Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Bio-Inspired Solutions for Roadside Barriers: Exploring 3D Printing as Alternative Precast Technology — Phase II
Project N: (PU-23-RP-03)

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

Submitted by:
Jan Olek[1](olek@purdue.edu),
Jeff Youngblood[2](jpyoungb@purdue.edu),
Pablo Zavattieri[1](zavattie@purdue.edu)
[1]Lyles School of Civil Engineering, Purdue University
[2]School of Materials Engineering, Purdue University

Collaborators / Partners:
Sperra (former RCAM Technology)
AccelNet (Arizona State University, West Pomeranian University of Technology, Poland MS&T, UT Arlington, University of Puerto Rico)

Submitted to:
TRANS-IPIC UTC
University of Illinois Urbana-Champaign
Urbana, IL

TRANS-IPIC Quarterly Progress Report:

<u>Project Description:</u>

1. Research Plan - Statement of Problem

Building on our success with small-scale specimens demonstrated in Phase 1, we now focus on scaling up our tough, impact-resistant materials for roadside barrier applications using the Large-Scale Robotic Arm (LSRA). Up to now, we have been developing practical fabrication methods by developing new nozzle configurations, toolpaths, and fiber-reinforced concrete mixtures. This effort emphasizes both scalability and real-world relevance. Prototypes have been produced with larger nozzles and longer fibers to optimize strength, anisotropy, and deposition efficiency. Mechanical testing at this scale, includes quasi-static and dynamic loading to determine the effectiveness of these structures for absorbing energy and resisting fracture under impact. These findings will directly inform refinements in both design and fabrication. We have made significant progress toward IP protection of these discoveries, and, through the Purdue Office of Technology Commercialization, are expanding industry engagement to position 3D-printed concrete barriers as a competitive alternative to conventional roadside barrier and precast infrastructure solutions.

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

<u>Task 1- Architected Material Designs and Fabrication</u>: Task 1 comprises four integrated subtasks aimed at adapting and scaling the 3D concrete printing process for the Large-Scale Robotic Arm (LSRA) system. *Subtask 1.1* focuses on advancing toolpath design. Subtask 1.2 focuses on the development of a fork-type nozzle to improve flow control, speed, and reliability. This is key to demonstrating the feasibility and efficiency of industrial translation. Subtask 1.3 focuses on adapting the fiber-reinforced concrete mixture for large-scale printing, evaluating the impact of long fibers on printability, flowability, and structural performance. Subtask 1.4 is a study of printing parameters, including nozzle size, shape, and the interplay between fiber length and deposition quality, to optimize both process efficiency and mechanical outcomes in large-scale printed structures.

<u>Task 2 - Mechanical Testing</u>: We have initiated the mechanical testing of large-scale bioinspired architectures under both quasi-static and dynamic loading conditions. Current efforts focus on fabricating test specimens and setting up drop-tower impact experiments to evaluate strength, toughness, energy dissipation, and crack resistance. These results will provide critical insights and metrics for guiding final design refinements and commercialization.

<u>Project Progress:</u>

3. Progress for each research task

<u>Task 1 Architected Material Designs and Fabrication:</u>

<u>Task 1.1 Toolpath design (100% - please reference to previous quarterly reports)</u>

<u>Task 1.2 Nozzle development (95% Completed)</u>

To ensure fabrication efficiency and industrial feasibility, significant revisions were made to the multi-nozzle extrusion system design based on challenges identified during Task 1.4 of the experimental work. The initial concept, which featured iris-style diaphragm valves, flexible hoses, and PID controllers for individual flow control to each nozzle, was studied, analyzed, and evaluated. The risk analysis showed that this design is not practical for large-scale printing on 3D surfaces. Specifically, the nozzle shaving issues observed during printing trials (e.g., where the nozzle physically collided with and dragged through previously deposited material (when printed at steeper angles) necessitated a fundamental redesign that prioritizes geometric adaptability and simplified flow distribution for enhanced regularity over the active flow modulation.

We now have a revised design that simplifies the manifold architecture to a single, robust distribution block that uniformly distributes the concrete mixture to multiple nozzles, eliminating the need for individual valve control. This approach reduces mechanical complexity, eliminates potential failure points associated with moving parts in viscous cementitious flows, and provides a more reliable solution for continuous extrusion. To address the variable nozzle height requirements identified in Task 1.4, where optimal standoff distance varies significantly with surface inclination and printing direction, each nozzle will now incorporate an adjustable tip mechanism. These tips will dynamically modify their vertical position using time-of-flight (ToF) sensors that continuously measure the real-time distance between the nozzle and the substrate surface. This sensor-based feedback system, controlled by Proportional-Integral-Derivative (PID) algorithms, enables each nozzle to maintain an optimal height independently by continuously adjusting its position based on distance measurements. This prevents both material instability due to excessive standoff and geometric interference resulting from insufficient clearance. The integration of ToF sensors with PID control enables real-time adaptive height adjustment, eliminating the need for pre-programmed kinematic changes to the robotic arm. This provides a more flexible and responsive solution for printing complex, non-planar geometries.

