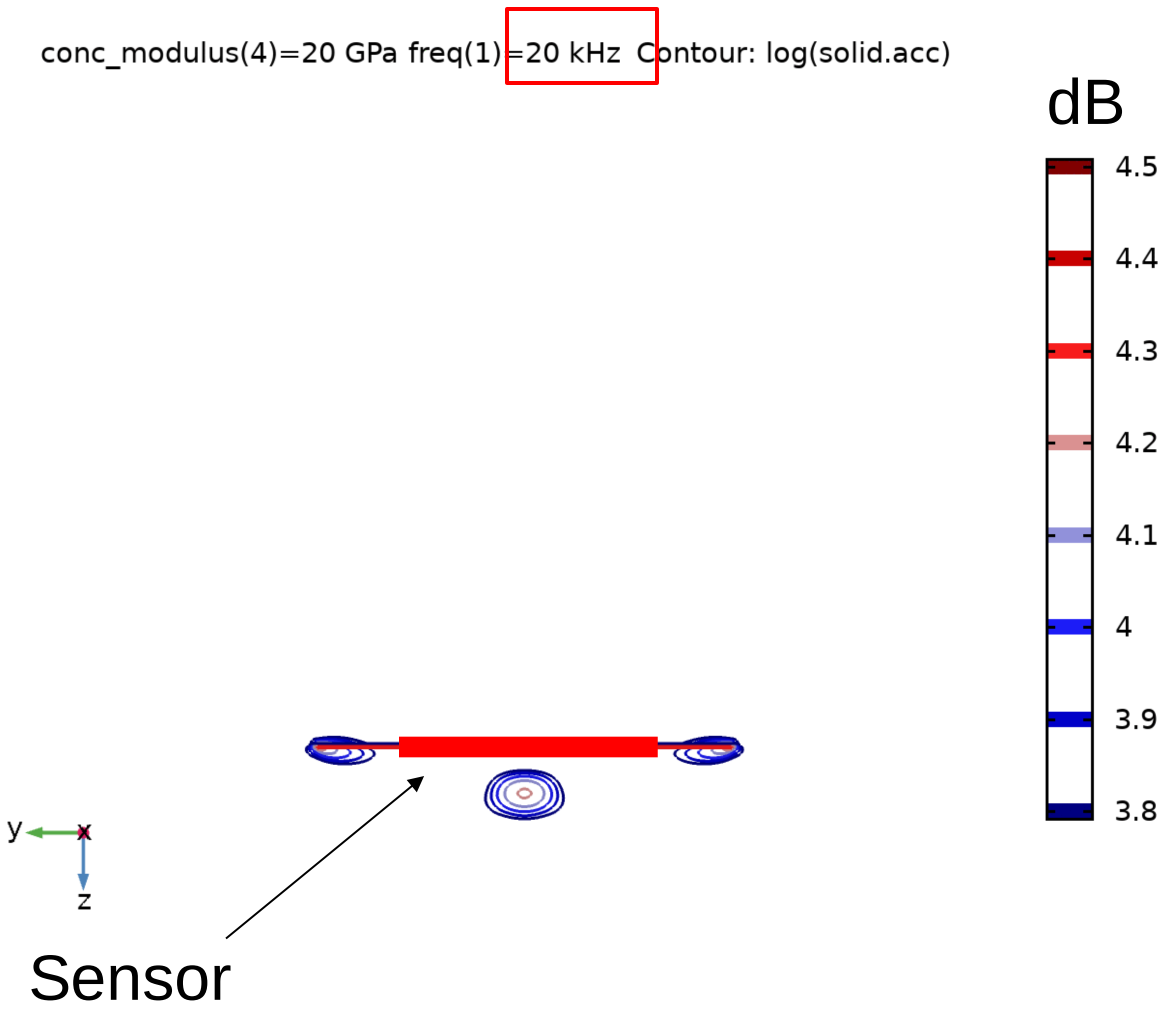
Our Solution – Direct Mechanical Measurements Using Piezoelectric Sensor

Piezo-sensor for Concrete Strength Monitoring

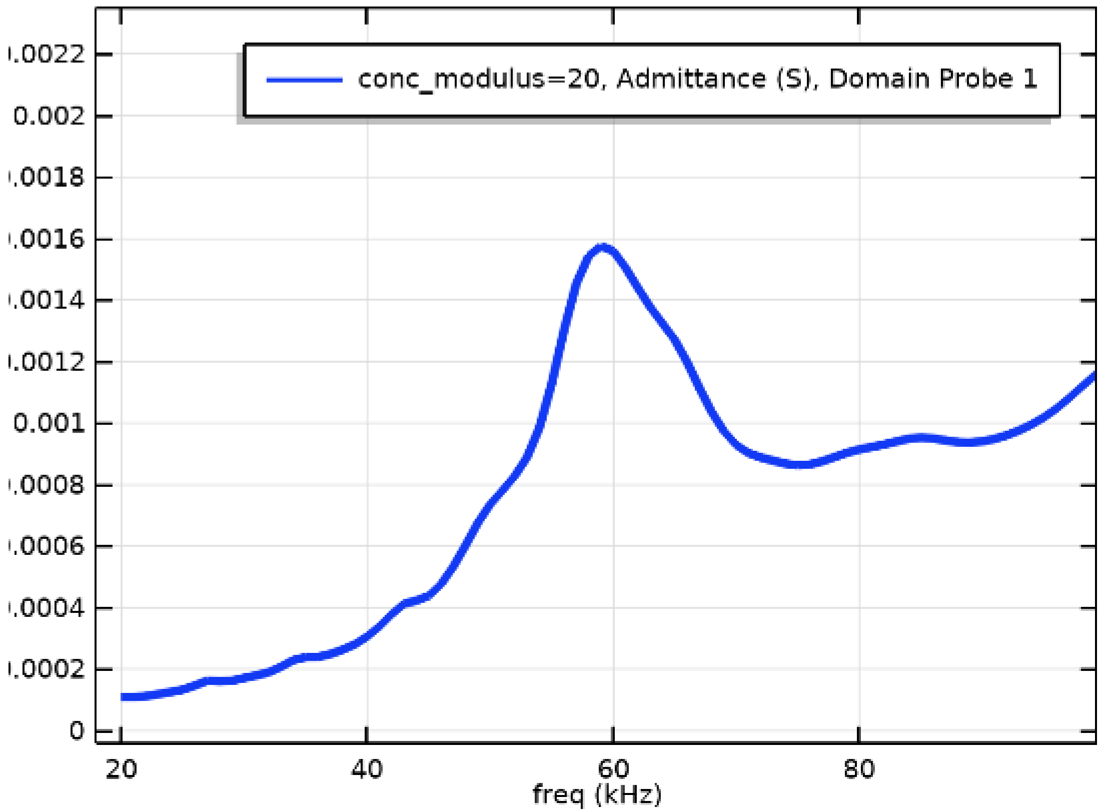


Using piezoelectric sensor to understand the concrete stiffness and strength through electromechanical coupling effect.

