TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): **Indiana Department of Transportation**

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # TPF-5(471)	**Transportation Pooled Fund Program - Report Period:** Year of 2024 Quarter 1 (January 1 – March 31) Quarter 2 (April 1 – June 30) Quarter 3 (July 1 – September 30) Quarter 4 (October 1 – December 31)	
Project Title: Real-time monitoring of concrete strength to determine optimal traffic opening time		
Name of Project Manager(s): Tommy Nantung	**Phone Number:**	**E-Mail** tnantung@indot.in.gov
Lead Agency Project ID: TPF-5(471)	**Other Project ID (i.e., contract #):**	**Project Start Date:** June 1, 2021
Original Project End Date: May 31, 2023	**Current Project End Date:** December 31, 2025	**Number of Extensions:**

Project schedule status:

☒ On schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Percentage of Work Completed to Date
$375,000		80%

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date

Project Description

Background

The Pooled Fund Project TPF-5(471) is led by Indiana with participation from FHWA, Texas, Kansas, Missouri, Tennessee, Colorado, North Dakota, and California. The project has been funded for a total of $375,000 for three years.

Fast-paced construction schedules often expose concrete pavement and/or structures to undergo substantial loading conditions even at their early age, which causes premature failure or a significant reduction in the life span of pavement and bridges. Current methods for determining traffic opening times can be inefficient and expensive, causing construction delays and cost overruns. For instance, maturity testing and compressive strength testing of concrete are two commonly used methods. The maturity test requires extensive calibrations of the maturity meter and trial batches for each mix design, causing inefficiency and high costs. The compressive strength testing of concrete cylinders often provides unreliable results due to the differences between laboratory and field conditions. It is also time and labor-consuming.

To address this critical need, INDOT, and Purdue University have developed an in-situ nondestructive sensing method that enables direct measurement of concrete stiffness and strength using the electromechanical impedance (EMI) method coupled with piezoelectric sensors. It proved to be reliable for in-situ monitoring of concrete strength development regardless of mix design (e.g., water-to-cement ratio, cement type, SCMs, aggregate content). We have also set a precedent for the reported strength property of concrete at the very early age of 4-8 hours. These properties could not be obtained using conventional cylinder testing as concrete is often not hard enough to be de-molded at this point. This has also proved that the sensing method does not need any calibrations for different concrete mix designs during each test run, which has been significantly cumbersome for maturity testing.

Even though the novel EMI method developed by INDOT and Purdue University can accurately measure the concrete strength in real-time without any database or calibration, the method cannot be deployed in fields. The data acquisition and processing tools consist of heavy and bulky equipment that can cause safety concerns at construction sites. To address these problems, the project will initially focus on developing an on-chip device with wireless capabilities to acquire and process EMI data. Such a device can then be deployed on transportation construction sites and transfer the concrete strength data to project managers or superintendents remotely using wireless capabilities. The EMI concrete sensors will be installed and tested in construction sites and various concrete mixes of participating DOTs. Feedback from the DOTs' project managers and superintendents will be considered, and the sensing technology will be improved.

The ultimate goal of this pooled-fund study is to develop the standard testing procedure for field testing by implementing it in all the participating states and developing AASHTO-ready specifications for using this method. A detailed cost/benefit analysis of this method, along with a set of recommendations for traffic opening time and maintenance schedule, will be conducted during the program.

Project Objectives

The objectives of the proposed pooled-fund study are as follows:

1) Develop the field implementable wireless sensing technology enabling data automation and transmission.
2) Implement the smart sensing methods in all participating states and train state engineers to use the sensing methods effectively.
3) Provide guidance on using EMI methods to determine the optimal concrete pavement traffic opening time, maintenance, and repair schedule.
4) Develop AASHTO-ready specifications

Progress per Quarter (includes meetings, work plan status, contract status, significant progress, etc.):

June 1 – June 30, 2021

- Conducted a conference meeting with representatives from DOTs of Indiana, Colorado, Texas, California, Tennessee, and North Dakota. Following were the topics of discussions
  - Prior accomplishments from INDOT and Purdue team relevant to the pooled fund project
  - On-going works
  - Project objectives and timeline
  - Plan and recommendations for following works
- Work on the initial design and development of sensors and data loggers with data storage has been started.
- Discussions on mix designs to be tested have been initiated with participating DOTs.