Figure 1. Experimental validation of nozzle height effects on filament deposition quality across planar inclined surfaces

Task 1.3 Mixture development (100% completed)

Building on the first quarter's optimization of fiber dosage ranges and pumping requirements, exploratory work focused on investigating fiber reinforcement strategies aimed at improving interlayer bonding and mechanical properties of 3D printed elements. Initial printing trials were conducted using 12 mm and 8 mm PVA fibers, with excellent fiber alignment observed during extrusion. Fibers were consistently oriented along the print direction, which is particularly critical for achieving the anisotropic mechanical behavior targeted in the sinusoidal Bouligand architecture. This alignment enhances the material's ability to redirect and twist propagating cracks—a fundamental toughening mechanism that significantly increases energy absorption and damage tolerance, essential properties for impact-resistant roadside barriers.

Task 1.4 Printing parameter study progress (63% completed):

During the second quarter, we conducted a comprehensive evaluation of printing quality on planar inclined surfaces using the theoretical model established during the previous reporting period. This study specifically investigated the relationship between nozzle height and filament geometry when printing on flat planes inclined at 15°, 30°, and 45° angles, revealing critical insights into the challenges of out-of-plane printing at large scale. These planar tests serve as foundational work toward the goal of printing sinusoidal Bouligand structures with varying amplitude-to-wavelength ratios (A/λ). The primary objective was to determine the optimal nozzle height that would yield filament geometries with aspect ratios (width/thickness) closest to 1.0, which represents ideal filament shape for structural integrity and consistent layer bonding.

Tests were performed across five different nozzle heights (Position 1=17.6 mm, position 2=29.3 mm, position 3=41.0 mm, position 4=52.7 mm, and position 5=64.4 mm) for each slope angle as shown in Fig. 1, with measurements taken for both upward and downward printing directions. The results, shown in Fig. 2, demonstrated significant variation in aspect ratios depending on the combination of nozzle height, slope angle, and printing direction. At the 15° slope, nozzle heights of 41.0 mm produced moderately consistent aspect ratios of 2.01 (upward) and 2.23 (downward). For the 30° slope, the 41.0 mm nozzle height showed aspect ratios of 1.76 (upward) and 2.38 (downward), while the 29.3 mm height yielded 1.58 (upward) and 2.93 (downward). At the steepest 45° angle, the trends became more pronounced: the 52.7 mm nozzle height produced aspect ratios of 1.21 (upward) and 3.22 (downward), while the 64.4 mm height achieved 1.29 (upward) and 2.04 (downward), suggesting that greater

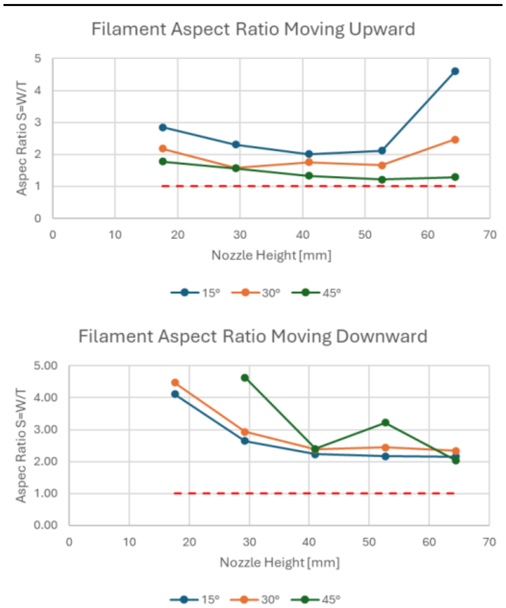


Figure 2. Filament Aspect Ratio S, for different Nozzle heights at 15°, 30°, and 45° moving upward (Top figure) and downward (bottom).

nozzle heights are necessary to maintain filament quality on steeper inclines. Notably, several test conditions at extreme geometries resulted in unmeasurable filaments. Experimental validation revealed significant practical challenges that were not captured by the theoretical model. As shown in Figure 3, filament deposition remained relatively controlled across all three angles in the upward direction. As the nozzle height increased to positions 4 and 5, printing stability deteriorated significantly. The increased distance between nozzle and surface caused the extruded material to exhibit a wobbly, uncontrolled deposition pattern, particularly evident in the 15° samples, where the filament lost its defined shape. More critically, at the steeper angles of 30° and 45°, the combination of high nozzle position and surface inclination resulted in nozzle collision with previously deposited material. The nozzle physically shaved or dragged through the fresh filament during subsequent passes, disrupting the layer geometry and compromising interlayer bonding. These observations revealed that while higher nozzle positions theoretically reduce aspect ratios, they simultaneously introduce flow instability and kinematic interference issues, making them unfeasible.