Piezoelectric Resonance Sensor



Dynamic modulus= 20 GPa



Wave field behavior vs. wave frequency emitted by the sensor

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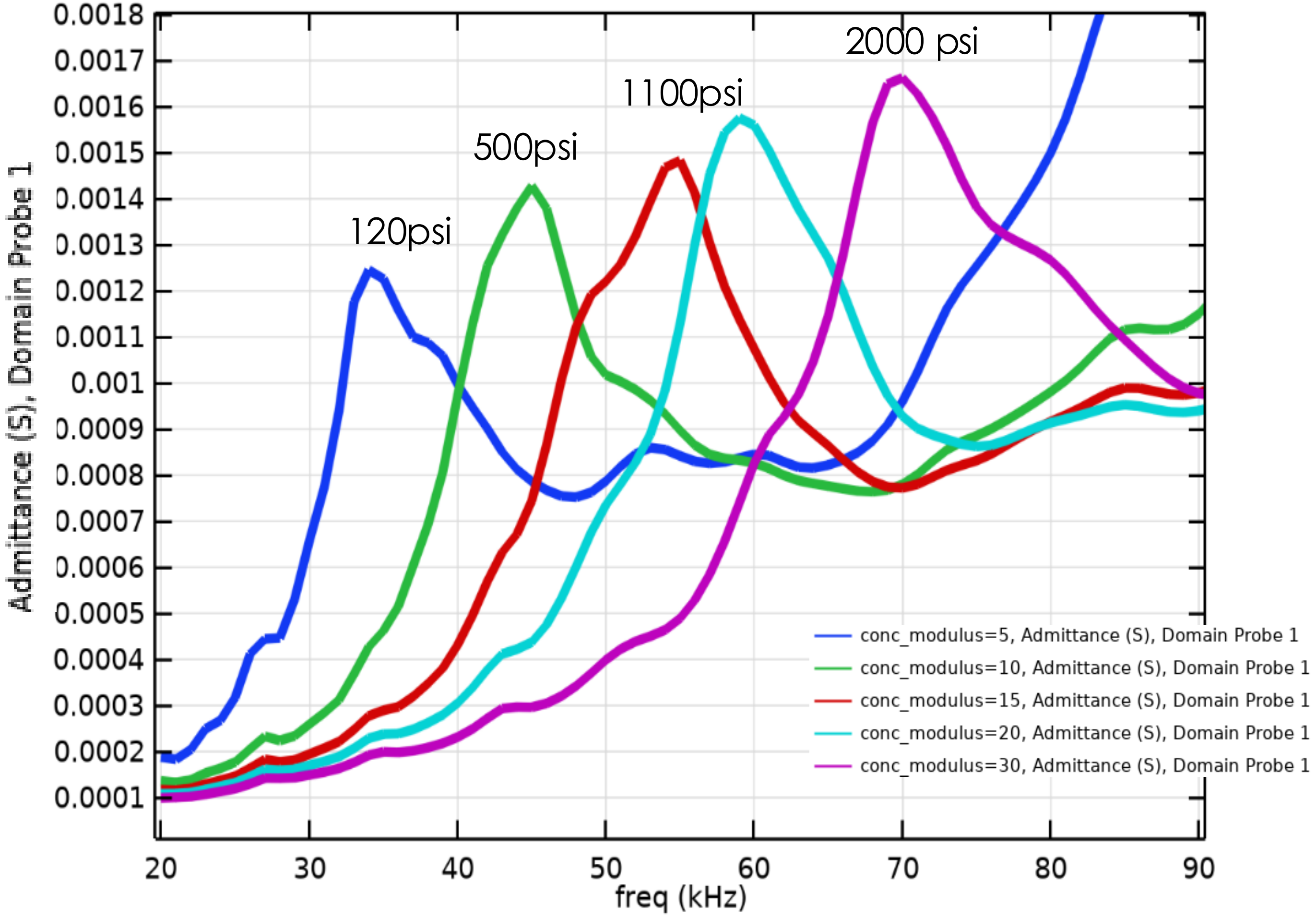
AASHTO T 412 standard



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

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

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

AASHTO T412- 24, TS 3c

Z. Kong, and N. Lu, *Journal of Aerospace Engineering* 33, no. 6, 2020

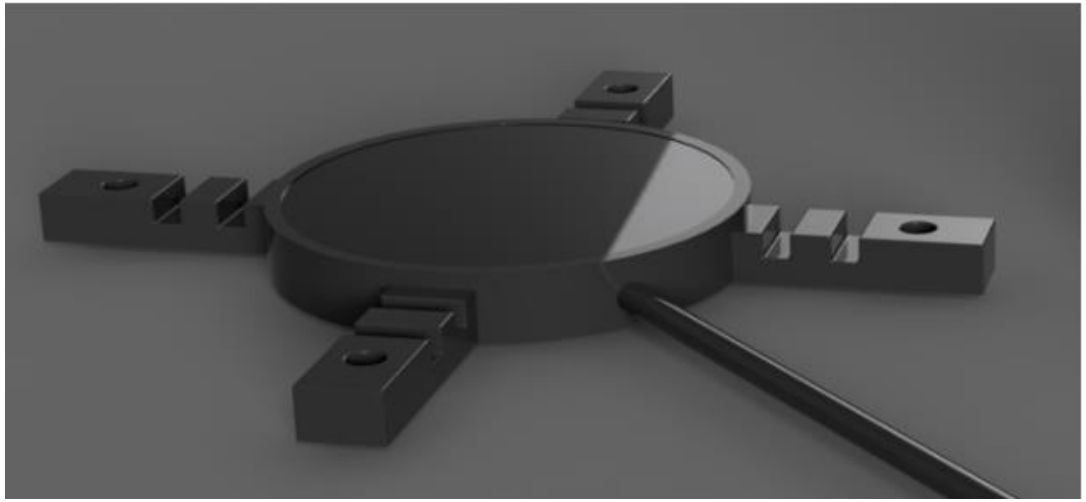
What is the REBEL Sensor System?

- Miniaturized IoT Hardware for
  - Data collection and Computational Transmission

- AI-guided algorithm for
  - Concrete strength measurement Concrete strength prediction

Concrete Strength Sensor

Inside: Piezo wave generator and temperature probe



Data Logger

Inside:
- Impedance meter
- GPS location chip
- Cellular radio
- LiIon Battery (28 day capacity)
- Wireless recharging with a cradle charger
- Sealed case that can work under water
- Durable housing to withstand environmental pressures

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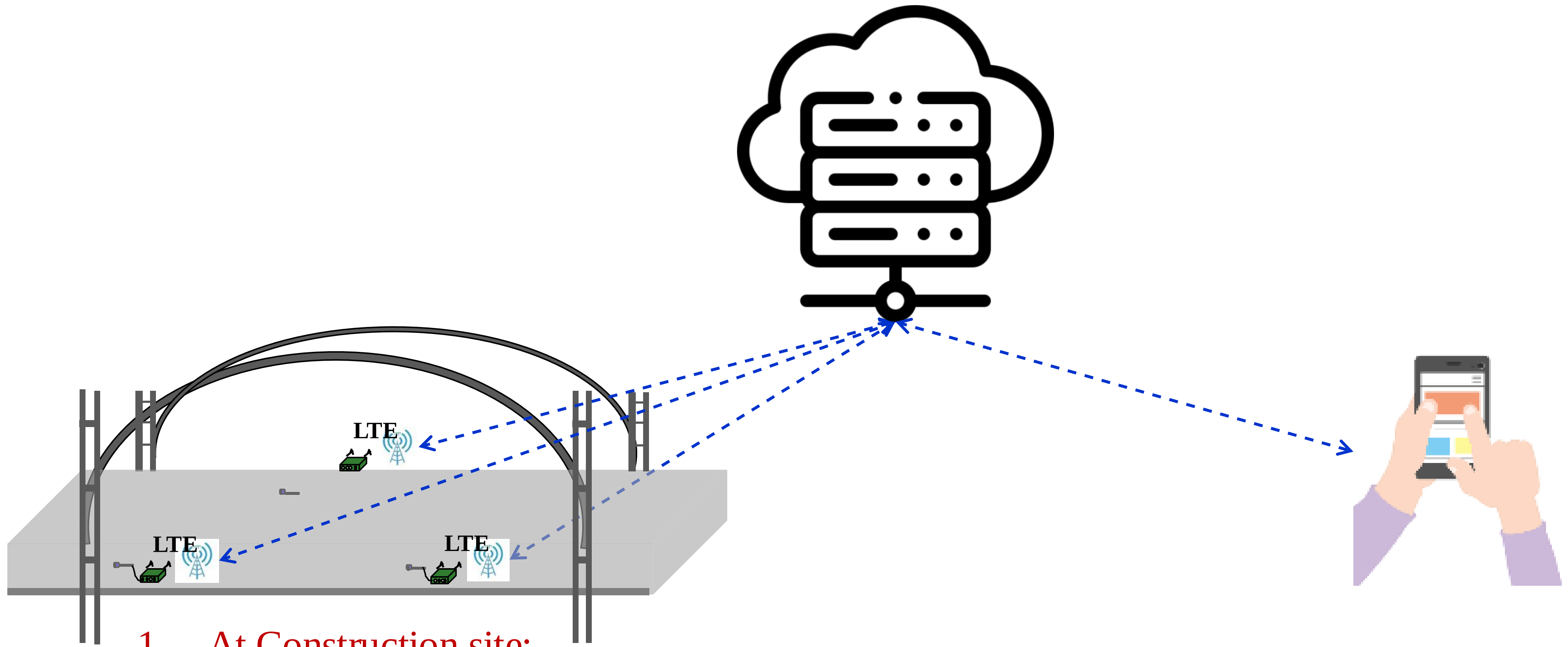
Product – End to End IoT Solution

