Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

3D Printed Smart Permanent Concrete Formwork for Precast Structural Component
LS-24-RP-02

Quarterly Progress Report
For the performance period ending *[09/30/2025]*

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Collaborators / Partners:

Submitted to:
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Project Description:

1. Research Plan - Statement of Problem:

   A crucial choking point of transportation infrastructure is the degradation over a long period of time. The detection of change in the structural integrity of roads, bridges, tunnels, etc. requires a practical and economical approach. A commonly used method for structural health monitoring (SHM) is the utilization of external sensors that require constant power supply, protection against weathering, and higher budget. However, these restrictions potentially can be obviated through the usage of advanced materials and fabrication methods. This research utilizes novel self-sensing cementitious composites (SSCCs) to achieve stress-sensing property in precast concrete components. Furthermore, conventional molds for precast concrete elements are replaced with additively manufactured permanent molds facilitating the cost-effective fabrication geometrically irregular shapes. Finally, the layer-by-layer deposition system, which is the defining feature of AM, aids with topological optimization and precise control over the properties of individual layers.

2. Research Plan - Summary of Project Activities (Tasks)

   Task 1: Material Properties assessment
   Task 2: Specimen fabrication and determining the preliminary SSCCs placement
   Task 3: Load testing and strain monitoring
   Task 4: Construction of preliminary Multiphysics model

Project Progress:

3. Progress for each research task

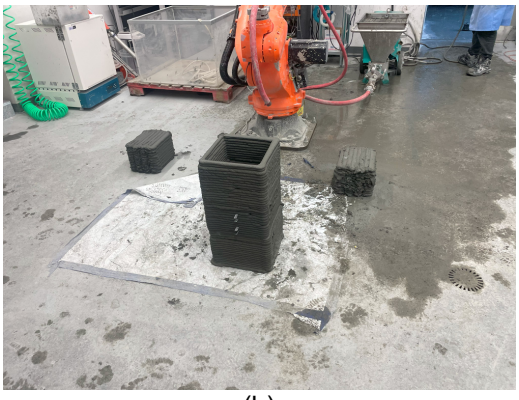
Task 1: *Completed*

Task 2: Specimen fabrication and determining the preliminary SSCCs placement & Task 3: Load Testing and strain monitoring

Based on the rheological, mechanical, and piezoresistive performances of the cementitious mixes with varying types and dosages of conductive fillers, milled CF at 0.5 wt% was chosen for the next step. In this step, an additively manufactured 3D printed mortar shell was aimed. To this end, initially, 12”x12”x24” shells were printed (Figure 1. a, b). These shells contained a reference mix at the top 1/3 and bottom 1/3. The middle 1/3 consisted of the self-sensing mix (e.g., CF05). Additionally, solid blocks of mortar with a height of 8” were 3D printed to be used in the future for obtaining a stress-strain curve. Due to the limitations we faced in compressively loading the large-scale 3D printed specimens, we opted to print and test smaller specimens. In this case, the size of the shell was modified to 6”x6”x12” (Figure 1. c). 6 specimens with the same mix designs and configurations were printed simultaneously. This is done to ensure the ability to replicate the testing on more than one specimen. At the end of 28 days of curing, specimens will be subjected to compressive cyclic loading, and the change in the electrical voltage will be detected using a galvanostat (Figure 1. d). The 4-probe method will be used for performing the self-sensing test.

Images seen in Figure 1. (e), show the coring process of the 3D printed mortar block and the 4”x8” specimen. After 28 days of curing, a compressiometer with two LVDTS will be fixed on the shown specimen, and the specimen will be loaded until failure compressively.

(a)



(b)

(c) (d)

(e) (f)

Figure 1. (a) printing process of 12”x12” square columns (b) completed 12”x12”x24” specimen and block for coring (c) 3D printed 6”x6”x12” specimens (d) piezoresistivity test on 3DCP specimens (e) coring process from 3DCP block (f) cored 4”x8” specimen

Task 4: **Construct Preliminary Multiphysics Model**

A preliminary multiphysics model developed using COMSOL Multiphysics simulation software was further refined to better simulate the self-sensing behavior of concrete. The Electric currents and the Solid Mechanics interfaces were employed for this purpose.

The specimen was modeled as 2×2×2 in^3 cubes with four electrodes embedded in them. Concrete was assigned an elastic modulus of 25 GPa, Poisson’s ratio of 0.2, and a relative permittivity of 1. Electrodes were modeled as steel with an elastic modulus of 205 GPa, Poisson’s ratio of 0.28, and a relative permittivity of 1.

To simulate the self-sensing behavior of concrete, strain-dependent electrical conductivity was defined using the exponential model in Eq. 1:

$$\sigma(\varepsilon) = \sigma_0 e^{-k\varepsilon} \quad \text{Eq. 1}$$

where σ_0 is the base conductivity, k is the piezoresistive constant, and $\mathcal{E}$ is the strain.

The model was calibrated to match the resistance response observed in the LR200 specimen. LR200 was supplied with a 1 mA DC current and subjected to loading at a rate of 200 psi/s, oscillating between an upper threshold of 500 psi and a lower threshold of 25 psi. The corresponding resistance signal for LR200 is presented in Figure 6.