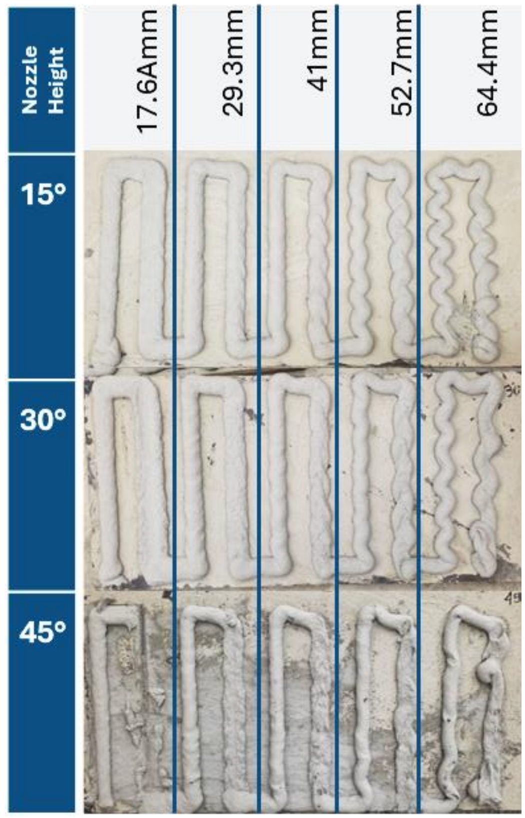


Figure 3. Filament deposition quality on inclined surfaces at varying nozzle heights. Positions 1 to 5 from left to right

To address these challenges for future sinusoidal surface printing, we explored an alternative approach that involved positioning the nozzle normal to the target surface throughout the print path. Using the toolpath generated in Task 1.1, we programmed the robotic arm with a custom reference frame in which the *x*-axis was oriented tangent to the toolpath and the *z*-axis was perpendicular to the local surface mesh. The intent was to maintain a consistent nozzle-to-surface relationship regardless of the local slope angle, thereby potentially achieving more uniform filament deposition across varying inclinations. However, this approach also proved unfeasible for large-scale implementation. The continuous reorientation required to maintain normal alignment with the sinusoidal surface resulted in drastic and rapid changes in the arm's joint configurations. These transitions exceeded the kinematic limits of the robotic arm's wrist joints, generating uncorrectable motion errors in the compiled RAPID program. The software indicated multiple instances where the required orientations were either unreachable or would necessitate singularity passages that could not be resolved within the arm's operational envelope. Figure 4 depicts the generated RAPID code simulation, showing the position of the robotic arm for two consecutive toolpath lines. The drastic change in arm configuration between these adjacent lines is clearly visible, requiring joint rotations that exceed the system's kinematic capabilities. These findings underscore the complexity of maintaining dimensional accuracy in large-scale 3D concrete printing on non-planar surfaces. Both the fixed-nozzle height approach and the normal-surface alignment strategy revealed fundamental limitations when applied to steep inclinations and sinusoidal geometries. Our focus has now shifted to alternative methods for managing out-of-plane printing quality (task 1.2).

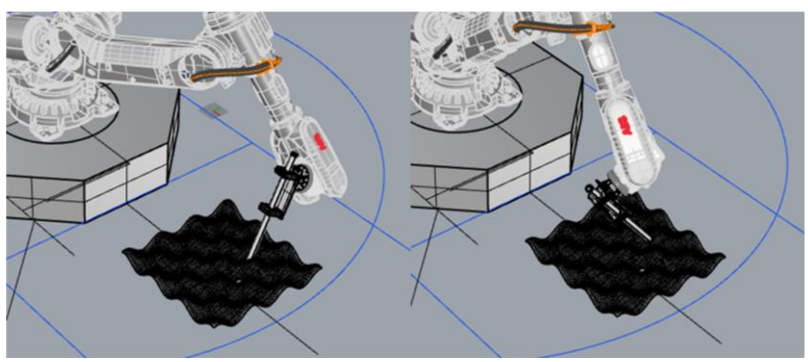


Figure 4. RAPID code simulation showing robotic arm configuration for two consecutive toolpath lines during normal-surface alignment printing.

Task 2 Mechanical Testing:
Task 2.1 Flexural and compressive tests (30% Completed)

Progress in Task 2.1 this quarter focused on completing essential preparatory activities and finalizing test protocols to enable the next phase for material and structural testing. With the successful fabrication of foam support structures (as described in the previous report) now complete, and the ongoing resolution of printing parameter challenges in Task 1.4, the groundwork is firmly in place to begin specimen fabrication. The optimization of printing parameters—particularly regarding nozzle height management on inclined surfaces and fiber alignment strategies developed in Task 1.3—has positioned the team to commence specimen production for flexural and compressive testing during the next reporting period. The abovementioned challenges had to be resolved before reliable test specimens could be manufactured, and their completion marks a significant milestone in advancing toward mechanical characterization of the sinusoidal Bouligand structures.