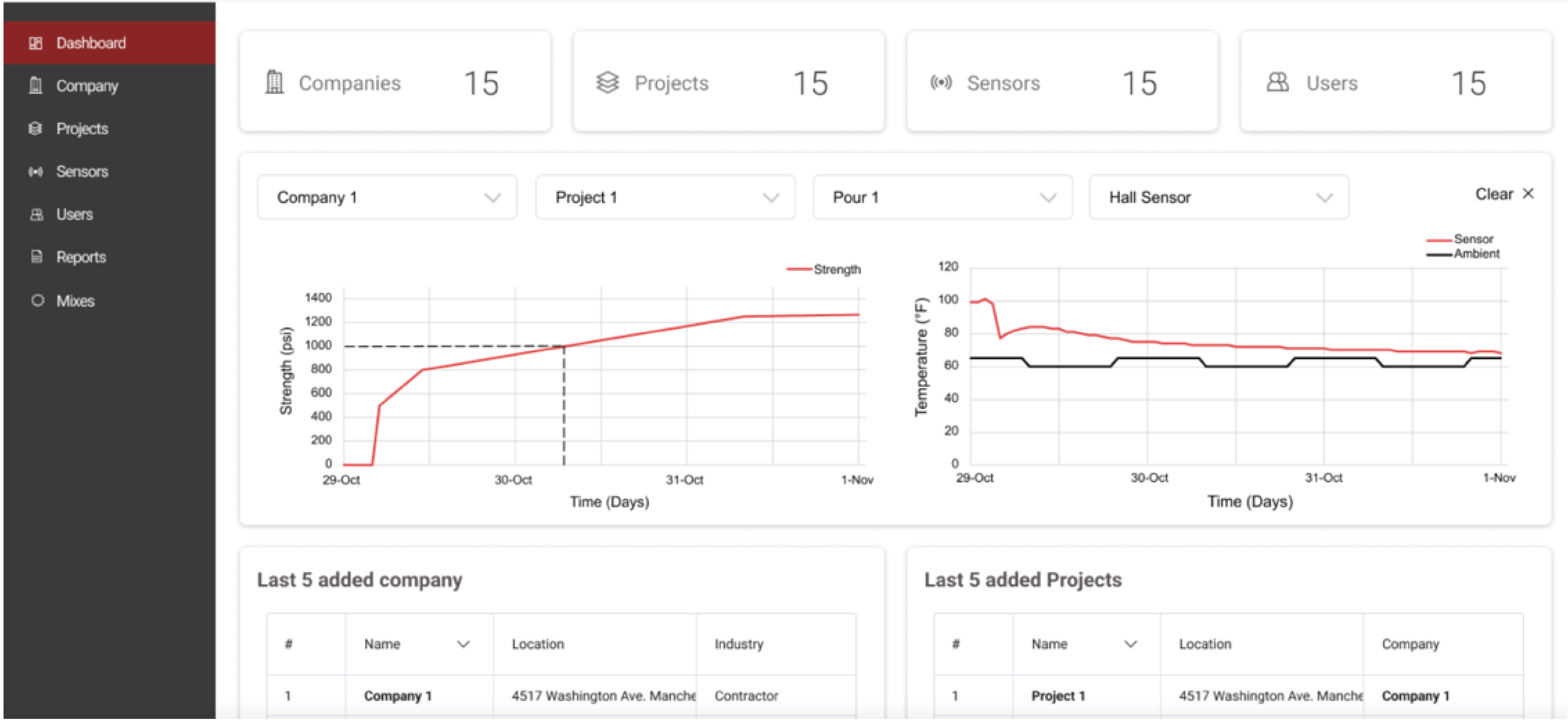


1. At Construction site: Sensors embedded in concrete

2. Cloud server

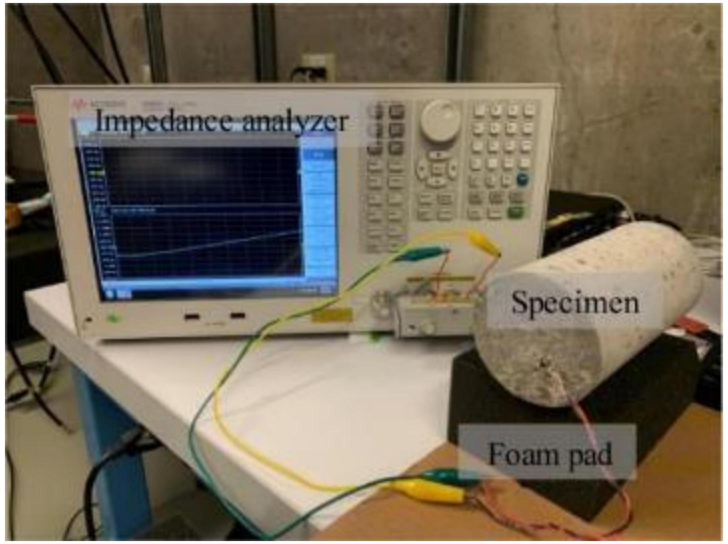
3. Mobile App Interface

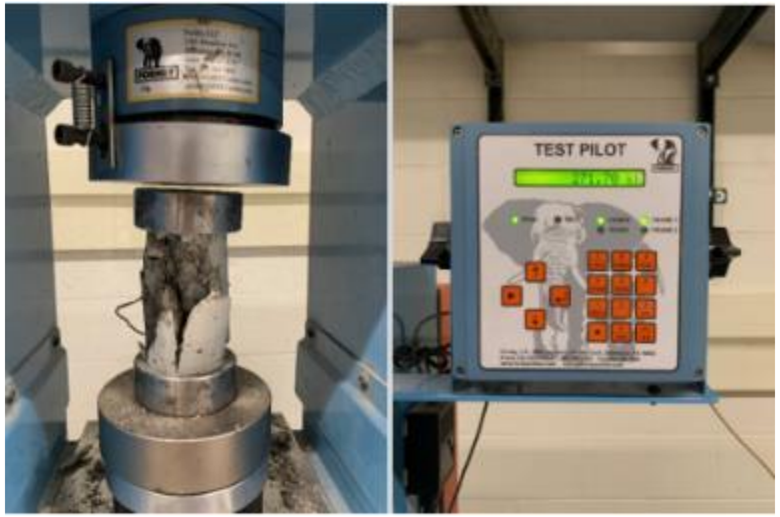
Dashboard and User Interface



Compression Testing Comparison

No calibration is needed, direct measurement





Sensed strength 8847 psi

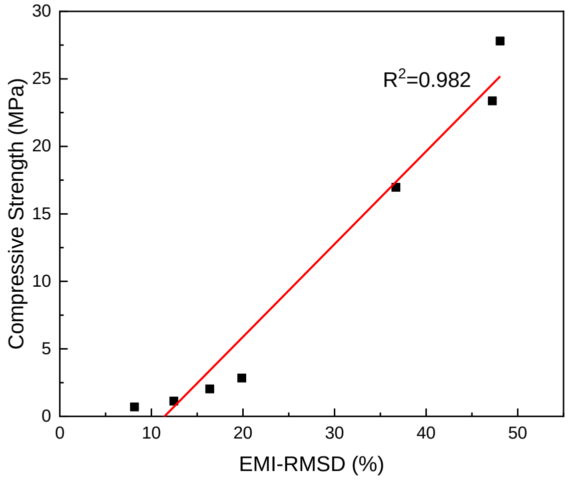
Tested strength 8784 psi

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

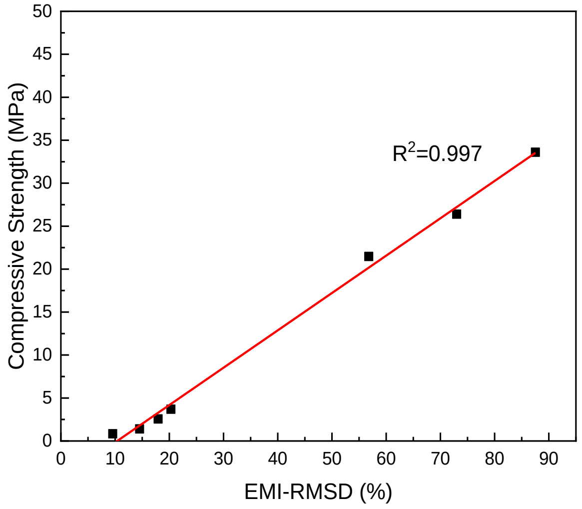
Z. Kong et. al Journal of Aerospace Engineering, 33, 04020079, 2020

