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 2023 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:** May 31, 2024	**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	$22,000	10%

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date
	$14,000	10%

Project Description

Background

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

Fast-paced construction schedules often expose concrete pavement and/or structures to undergo substantial loading conditions even at its early age, which causes pre-mature 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 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, fly ash, slag and silica fumes). 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 demolded 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 which can cause safety concerns on construction sites. To address these problems, the project will initially focus on development of on-chip device to acquire and process EMI data with wireless capabilities. Such a device can then be deployed on transportation construction sites and can 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. Feedbacks 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 develop AASHTO ready specifications for using this method. A detailed cost/benefit analysis of this method along with a set of recommendation 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 effectively use the sensing methods.

3) Provide guidance on how to use EMI methods to determine the optimal traffic opening time of concrete pavement, 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 next works
- Work on 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 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 EMI spectrum of concrete materials can be accurately obtained.
- Results from the on-chip board match with the bulky EMI and strength measurement setup. The board still cannot be implemented on-site. It requires 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 power management circuit.
- The firmware of the board is updated to enable automated timing data collection to customize the testing period.
- The board now has an 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 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 are used, which passed the testing in concrete.

April 1 – June 30, 2022

- The firmware of the datalogger was updated.
- The battery performance was evaluated, and the power management is improved.
- The backend of the database management interface is almost done. It will allow the user checking the real-time data in the browser and download report in pdf or spreadsheet format.
- The mass production of sensor 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 at I35E highway at Hillsboro, Texas. The testing results were comparable to the filed cylinder testing. The team deployed 6 sensors and 6 dataloggers. One of the datalogger failed and the rest of them performed well.
- The datalogger had circuit issues that may cause short current, which have been resolved completely by a new board design.

October 1 – December 31, 2022

- Sensor and testing system 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 to 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.
- Dataloggers 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

- AI algorithm is further developed and deployed on our web app.
- Field testing is planned for Tennessee, Indiana, Kansas, Missouri, Colorado; tools, personnel, vehicles are purchased for those testing.
- We built up a dedicated concrete lab for the concrete casting and data collection.
- We improved the manufacture 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 the Figure 1 below) and implemented the sensing system.

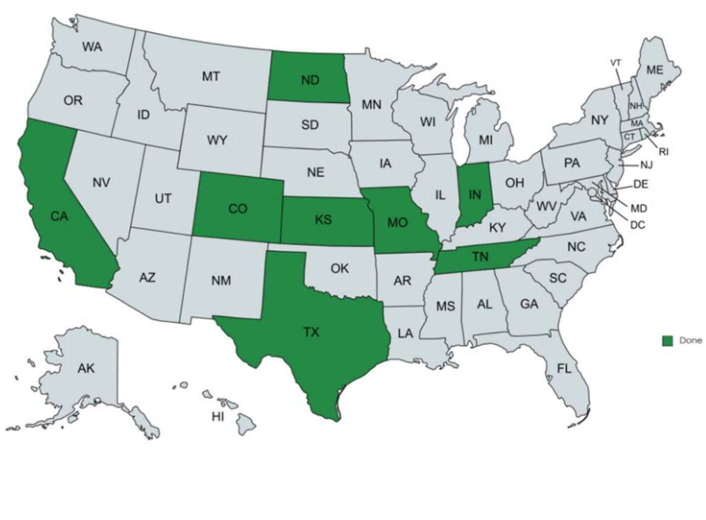

Figure 1. States with field implementation of REBEL sensor.

The field testing shows promising results, for example, the difference of 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, in order to assess the strength development of concrete 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 results and cylinder break results are presented in the Figure *2* below. Each prediction curve represents the mean value of three (3) sensors, which were generated using a proprietary machine learning (ML) algorithm to convert sensor output along with 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 as well as 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.