Task 2.2 Perform drop-tower impact test (20% Completed):

The Manual for Assessing Safety Hardware [31], which regulates various roadside safety devices, elements and barrier systems, defines six levels of testing. For each level, a design vehicle, speed, and impact angle are specified based on the scenarios most likely to occur during the service life of the device. The impact severity and total kinetic energy were calculated using equations (1)– (2):

Kinetic energy for each Test Levels					
Test Level	Design Vehicule weight (Kg)	Speed (Km/h)	Angle	Impact severity (kJ)	Total Kinetic Energy (kJ)
1	1100	50	25	18.95	106.10
	2270	50	25	39.10	218.94
2	1100	70	25	37.14	207.95
	2270	70	25	76.64	429.13
3	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
4	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	10000	90	15	209.34	3125.00
5	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	36000	80	15	595.44	8888.89
6	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	36000	80	15	595.44	8888.89
				595.44	8888.89

Table 1. Impact severity and total kinetic energy

$$IS = {}^{1}/_{2}\, M(V \sin(\theta))^2 \quad (1) \qquad KE = {}^{1}/_{2}\, MV^2 \quad (2)$$

As shown in Table 1, the maximum impact severity corresponds to Design Level 6, which involves a 36,000 kg truck impacting at a velocity of 80 km/h and an angle of 15°. This results in approximately 600 kJ of energy. As full-scale crash testing is planned pending collaboration and support from industry partners, the team is using tests that can still capture energy dissipation and validate structural performance of the barrier material. The first approach considered was to validate the concept using a conventional drop-tower test. The drop tower, owned by the research group at the Pankow Laboratory in the Hampton building on Purdue's campus, has a usable height of 1.82 m and a plate mass of approximately 105 kg. The current configuration of this machine is shown in Figure 5. With this setup, the maximum speed that the mass can achieve is given in equation (3).

$$V = \sqrt{2gh} = \sqrt{2 * 9.81\ {}^{m}/_{s^2} * 1.82m} = 5.975\, {}^{m}/_{s} \qquad (3)$$

With this velocity, the maximum achievable energy is expressed in equation (3). Based on the volume of the actuator, the maximum available mass is approximately 105 kg. Accordingly, the maximum impact severity and total kinetic energy for this machine are given in equation (4):

$$KE = {}^{1}/_{2} * 105\ kg * (5.975\, {}^{m}/_{s})^2 = 1.874\ kJ \qquad (4).$$

These calculations confirm that laboratory drop-tower testing operates at a different energy scale than full-scale vehicular impact, which is expected and appropriate for this research phase. The 1.874 kJ available energy provides sufficient capacity to characterize the fundamental mechanical response of the sinusoidal Bouligand architecture, including crack propagation patterns, energy dissipation mechanisms, and failure modes. To maximize the scientific value of this testing regime, specimens are being designed at a scale that enables meaningful deformation and damage progression within the available energy range while preserving the critical architectural features fiber orientation, layer interface geometry, and sinusoidal periodicity, that govern the material's toughening behavior.

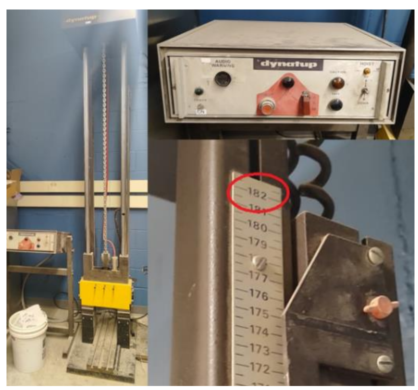
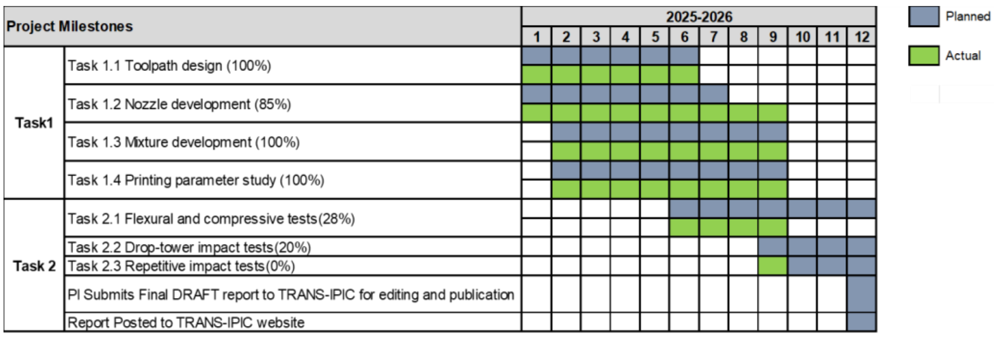


Figure 5. Drop tower set up

Current work focuses on establishing the relationship between specimen geometry, impact energy, and measured performance metrics such as peak force, displacement, and total energy absorbed. These data will quantify the specific energy absorption capacity (energy per unit volume) of the bio-inspired architecture, providing a material property that can be scaled to predict full-scale barrier performance. Parallel quasi-static testing performed as part of Task 2.1 will complement the dynamic results by isolating rate-dependent effects and validating the architecture's ability to redirect crack propagation through the designed layer interfaces. This combined experimental approach provides comprehensive mechanical characterization of the sinusoidal Bouligand concept, establishing the performance foundations necessary for future full-scale validation and enabling direct comparison with conventional precast barrier materials.