Sensor Performance with Various SCMs

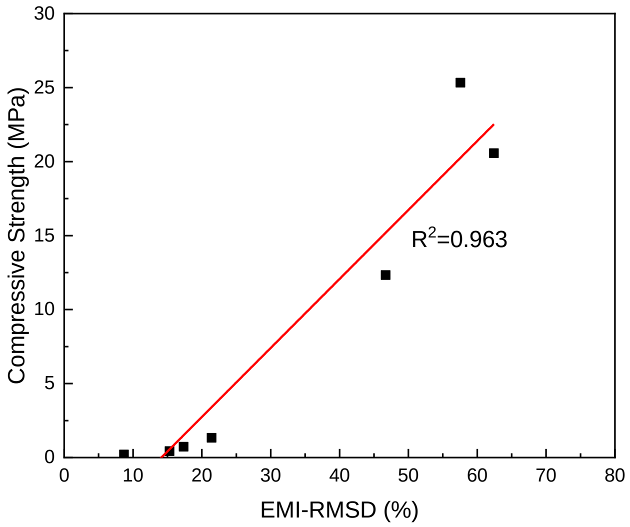
Slag 15%



Silica Fume 15%



Fly Ash 15%



R^2 value are above 0.96 , high accuracy

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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%

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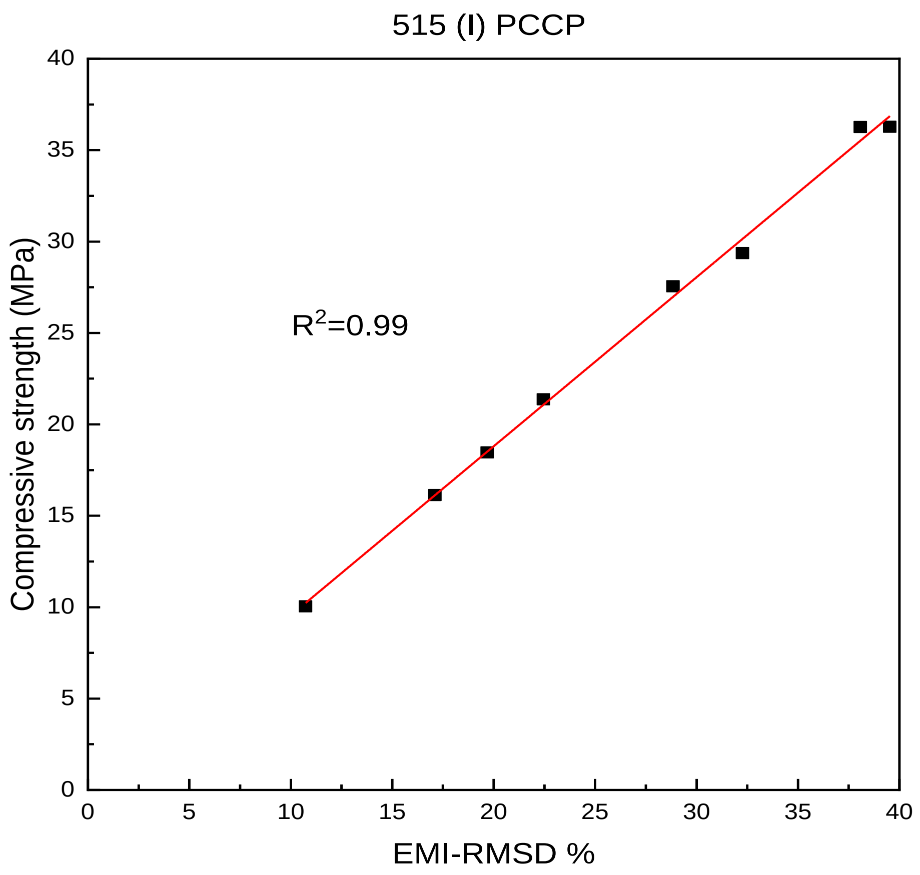
Testing Result for 10 Different PCCP Mixes

- 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

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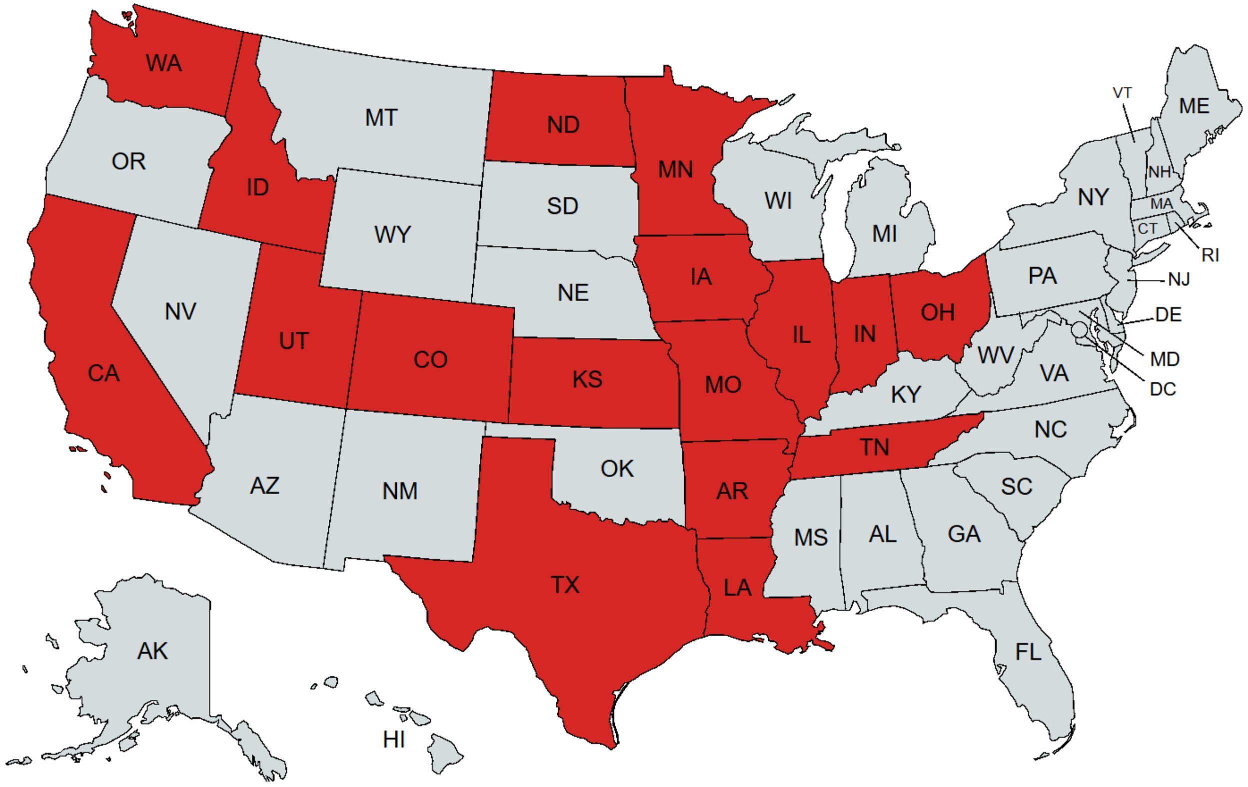
Usage of the Concrete Strength Sensor as of Oct 2024

- Wavelogix conducted testing in ***17 states*** throughout July 2023 to October 2024.
- REBEL Sensors were deployed ***over 60 projects.***
- Applications included pavement, bridge deck, and road repair.