July 1 – September 30, 2021

- Literature review of chips and devices that could measure electromechanical impedance (EMI) and strength of concrete was performed.
- A board with a chip that could have EMI-measurement capabilities was selected for initial measurement.
- Circuit components of the board, such as the resistors in operational amplifiers, were tuned so that the EMI spectrum of concrete materials could be accurately obtained.
- The on-chip board results match the bulky EMI and strength measurement setup. The board still cannot be implemented on-site. It requires a laptop and external power. It is not self-controlled and automated. Also, the board and chip need more testing.

October 1 – December 31, 2021

- The board is updated to incorporate rechargeable batteries and a power management circuit.
- The board's firmware is updated to enable automated timing data collection to customize the testing period.
- The board now has internal storage and a USB port. The data can be stored locally and downloaded to a laptop.
- The Bluetooth communication module was selected and programmed. Multiple boards will send data to a hub, and the hub will transmit data to a remote server, which requires further work.

January 1 – March 30, 2022

- The datalogger now uses new batteries with reduced size and improved charge volume.
- The LTE hardware module has been developed, which enables the datalogger to transmit data to the remote server without the mediation of routers.
- The remote server is being developed. The front end of the database management is done, and we are working on the database API.
- New packaging materials for sensors, which passed the testing in concrete, are used.

April 1 – June 30, 2022

- The firmware of the datalogger was updated.
- The battery performance was evaluated, and the power management was improved.

- The backend of the database management interface is almost done. It will allow the user to check the browser's real-time data and download reports in pdf or spreadsheet format.
- The mass production of sensors is in process. The selection of proper epoxy material is one of the challenges.

July 1 – September 30, 2022
- The packaging material of the sensor is improved to withstand thermal conditions in practical projects.
- The influence of temperature on sensor performance was studied at lab prism specimens and outdoor large slabs.
- Machine learning methods were applied to improve the accuracy and consistency of testing methods.
- Field testing was implemented on I35E highway at Hillsboro, Texas. The testing results were comparable to the field cylinder testing. The team deployed 6 sensors and 6 dataloggers. One of the dataloggers failed, and the rest of them performed well.
- The datalogger had circuit issues that may cause short currents, which were resolved entirely by a new board design.

October 1 – December 31, 2022
- Sensor and testing systems were tested with various concrete mix designs.
- Temperature data were recorded and used as an input of AI models.
- Multiple AI models were built and studied based on the collected data.
- AI models were incorporated into the cloud server to enable cloud computation.

January 1 – March 30, 2023
- Various concrete mix designs were cast to enrich the database for AI algorithm development.
- More algorithm structures were studied to provide more robust strength prediction for concrete.
- Datalogger hardware was revised to store and transmit more data.
- Transfer learning was studied to accommodate various types of sensor signals.

April 1 – June 30, 2023
- The AI algorithm is further developed and deployed on our web app.
- Field testing is planned for Tennessee, Indiana, Kansas, Missouri, and Colorado; tools, personnel, and vehicles are purchased for those testing.
- We built a dedicated concrete lab for concrete casting and data collection.
- We improved the manufacturing process of sensors and made them more consistent.

July 1 – September 30, 2023
- Field testing was implemented in 8 states.

  The research team has traveled to 8 states (shown in Figure 1 below) and implemented the sensing system.

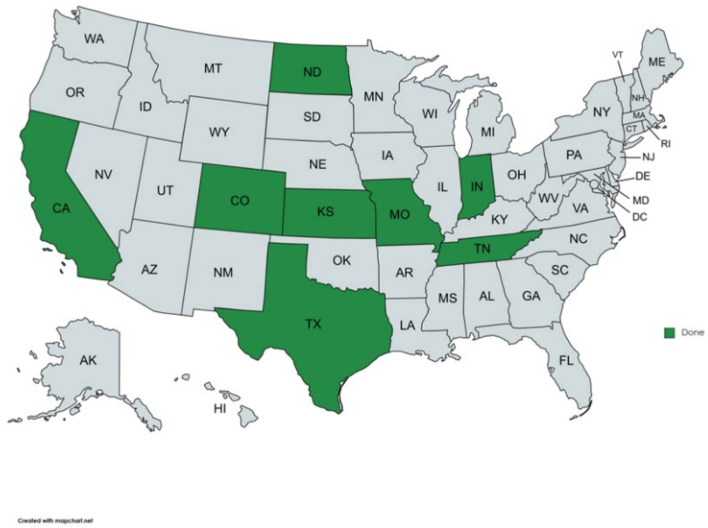

Figure 1. States with field implementation of REBEL sensor.