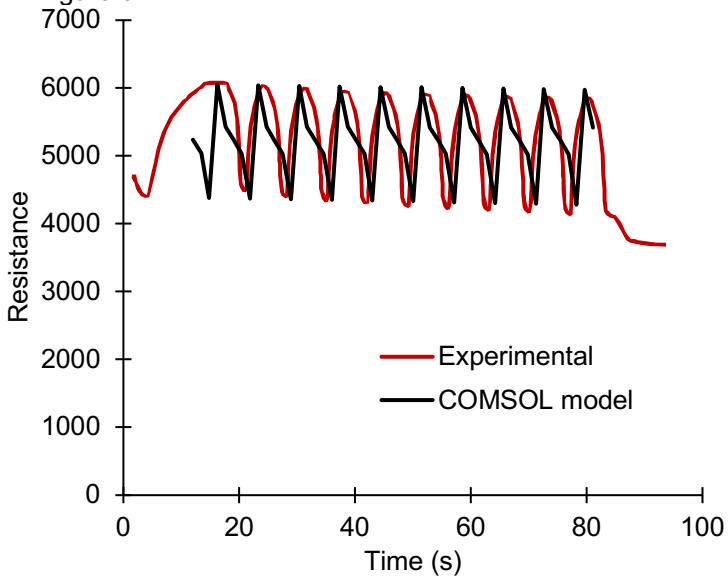


Figure 6. Comparison of experimental resistance and resistance obtained from the multiphysics simulation

Calibration yielded a σ_0 of 0.00096 S/m and a k of 25,695. Figure 6 shows the resistance output obtained using the model. The model successfully captured the amplitude and the frequency of the signal. It also predicts the downward trend observed in the experimental resistance response as the number of cycles increases. The comparison of the experimental and model results yielded a coefficient of determination (R^2) of 0.25 for cycle 2. However, the experimental-to-model ratio of 0.999 indicates a strong match between them.

As the next step, the model will be validated using additional experimental data. Furthermore, alternative strain-dependent conductivity models will be explored.

4. Percent of research project completed

Task 1: Material properties assessment (100% complete)
Task 2: Specimen fabrication and determining the preliminary SSCCs placement (100% complete)
Task 3: Load Testing and strain monitoring (40% complete)
Task 4: Construct preliminary Multiphysics model (50% complete)

5. Expected progress for next quarter

For the next quarter, load testing of 3D printed self sensing concrete permanent formwork with will be completed. Piezoresistivity under monotonic and cyclic loading will be applied and strain monitoring will be performed using DIC. A Multiphysics model will be used for to simulate the loading test.

6. Educational outreach and workforce development

Mentoring two undergraduate students on conducting undergraduate research. One undergraduate student will presenting his work in the conference next month.

7. Technology Transfer

None

Research Contribution:

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:
   (G: Graduate Student)
   (1) K. Taj[G], Y.-F. Su*, "Durability Evaluation of Economical Self-Sensible Cementitious Composites," *Case Study in Construction Materials,* 2025 *(Under review)*
   (2) K. Taj[G], D. Palipana, Y.-F. Su*, "Systematic Investigation of Testing Configurations Toward Standardization of Piezoresistivity-Based Self-Sensing Method for Smart Concrete Structure", *Transportation Research Record*, 2026 *(Under review)*
   (3) K. Taj[G], Y.-F. Su*, "Load-Bearing and Sensing Capabilities of 3D Printed Self-Sensing Concrete Column" *Engineering Structure*, 2026 (In preparation)

9. Presentations and Posters of TRANS-IPIC funded research: *(G: graduate student)*

Not in this period but will have three presentations in the following quarter.

   (G: Graduate Student, UG: Undergraudate Student)
   (1) K. Taj[G], S. Timilsina[G], Y.-F. Su, "The Effect of Environmental Conditions on Self-Sensing Performance of 3D-Printed Structural Elements", *C3 Symposium 2025*, Chicago, October 02-05, 2025
   (2) Y.-F. Su, D. Palipana, K. Taj[G], "Effect of Temperature and Voids on the Electrical Behavior of Self-Sensing Concrete" *ACI Convention, Baltimore, MD, USA,* October 26-29, 2025
   (3) Ted Atera[UG], M. Pasbani[G] ,Y.-F. Su, **"***Development of Embedded Sensors for Real-Time Monitoring of Concrete Properties in 3D Printing" ASME International Mechanical Engineering Congress & Exposition, Memphis, TN, November 16-20, 2025*

10. Please list any other events or activities that highlights the work of TRANS-IPIC occurring at your university (please include any pictures or figures you may have). Similarly, please list any references to TRANS-IPIC in the news or interviews from your research.
    None.

Appendix 1: Research Activities, leadership, and awards (cumulative, since the start of the project)

A. Number of presentations at academic and industry conferences and workshops of UTC findings
   - No. = 3 + (3)

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 2 + (1)

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 4

D. Number of peer-reviewed conference papers published by faculty.
   - No. = 0

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0
   - No. PhD dissertations = 0
   - No. citations of each of the above = 0

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   None

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in =2
     - No. lead =0
   - Advisory committees (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0
   - Conference Organizing Committees (No. participated in & No. led)
     - No. participated in = 3
     - No. lead =0
   - Editorial board of journals (No. participated in & No. led)
     - No. participated in =0
     - No. lead =0
   - TRB committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0

H. Number of relevant awards received during the grant year
   - No. awards received = 0

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 2
   - No. Graduate = 3

J. Number of internships and full-time positions secured in the industry and government during the grant year.
   - No. of internships = 0
   - No. of full-time positions = 0

References:

N/A