4. Percent of research project completed



5. Expected progress for next quarter

As we enter the final quarter of Phase II, efforts will focus on specimen fabrication, mechanical testing, and project completion. The first third of the period will be dedicated to fabricating specimens for flexural and compressive strength testing using the refined printing parameters established in Task 1.4 and the fiber-reinforced mixtures validated in Task 1.3. Particular attention will be paid to maintaining consistent fiber alignment and achieving uniform layer deposition across the sinusoidal geometry to ensure representative mechanical behavior.

During the second third of the quarter, fabrication will shift to producing specimens specifically designed for impact testing, allowing the previously printed flexural and compressive specimens to complete their 28-day curing period and develop full mechanical properties. Concurrently, any final adjustments to mix proportions and printing parameters will be implemented in Tasks 1.3 and 1.4 to optimize printing quality based on observations from the specimen fabrication runs.

The final third of the quarter will focus intensively on mechanical testing and data analysis. Flexural and compressive tests will be conducted on cured specimens to quantify strength, stiffness, and failure mechanisms of the sinusoidal Bouligand architecture. Impact testing will follow to evaluate energy absorption and damage tolerance under dynamic loading conditions. These results will provide comprehensive validation of the bio-inspired design's structural performance and will be mapped to AASHTO/FHWA performance thresholds. Final documentation, including preparation of manuscripts for submission and compilation of the Phase II final report, will also be completed during this period.

6. Educational outreach and workforce development

The team of 3-co-PIs and 5 PhD students are teaching CE497: “3D Printing for Infrastructure Applications” at Purdue University

Figure 6. Faculty and students in our CE497 class (Fall 2025)

7. Technology Transfer – To date, this project has generated five provisional patent applications and disclosures with the Purdue Office of Technology Commercialization (OTC). In parallel, we have increased our industry engagement efforts. Three NDAs have already been signed with companies, and a list of 20 additional companies has been identified by Purdue Innovates and OTC for targeted outreach. Our team is now taking a more aggressive approach to coordinating meetings and exploring collaboration opportunities with these firms. This expanded effort will accelerate the translation of our research into commercial products and help ensure that the solutions developed are aligned with industry needs.

Research Contribution:

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:

   - *Y. Wang, A.E. Douba, J. Olek, P. D. Zavattieri,J.P. Youngblood, Better, Cheaper, Greener: A high-performance Cementitious Composite for Sustainable Concrete 3D Printing, to be submitted to Nature Communications.*

   - *Y. Wang, L. Shyamsunder J. Olek, P. D. Zavattieri, J.P. Youngblood, Impact resistant sinusoidally-architected Bouligand 3DPC materials inspired by the mantis shrimp, to be submitted to Advanced Materials.*

Provisional Patent Applications submitted (Purdue Office of Technology Commercialization)

1. *Youngblood, J. P., Olek, J., Zavattieri, P. D., Wang, Y., Douba, E. A., Low Carbon, Low Cost Cement Mix Containing Cellulose Nano Fiber and Limestone Filler For 3D Concrete Printing, (Available for License)*
2. *Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Energy-Absorbing Roadside Barriers Using Bio-Inspired Architecture and 3D Concrete Printing (Available for License)*
3. *Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Cubillos, L. David, Reconfigurable acoustic metamaterials for traffic noise reduction (Available for License)*
4. *Zavattieri, P. D., Olek, J., Marika Santagata, Youngblood, J. P., Wang, Y., Hygrolock - reinforcement for building blocks made of earth materials (Available for License)*
5. *Cubillos, L. David, Zavattieri, P. D., Youngblood, J. P., Olek, Multi-Nozzle Extrusion System for Large-Scale Concrete Printing (Disclosure in preparation).*

9. Presentations and Posters of TRANS-IPIC funded research:

   [List any presentations or posters presenting TRANS-IPIC research

   For each presentation or poster provide citation]

   - Delivered the talk titled 'Bio-Inspired Solutions for Roadside Barriers: Exploring 3D Printing as an Alternative Precast Technology' at the TRANS-IPIC Research Highlights Webinar on February 19, 2025, as part of the project's dissemination efforts.
   - Presented "*Effect of Cellulose Nanofibers and Limestone Filler on the Hydration, Rheological Behavior, and Printability of Mortars"*, by Prof. Youngblood and "*Bioinspired Use of Anisotropy and Weak Interfaces to Engineer Damage-Tolerant Cementitious Materials"*, by Prof. Zavattieri *at* DuRe-Transp Workshop, July 27-29, 2025 at University of Texas, Arlington, Arlington TX.
   - Presented the poster "Bio-inspired solutions for roadside barriers: exploring 3d printing as alternative precast technology" at 2025 TRANS-IPIC UTC Workshop.