The field testing shows promising results. For example, the difference in concrete curing conditions is reflected in the sensing results. *We take the testing results of California as an example. Other states' results will be available in the final report of this TPF project*.

California Testing Results

Background:

On September 15, 2023, a construction project was undertaken along the Highway-50 Corridor. The pavement for this project consisted of a continuously reinforced concrete pavement (CRCP). Rui He (email: he566@purdue.edu), a PhD student at Purdue University, was on-site to install REBEL™ sensors along with dataloggers. The Caltrans engineering team prepared two standard concrete beam samples, each measuring 6 inches by 6 inches by 22 inches, to assess the concrete's strength development under various curing conditions. In total, nine (9) sensors were embedded, including three (3) in the pavement, three (3) in the on-site cured beam, and three (3) in the beam cured under laboratory conditions.

Sensing Results of Concrete Strength:

The sensing and cylinder break results are presented in Figure *2* below. Each prediction curve represents the mean value of three (3) sensors, generated using a proprietary machine learning (ML) algorithm to convert sensor output and temperature profile into compressive strength. The team has observed discrepancies among sensor outputs attributed to the inconsistent quality of the hand-made sensors and dataloggers at Lu's lab and the intrinsic material inhomogeneity of concrete. Consequently, the post-processed mean value of the sensing results in each beam (or pavement) was used as the result, a process similar to that outlined in ASTM C39 section 11.1.

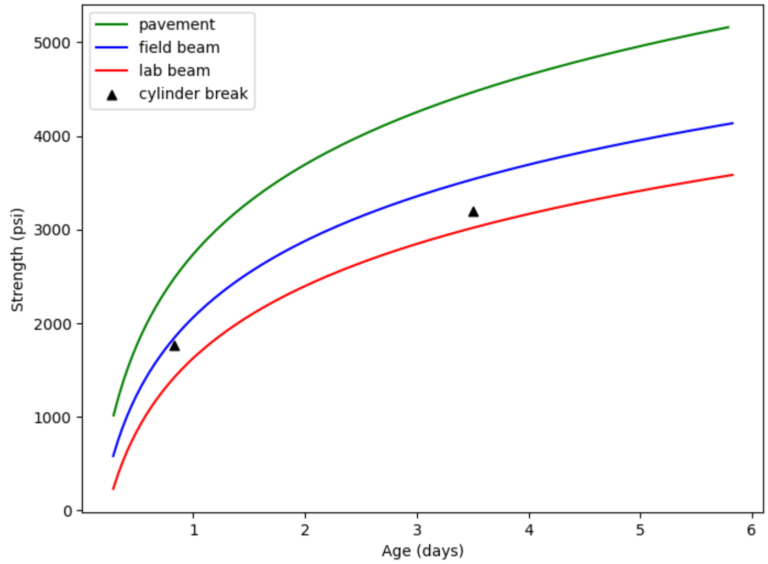

Figure 2 Sensing results versus cylinder break

As shown in Figure *2*, the sensing results for two concrete beams (one cured on site and the other in the lab) closely align with the cylinder break as per ASTM C39. However, the results of sensors embedded in the pavement are substantially higher, as explained below.

The variance in sensing results among the beam and pavement can be rationalized by examining the temperature and maturity profiles presented in Figure *3* and Figure *4*. The maturity data of three concrete structures (lab-cured beam, field-cured beam, and pavement) agrees with our sensing results, therefore validating our hypothesis that the significant difference in thermal profile for pavement and beam caused the difference in strength between the pavement and cylinder.