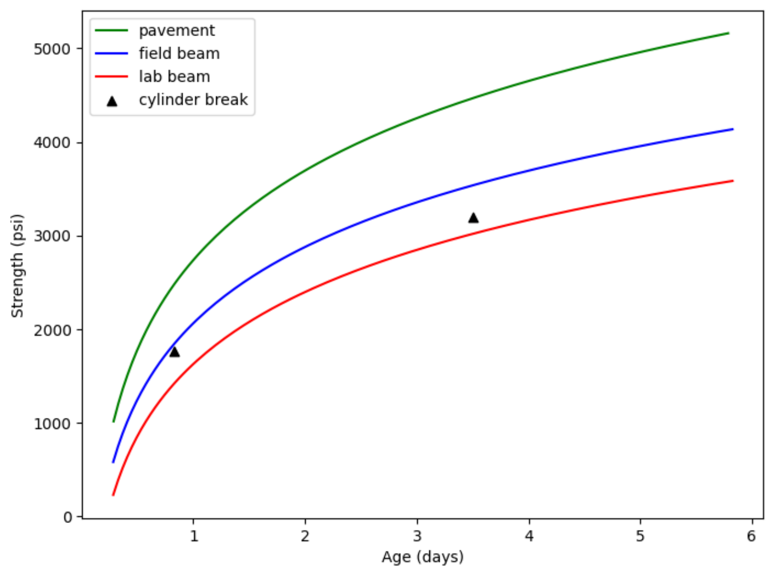

Figure 2 Sensing results versus cylinder break

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 that of cylinder break as per ASTM C39. However, the results of sensors that 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 the 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 difference in strength between the pavement and cylinder was caused by the significant difference of thermal profile for pavement and beam.

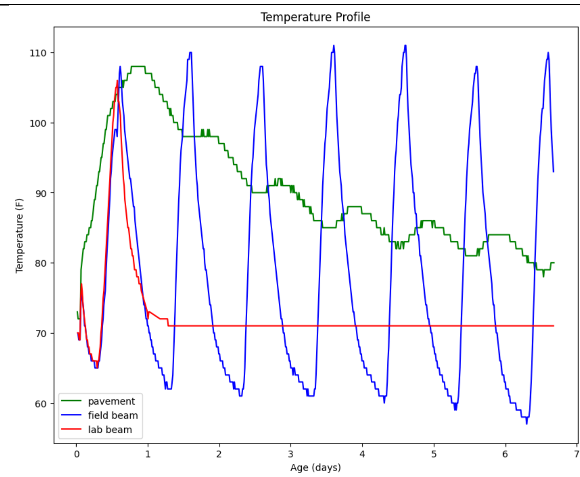

Figure 3 Temperature profile

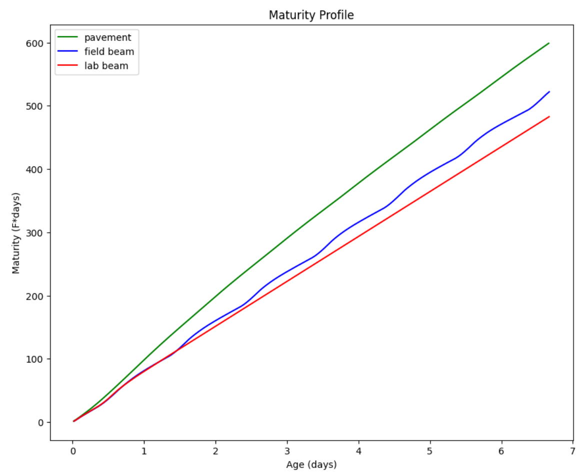

Figure 4 Maturity profile

In summary, we hope that this preliminary dataset has demonstrated the feasibility of using the REBEL sensor to directly measure the in-place strength of concrete structures at any given point of 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 could service. This enables us to perform grid searches to find optimal model parameters.

Anticipated work next quarter (October 1 – December 31, 2023)**:**

- Implement planned field testing.
- Further polish our AI program for data processing.
- Develop an input signal classifier to remove abnormal input data

Significant Results:

- We developed a minimum viable product (MVP) and implemented it in 8 states

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 the year 3 of the project