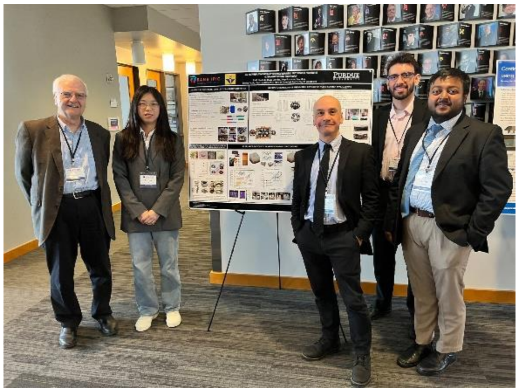


Figure 7. Poster presentation at 2025 TRANS-IPIC UTC Workshop.

   - Presented the poster *"Large-Scale Additive Manufacturing of Bioinspired Bouligand Structures via Controlled Flow, Multi-Axis Printing, and Mix Design Optimization" at* ASU – Swinburne Workshop on Advances in Concrete 3D Printing.

Figure 8. Poster presentation at ASU – Swinburne Workshop on Advances in Concrete 3D Printing.

- Displayed the posters *"3D printed Concrete Metamaterials: Innovative Solution for Traffic Noise Reduction" and "Mechanical Performance and Novel Development Mixtures for Multi-Scale Additive Manufacturing" at* DuRe-Transp Workshop, July 27-29, 2025 at University of Texas, Arlington, Arlington TX.

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.

Purdue CCE Impact Magazine: Purdue University's recent research highlights significant advancements in 3D-printed construction. Collaborating with Terran Robotics, Purdue engineers are developing sustainable and affordable housing solutions by integrating artificial intelligence with 3D printing technologies. The team is experimenting with 'cob,' a low-carbon material composed of clay, sand, water, and straw, aiming to optimize its strength and resilience for construction applications. This initiative not only addresses environmental concerns but also offers innovative approaches to modern housing challenges.

https://engineering.purdue.edu/CCE/Media/Impact/2025-Spring/building-the-future

Purdue Engineering Distinguished Lecture Series – (September 12th 2024) Description: The Concrete 3D Printing Team presented a poster featuring their latest work, in which research from TRANS-IPIC was highlighted. The poster emphasized Purdue's efforts to advance sustainable and resilient infrastructure through innovative 3D printing technologies.

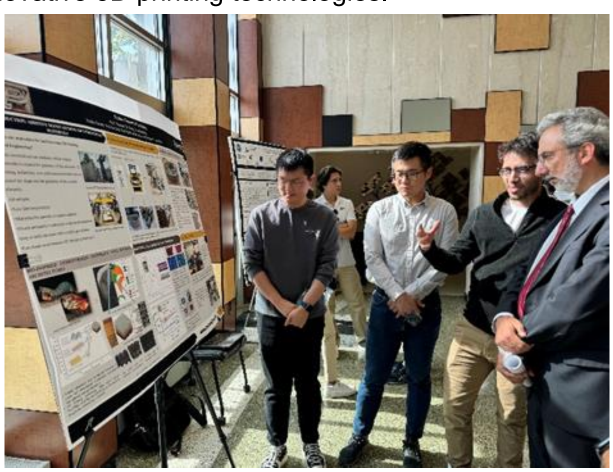


Figure 9. Poster presentation at Purdue Engineering Distinguished Lecture Series research showcase.

6th Annual CEGSAC Research Symposium - – (April 25th, 2025) Description: The symposium brought together students, faculty, and industry leaders to showcase cutting-edge research in civil and construction engineering. Graduate and undergraduate researchers presented their work during the poster session, highlighting advancements in sustainable infrastructure, materials innovation, and smart construction technologies. The event also featured networking opportunities with industry partners, fostering collaboration between academia and the professional sector, The Concrete 3D Printing Team presented a poster featuring their latest work, in which research from TRANS-IPIC was highlighted.

Figure 10. Poster presentation at 6th Annual CEGSAC Research Symposium.

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. = 4(in 2025, for phase II)

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 2 papers to be submitted that include an acknowledgement of TRAN-IPIC.

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 2 papers to be submitted that include an acknowledgement of TRAN-IPIC.

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

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0
   - No. PhD dissertations = 1 (Dec. 2024)
   - No. citations of each of the above = 0 (the PhD thesis has not been published yet)

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Research Tool #1 (Toolpath development) = Parametric Toolpath Generation Model for Non-Planar 3D Printing, a computational model developed in Grasshopper for generating toolpaths tailored to non-planar, multi-axis 3D concrete printing. The model allows users to define sinusoidal surface geometries, discretize them into point sets, and create interpolated curves that serve as custom toolpaths for robotic extrusion. This tool supports real-time geometry adjustments and can be adapted to different nozzle configurations and print parameters. Link available upon request.