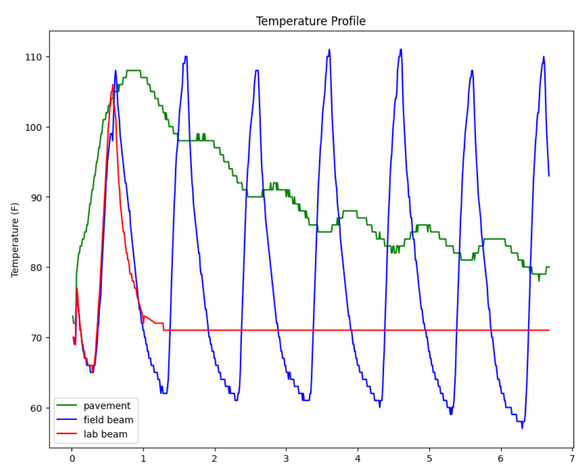

Figure 3 Temperature profile

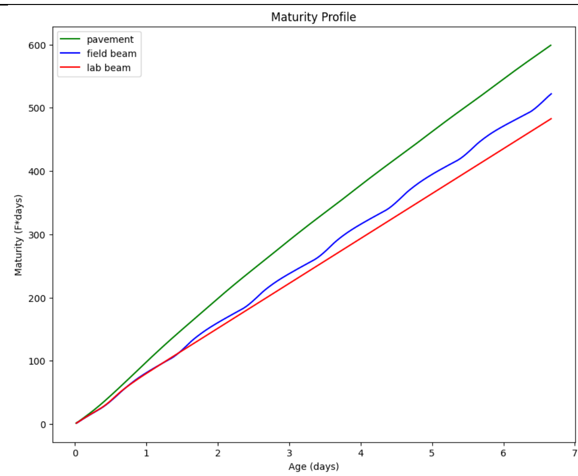

Figure 4 Maturity profile

In summary, we hope that this preliminary dataset has demonstrated the feasibility of using the REBEL sensor to measure the in-place strength of concrete structures directly at any given point in time. The mean values of sensing results are comparable to those obtained through cylinder testing and maturity testing within the same concrete structure. As explained earlier, all sensors and dataloggers were handcrafted in our research lab at this stage, leading to significant discrepancies among the three sensors. This issue can be addressed by implementing a standard manufacturing process. We are currently collaborating with manufacturing partners to ensure the quality and consistency of both the sensors and dataloggers.

- Database and machine learning are migrated to Microsoft Azure cloud service, providing scalability and better maintenance. The ML development and operations are now more streamlined and standardized using Microsoft Azure cloud service. This enables us to perform grid searches to find optimal model parameters.

October 1 – December 31, 2023

- We improved the performance of REBEL sensor and datalogger system, the V1.1 system is manufactured and is ready for lab and fiield testing.
- The V2 sensor, named the REBEL Echo, now has a more durable design and a new connector for improved usability.
- The new design has been prototyped and, after several revisions, is being prepared for a small-volume run of 1000 units.
- The V2 datalogger, named the REBEL Sentry, has been redesigned from the ground up to provide more accurate sensor measurements and an improved user experience by offering additional mounting points on the case.
- Implement transfer learning algorithms to interpret the sensing results from V1.1 and V2 systems.

January 1 – March 30, 2024

- We assessed the Jittering in our machine learning model where Gaussian noise was added to the data spectra.

- We employed a Representation Learning pre-training approach and fine-tuning to the target objective.
- We developed models that output sequences of strength predictions instead of single-output regression models.
- The V1.1 system has been shipped and used in several lab and field projects throughout the Midwest.
- The REBEL Echo design is finalized, and the manufacturing process is almost ready to commence the first run of 1000 units in April.
- The REBEL Sentry design is nearing completion and will undergo a final testing phase in April to determine if it is ready for field use.
- The backend systems in the cloud have been updated to capture the more sophisticated data generated by the new versions of the datalogger and sensor.
- Preparations are almost complete for a batch of internal concrete testing consisting of over 300 samples to further train and increase the accuracy of the machine learning model.

April 1 – June 30, 2024

- Updated LED design on the datalogger to make it more straightforward for the user.
- The battery design of the datalogger is improved to have longer service life.
- During the last quarter, machine learning efforts were enhanced by integrating field and laboratory data, leading to improved predictive accuracy of the ML model.
- The combination of multimodal data and a specialized model enables more precise and reliable prediction outcomes.
- We have also deployed more sensors with TxDOT, CalTrans, and INDOT within this project's scope. The improved reliability of the system has provided more accurate sensing data.

July 1 - September 30, 2024

- The working stability and battery life of the datalogger are further improved.
- The machine learning output accuracy is increased, and a more robust model is established.
- The sensor system has been deployed in more states, as shown in Figure 5.