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Nationwide Field Testing


Garrett, IN


Tennessee


Missouri


Indy


Kansas


Colorado

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Usage of the Concrete Strength Sensor as of Oct 2024

- A wide variety of mix designs were covered in the trials:
  - Water-to-cement ratio range of 0.32 to 0.55
  - Cement amount ranges from 360 lbs/CY to 800 lbs/CY
  - Cement replacement up to 35% with Supplementary Cementicious Material (SCM), such as slag, fly ash, silica fume, and natural pozzolan.
  - Fine-to-Coarse aggregate ratio ranges from 0.60 to 0.79.
  - Type IL cement used for all DOT projects

Testing Setup

Drop on Roadbed

Strap to Rebar

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Indiana I-69 Paving

Date	2023-7-25
Location	Indianapolis, IN
Pavement Thickness	11”
Rebar	#6 (0.75”)

Ingredients	**Amount (/yd³)**
Fine Agg.	1268 lbs
Coarse Agg.	1830 lbs
Cement	425 lbs
Slag	145 lbs
Water	233.7 lbs
W-C-Ratio	0.410

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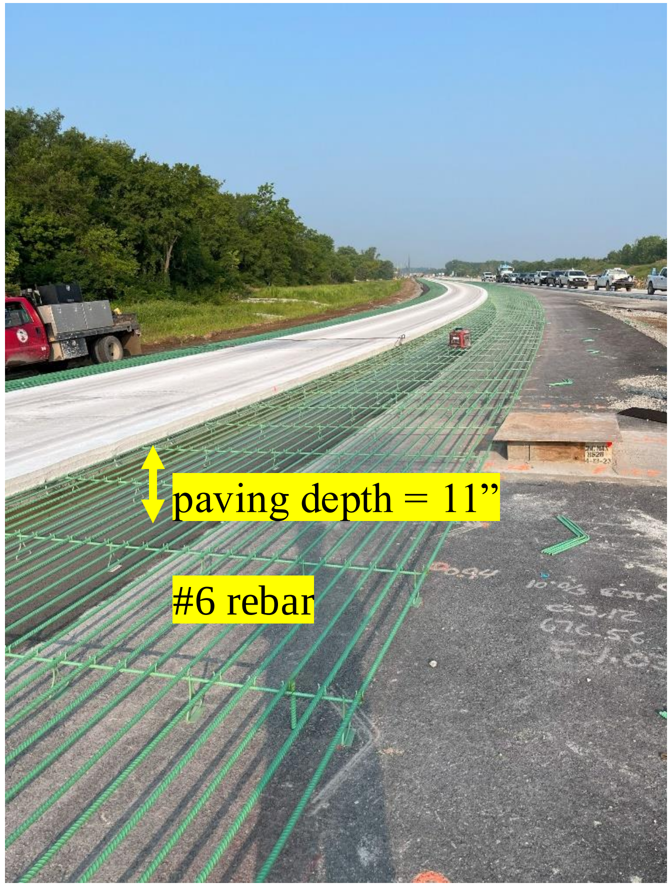
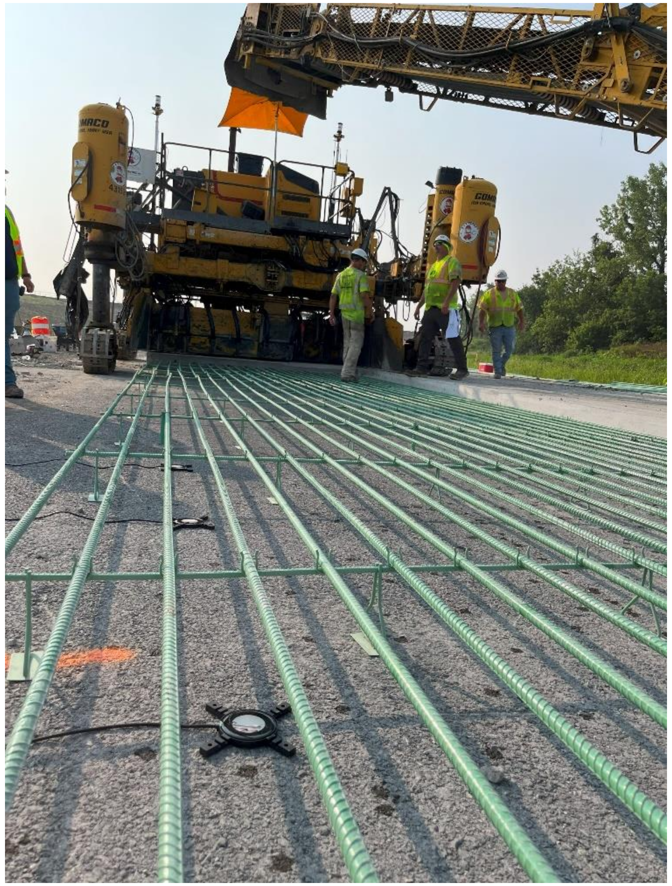
Indiana I-69 Paving





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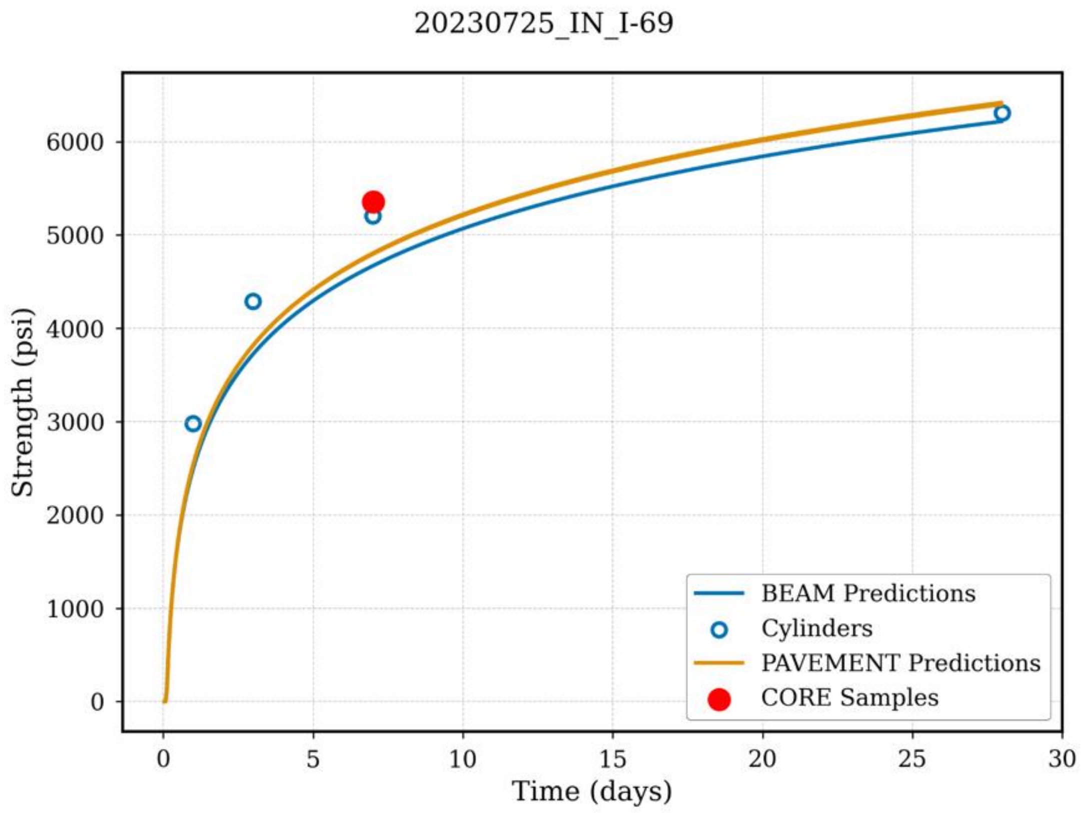
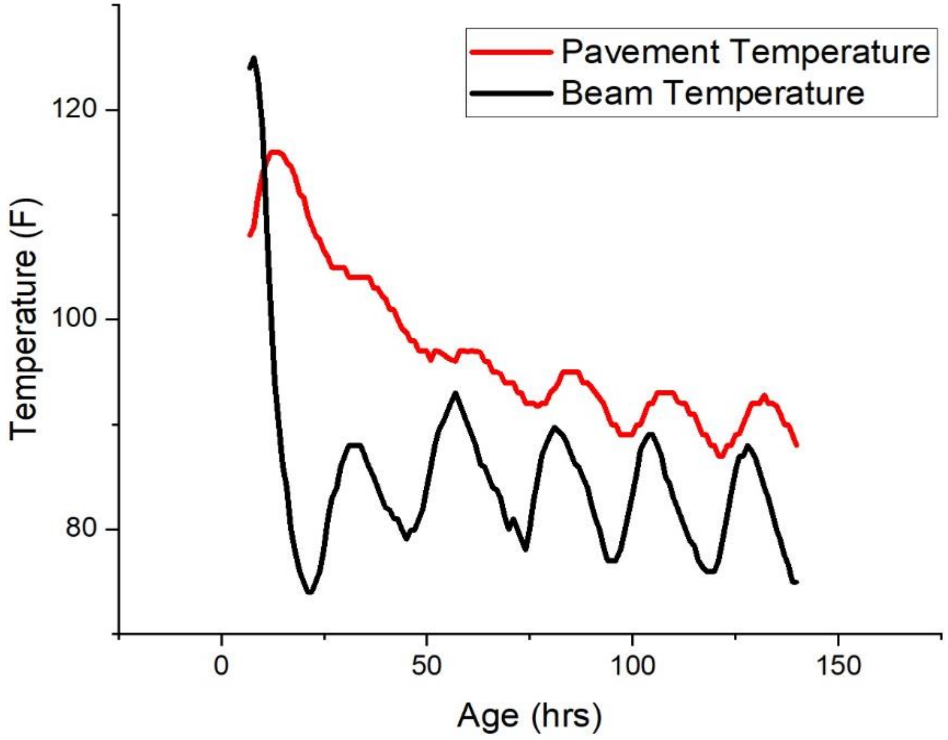
Indiana I-69 Paving