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in = 1
     - No. lead = 1
   - Advisory committees (No. participated in & No. led)
     - No. participated in = 1
     - No. lead = 0
   - Conference Organizing Committees (No. participated in & No. led)
     - No. participated in = 2
     - No. lead = 0
   - Editorial board of journals (No. participated in & No. led)
     - No. participated in = 2
     - No. lead = 0
   - TRB committees (No. participated in & No. led)
     - No. participated in = 1
     - No. lead = 0

H. Number of relevant awards received during the grant year
   - No. awards received = 1

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 1
   - No. Graduate = 1

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 = 1

References:

[1] L. Morita, A. Asad, X. Sun, M. Ali, and D. Sameoto, “Integration of a needle valve mechanism with cura slicing software for improved retraction in pellet-based material extrusion,” *Addit. Manuf.*, vol. 82, p. 104045, Feb. 2024, doi: 10.1016/j.addma.2024.104045.

[2] S. De Vries, T. Schuller, F. J. Galindo-Rosales, and P. Fanzio, “Pressure drop non-linearities in material extrusion additive manufacturing: A novel approach for pressure monitoring and numerical modeling,” *Addit. Manuf.*, vol. 80, p. 103966, Jan. 2024, doi: 10.1016/j.addma.2024.103966.

[3] M. K. Mohan, A. V. Rahul, K. Van Tittelboom, and G. De Schutter, “Evaluating the Influence of Aggregate Content on Pumpability of 3D Printable Concrete,” in *Second RILEM International Conference on Concrete and Digital Fabrication*, F. P. Bos, S. S. Lucas, R. J. M. Wolfs, and T. A. M. Salet, Eds., Cham: Springer International Publishing, 2020, pp. 333–341. doi: 10.1007/978-3-030-49916-7_34.

[4] L. He, J. Z. M. Tan, W. T. Chow, H. Li, and J. Pan, “Design of novel nozzles for higher interlayer strength of 3D printed cement paste,” *Addit. Manuf.*, vol. 48, p. 102452, Dec. 2021, doi: 10.1016/j.addma.2021.102452.

[5] N. Zhang and J. Sanjayan, “Extrusion nozzle design and print parameter selections for 3D concrete printing,” *Cem. Concr. Compos.*, vol. 137, p. 104939, Mar. 2023, doi: 10.1016/j.cemconcomp.2023.104939.

[6] M. David, N. Freund, K. Dröder, and D. Lowke, “The effects of nozzle diameter and length on the resulting strand properties for shotcrete 3D printing,” *Mater. Struct.*, vol. 56, no. 8, p. 157, Oct. 2023, doi: 10.1617/s11527-023-02246-1.

[7] A. Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, “Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture,” *Constr. Build. Mater.*, vol. 145, pp. 639–647, Aug. 2017, doi: 10.1016/j.conbuildmat.2017.04.015.

[8] A. V. Rahul, M. Santhanam, H. Meena, and Z. Ghani, “3D printable concrete: Mixture design and test methods,” *Cem. Concr. Compos.*, vol. 97, pp. 13–23, Mar. 2019, doi: 10.1016/j.cemconcomp.2018.12.014.

[9] B. Panda, C. Unluer, and M. J. Tan, “Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing,” *Cem. Concr. Compos.*, vol. 94, pp. 307–314, Nov. 2018, doi: 10.1016/j.cemconcomp.2018.10.002.

[10] T. T. Le, S. A. Austin, S. Lim, R. A. Buswell, A. G. F. Gibb, and T. Thorpe, “Mix design and fresh properties for high-performance printing concrete,” *Mater. Struct.*, vol. 45, no. 8, pp. 1221–1232, Aug. 2012, doi: 10.1617/s11527-012-9828-z.

[11] D. Asprone, F. Auricchio, C. Menna, and V. Mercuri, “3D printing of reinforced concrete elements: Technology and design approach,” *Constr. Build. Mater.*, vol. 165, pp. 218–231, Mar. 2018, doi: 10.1016/j.conbuildmat.2018.01.018.

[12] S. C. Paul, Y. W. D. Tay, B. Panda, and M. J. Tan, “Fresh and hardened properties of 3D printable cementitious materials for building and construction,” *Arch. Civ. Mech. Eng.*, vol. 18, no. 1, pp. 311–319, Jan. 2018, doi: 10.1016/j.acme.2017.02.008.

[13] F. Lyu, D. Zhao, X. Hou, L. Sun, and Q. Zhang, “Overview of the Development of 3D-Printing Concrete: A Review,” *Appl. Sci.*, vol. 11, no. 21, p. 9822, Oct. 2021, doi: 10.3390/app11219822.