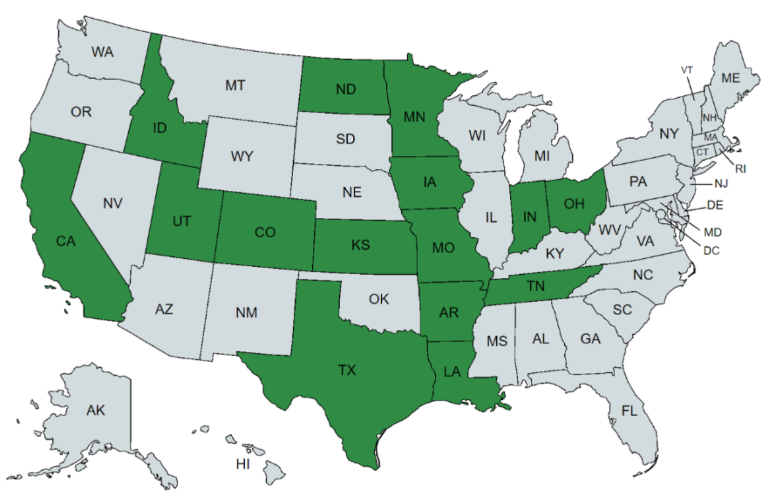

Figure 5. States with field implementation of REBEL sensor.

- The REBEL sensor system was deployed in INDOT CR200 over I69 bridge, and the sensing strength matched with the core drill strength, while the cylinder break strength showed a large deviation, as shown in Figure 6.

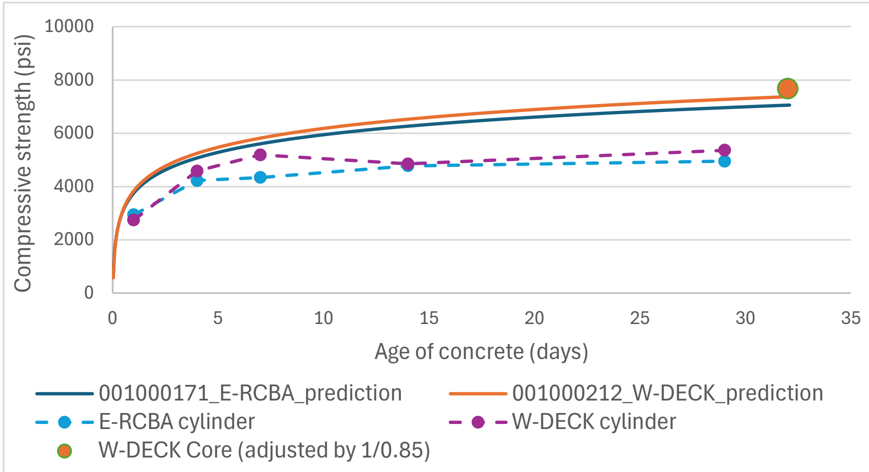

Figure 6. Sensing and break strengths of INDOT CR200 over I69 bridge

- The REBEL sensing system was also deployed in Texas on a patching project with rapid-setting concrete, and the REBEL system showed promising results, as shown in Figure 7.

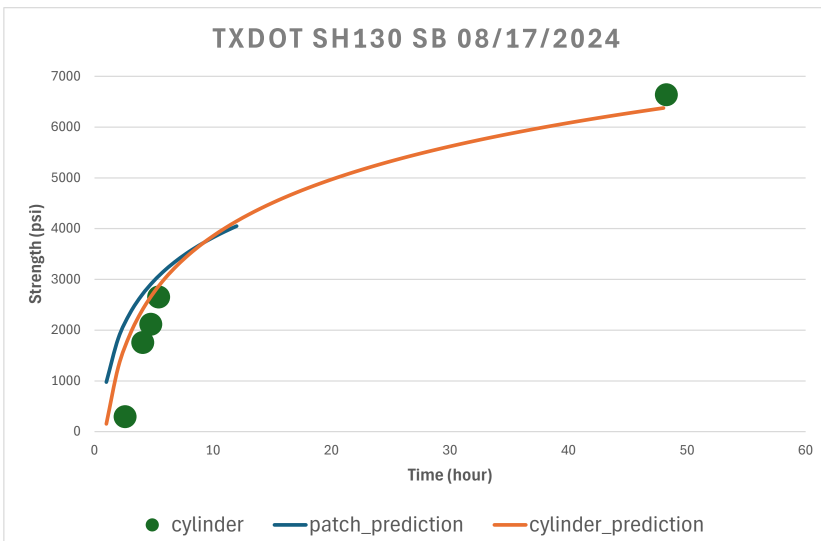

Figure 7. TxDOT patching project sensing results

October 1 - December 31, 2024

- The sensor system was applied in more field projects as shown in Fig. 8. Over 200 REBEL Sensors were deployed across 60 projects.