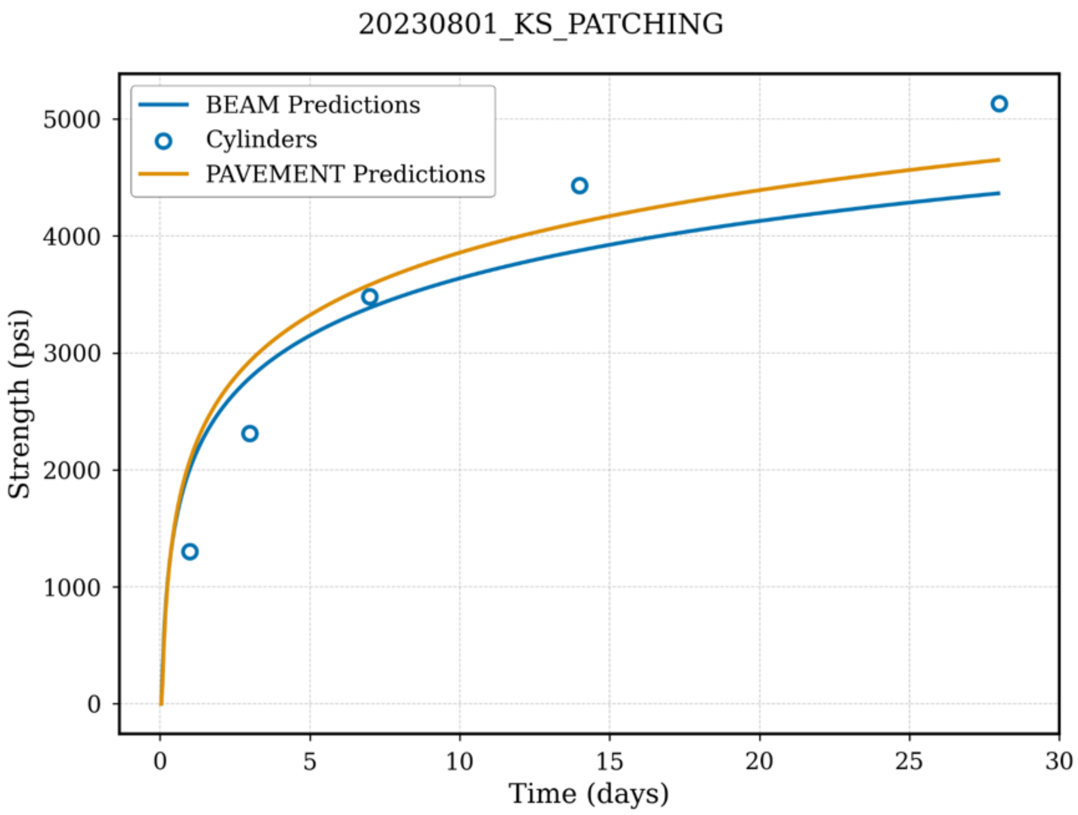
Indiana I-69 Paving, 7-25-2023



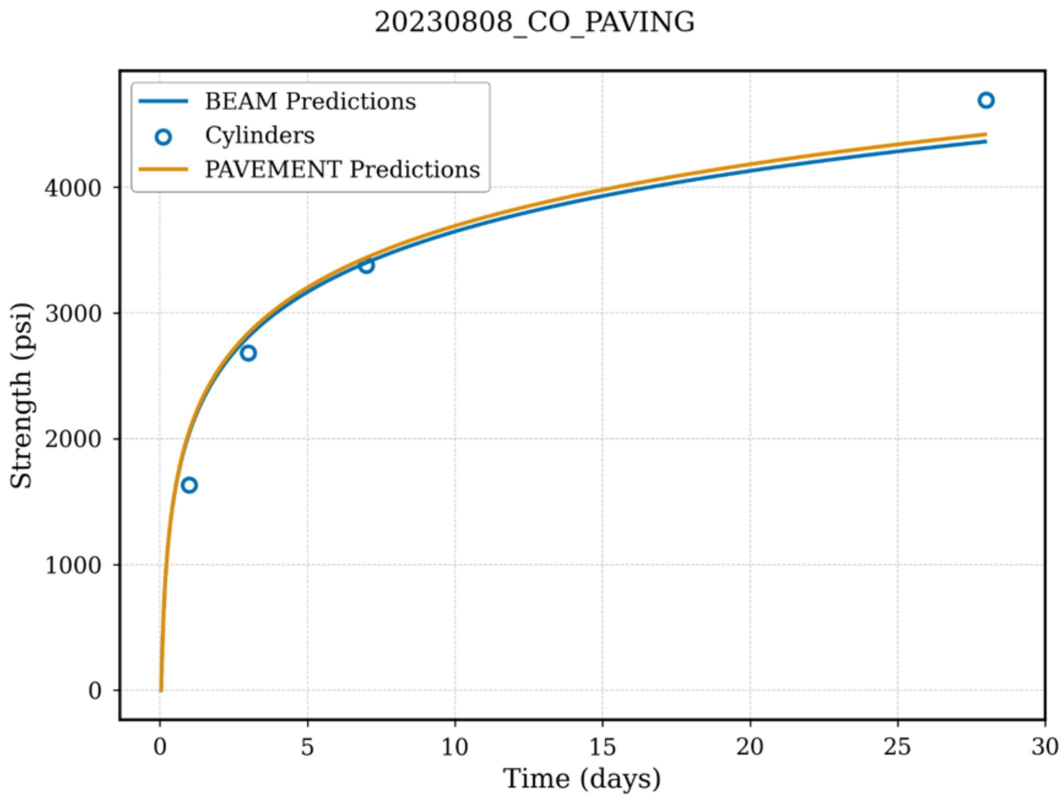


Sensing Results vs Cylinder Results

Kansas I-70 Bridge Patching (Fiber Used)