[14] H. Chen, D. Zhang, P. Chen, N. Li, and A. Perrot, “A Review of the Extruder System Design for Large-Scale Extrusion-Based 3D Concrete Printing,” *Materials*, vol. 16, no. 7, p. 2661, Mar. 2023, doi: 10.3390/ma16072661.

[15] T. Kim, R. Trangkanukulkij, and W. S. Kim, “Nozzle shape guided filler orientation in 3D printed photo-curable nanocomposites,” *Sci. Rep.*, vol. 8, no. 1, p. 3805, 2018.
[16] H. G. Şahin and A. Mardani, “Mechanical properties, durability performance and interlayer adhesion of 3DPC mixtures: A state-of-the-art review,” *Struct. Concrete*, vol. 24, no. 4, pp. 5481–5505, Aug. 2023, doi: 10.1002/suco.202200473.
[17] B. Liu and L. Wang, “Research progress on constructability of 3D printed concrete,” in *Journal of Physics: Conference Series*, IOP Publishing, 2024, p. 012048. Accessed: Mar. 25, 2025. [Online]. Available: https://iopscience.iop.org/article/10.1088/1742-6596/2853/1/012048/meta
[18] W. Lao, M. Li, L. Masia, and M. J. Tan, “Approaching rectangular extrudate in 3D printing for building and construction by experimental iteration of nozzle design,” 2017, Accessed: Mar. 25, 2025. [Online]. Available: https://dr.ntu.edu.sg/handle/10220/44502
[19] A. Perrot, D. Rangeard, V. N. Nerella, and V. Mechtcherine, “Extrusion of cement-based materials - an overview,” *RILEM Tech. Lett.*, vol. 3, pp. 91–97, Feb. 2019, doi: 10.21809/rilemtechlett.2018.75.
[20] V. Mechtcherine *et al.*, “Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review,” *Cem. Concr. Res.*, vol. 132, p. 106037, Jun. 2020, doi: 10.1016/j.cemconres.2020.106037.
[21] V. Nienhaus, K. Smith, D. Spiehl, and E. Dörsam, “Investigations on nozzle geometry in fused filament fabrication,” *Addit. Manuf.*, vol. 28, pp. 711–718, Aug. 2019, doi: 10.1016/j.addma.2019.06.019.
[22] S. W. Kang and J. Mueller, “Multiscale 3D printing via active nozzle size and shape control,” *Sci. Adv.*, vol. 10, no. 23, p. eadn7772, Jun. 2024, doi: 10.1126/sciadv.adn7772.
[23] R. O’Neill *et al.*, “Extent and mechanism of phase separation during the extrusion of calcium phosphate pastes,” *J. Mater. Sci.: Mater. Med.*, vol. 27, no. 2, p. 29, Feb. 2016, doi: 10.1007/s10856-015-5615-z.
[24] J. Jhun, D.-H. Lee, A. U. Rehman, S. Kang, and J.-H. Kim, “Development of a real-time geometric quality monitoring system for extruded filaments of 3D concrete printing construction,” *IEEE Access*, 2024, Accessed: Mar. 25, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10530624/
[25] F. Bos, R. Wolfs, Z. Ahmed, and T. Salet, “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing,” *Virtual Phys. Prototyp.*, vol. 11, no. 3, pp. 209–225, Jul. 2016, doi: 10.1080/17452759.2016.1209867.
[26] C. Joh, J. Lee, T. Q. Bui, J. Park, and I.-H. Yang, “Buildability and mechanical properties of 3D printed concrete,” *Materials*, vol. 13, no. 21, p. 4919, 2020.
[27] “3D Concrete Printing: A Systematic Review of Rheology, Mix Designs, Mechanical, Microstructural, and Durability Characteristics.” Accessed: Mar. 25, 2025. [Online]. Available: https://www.mdpi.com/1996-1944/14/14/3800
[28] Y. Zhou, F. Althoey, B. S. Alotaibi, Y. Gamil, and B. Iftikhar, “An overview of recent advancements in fibre-reinforced 3D printing concrete,” *Front. Mater.*, vol. 10, p. 1289340, Oct. 2023, doi: 10.3389/fmats.2023.1289340.
[29] A. Ramezani, S. Modaresi, P. Dashti, M. R. GivKashi, F. Moodi, and A. A. Ramezanianpour, “Effects of Different Types of Fibers on Fresh and Hardened Properties of Cement and Geopolymer-Based 3D Printed Mixtures: A Review,” *Buildings*, vol. 13, no. 4, Art. no. 4, Apr. 2023, doi: 10.3390/buildings13040945.
[30] W. Xu, D. Jiang, Q. Zhao, and L. Wang, “Study on printability of 3D printing carbon fiber reinforced eco-friendly concrete: Characterized by fluidity and consistency,” *Case Stud. Constr. Mater.*, vol. 21, p. e03589, Dec. 2024, doi: 10.1016/j.cscm.2024.e03589.
[31] American Association of State Highway and Transportation Officials Executive Committee “Manual for Assessing Safety Hardware,”, 2016.