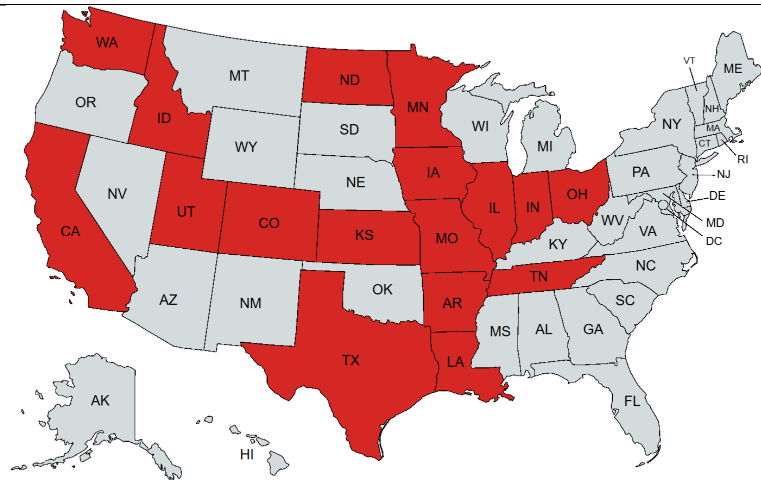

Figure 8. Map of states with REBEL sensor system deployment.

- Preparing the feature to handle LTE outages. We will now store and send any missed telemetry later when service is restored.
- We have been working on a more battery-efficient pour detection system.
- A diagnosis tool for gradient checking in ML training was developed, leading to improved ML model performance through more efficient gradient flow.
- Post-processing methods were used to improve the continuity of strength prediction time series. As shown in Fig. 9, the variability in REBEL sensor data is significantly lower than that of the cylinder break test.

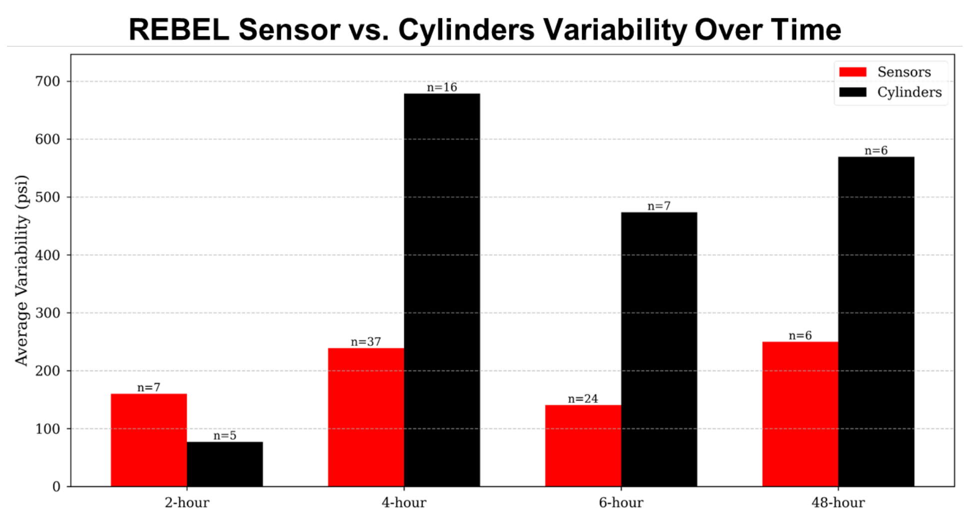

Figure 9. Compressive strength data variability comparison between REBEL sensor and cylinder break test.

Anticipated work next Quarter (January 1 – March 31, 2025)**:**

- Keep improving the machine learning model accuracy
- Deploy more field-testing sensor
- Apply the advanced machine learning model to field testing results

Significant Results:

- We extended the field testing to 15 states.
- The sensor system was standardized as AASHTO T412.
- The sensor system was deployed in more varied concrete types, such as calcium sulfate aluminum concrete.
- The datalogger battery can now work longer in cold environments.

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

Potential Implementation:

- Anticipated implementation of the developing sensing technology in bridges and pavements of participating DOTs in years 2-3 of the project
- Anticipated implementation in interstate highways in year 3 of the project