Colorado I-25 Paving



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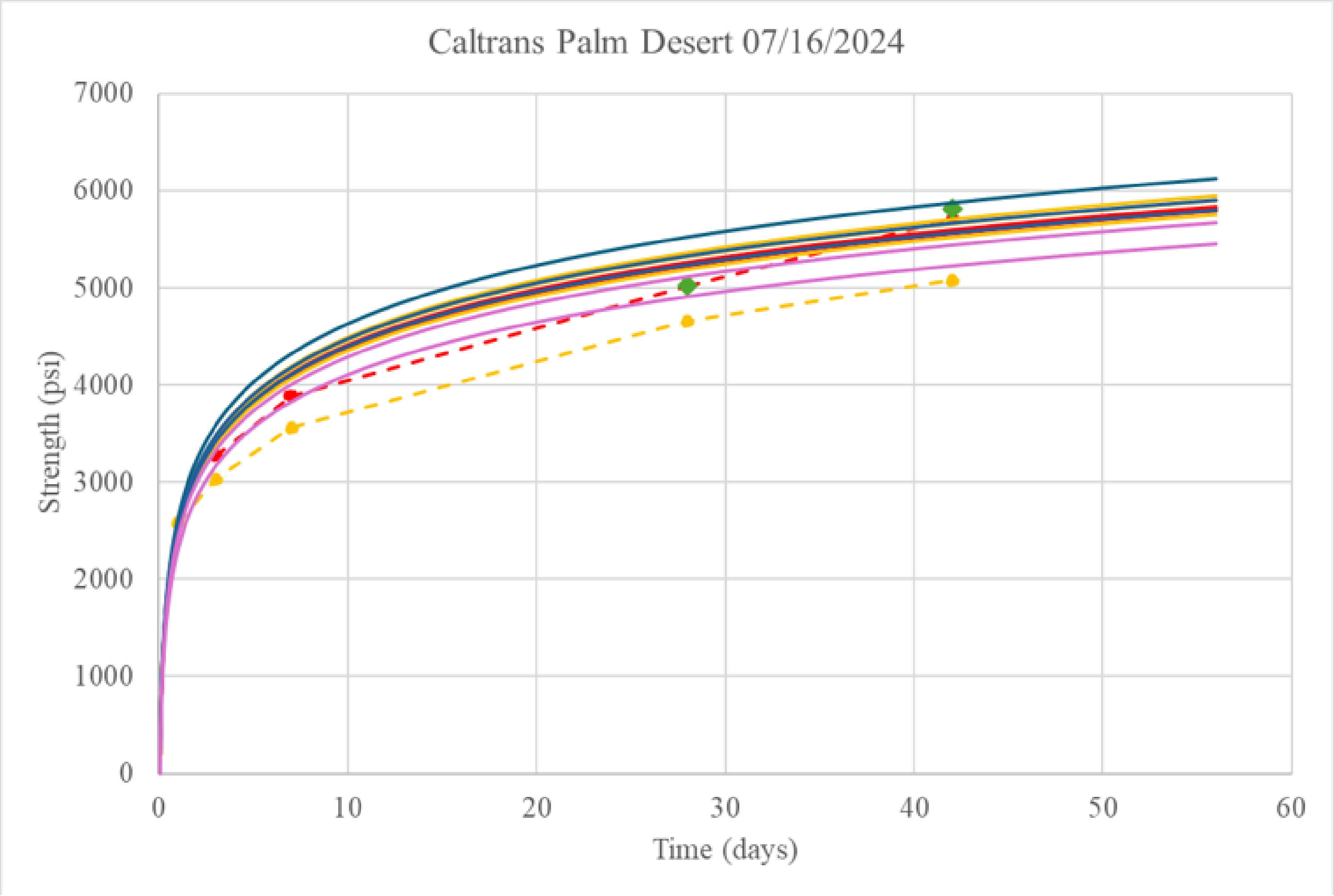
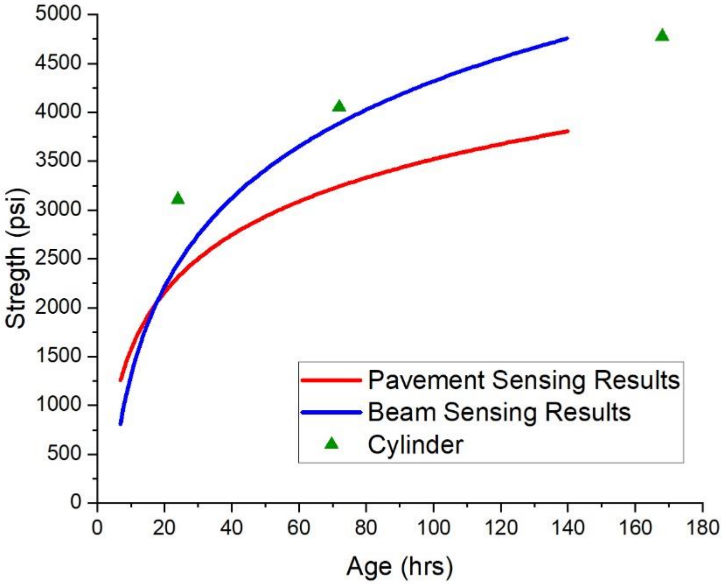
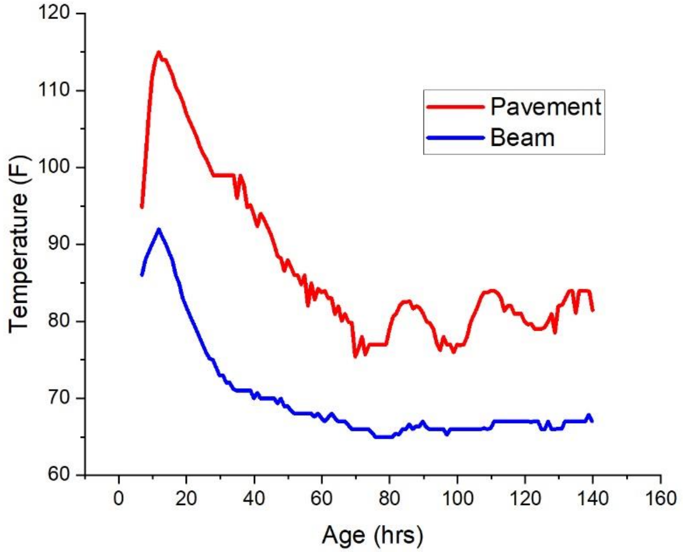
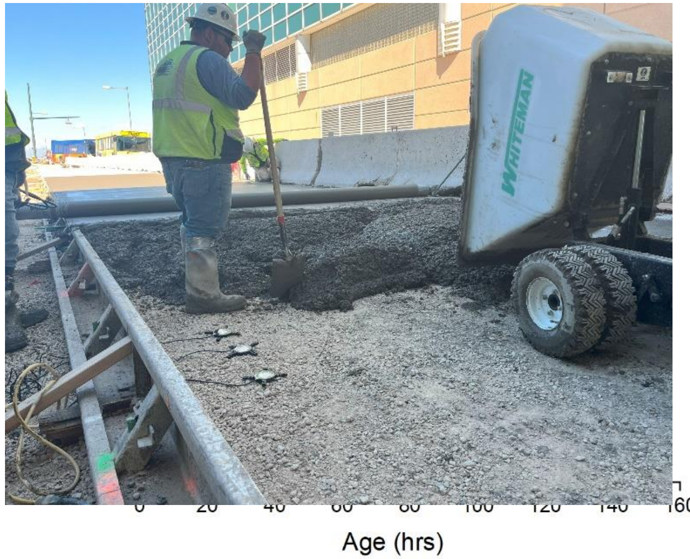
California Palm Desert Pavement



Colorado Denver Airport 8-11-23







- Cylinder break results are very close to sensing results in the beam.
- Since the base of the pavement was dry and loose, the loss of moisture resulted in low strength development at the sensing area, even though the temperature in the pavement was higher than that in the beam.

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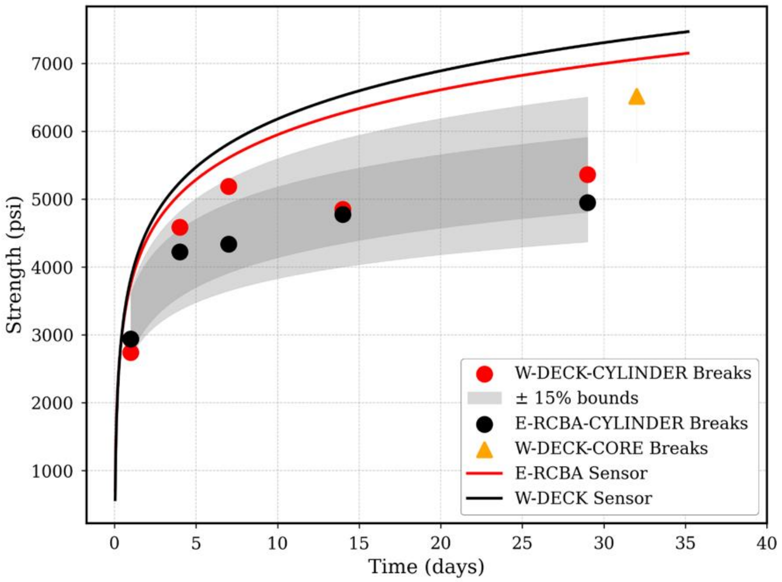
Case Study: Payment Insurance

Project Overview

- Bridge on I-69 in Indiana
- ~135 yards of concrete poured
- 6 REBEL sensors placed in concrete
- Cylinders taken at 1, 4, 7, 14, and 28 days
- 28-day Target Strength = 550 psi flex

Results



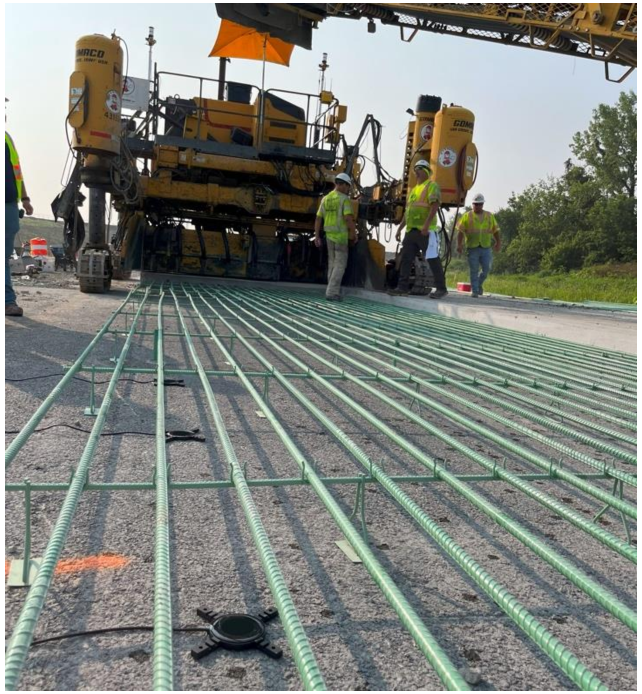
- 32-Day Core = 6.5K psi
- Sensor 32-Day Strength = 7.2k psi
- REBEL used to prove that contractor’s results were acceptable

Savings

- Replacement Cost of Concrete: $202,000K
- Sensor + Data Logger cost: $1.7K
- **Total Savings: $200K**

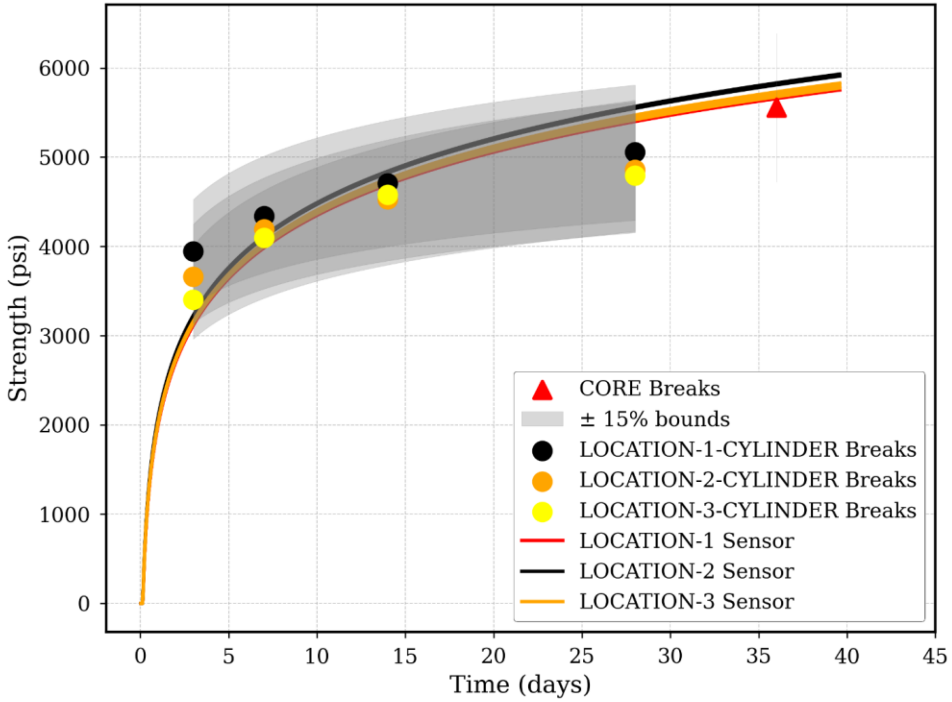
Case Study: Early Payment

Project Overview



- Caltrans I-10 Paving
- 3 REBEL sensors placed in concrete
- Cylinders taken at 1, 3, and 7, 28, and 42 days
- **Target Strength = 5,500 psi**

Results



Savings

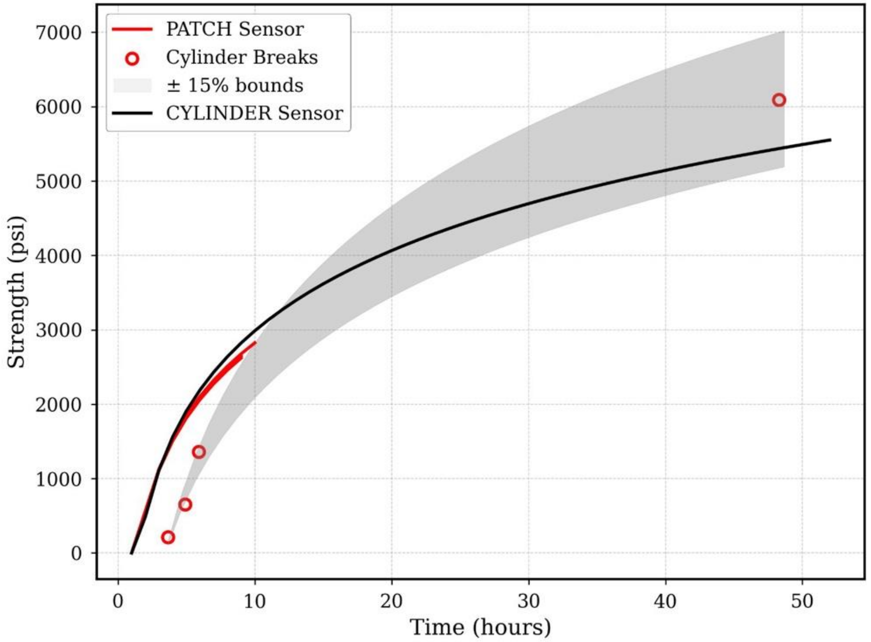
- REBEL sensors showed that concrete reached final strength at 30 days
- Contractor was able to break cylinders early to accelerate payment
- **Sped up payment from 56 to 30 days (26 days faster)**
- Sensor + Data Logger Cost: $1,100

Case Study: Accelerating Construction Schedule

Project Overview

- SH-130 Patching Project in Texas
- 3 REBEL sensors placed in concrete
- Cylinders taken at 2, 4, 6, and 48 hrs
- Target strength for road opening: 1800 psi

Results



	REBEL	Cylinder
Time >1.8k psi Measured	4.0 Hours	48.0 Hours

- REBEL sensors showed precise time that concrete hit 1800 psi
- Patch Sensor was unplugged for road opening
- Relying on cylinders alone would have required waiting 48hrs

Savings

- **Using REBEL, roads could be opened 44 hours earlier than using cylinders alone**
- **Sensor + Data Logger Cost : $1,100**

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Competitive Landscape

Concrete Strength Sensor Compared to Cylinder Testing and Maturity Sensors

Test Method	No Maturity Curves	No Cylinder Breaks	Mix Design Independent	In-Place Measurement	Real-Time	Long-Term Monitoring
Concrete Strength Sensor	✓	✓	✓	✓	✓	56 days
Cylinder Testing	✓		✓			*
Maturity Sensors				✓	✓	3 days

* Long-term monitoring dependent on number of created samples

Features

- IoT sensor for real-time strength information
- AI powered signal processing enabling complete automation
- AASHTO T 412-24 compliance

Benefits

- Calibration Free
- Obtain reliable real-time data
- Provide consistent testing results
- Cost and Time Efficiency
- Standards Compliant: AASHTO T 412
- Competitive Pricing and Project Advancement

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