Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Bio-Inspired Solutions for Jersey and Road Noise Barriers: Exploring 3D Printing as Alternative Precast Technology
PU-23-RP-03

Quarterly Progress Report
For the performance period ending *[10/01/2024]*

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TRANS-IPIC Quarterly Progress Report:

Project Description:

1. Research Plan - Statement of Problem

   The continuous improvement of transportation infrastructure is essential for ensuring the safety of road users and maintaining the efficiency of the transportation network. A critical element of this enhancement is the incorporation of impact-resistant structures in the construction and retrofitting of infrastructure components, such as roadside barriers. **Recently, the growing prevalence of electric vehicles (EVs) presents significant challenges to the performance and safety of these barriers. Due to their increased weight, primarily from large batteries, electric vehicles (EVs) generate greater impact forces that conventional barriers are not designed to withstand [1]-[5].** Recent crash tests have shown that current barriers, which are optimized for lighter gasoline-powered vehicles, often fail to contain heavier EVs, leading to catastrophic consequences [1]-[5]. For instance, as shown in Fig. 1, a 7,000-pound Rivian R1T truck crushed and tore through concrete barriers commonly used as freeway median barriers or to shield highway construction workers from ongoing traffic, with minimal deceleration, posing significant risks to both passengers and infrastructure [1][2]. This issue is due to the fact that EVs can weigh 20% to 50% more than traditional vehicles, drastically increasing the energy transferred during collisions [1][2].

   As EVs become a larger portion of the vehicle fleet, enhancing the energy absorption capacity and impact resistance of roadside barriers has become urgent and essential issue. Developing more robust barrier designs capable of handling these heavier loads is critical not only for public safety but also for preserving transportation infrastructures, which are not currently designed to accommodate vehicles of such weight. **Cody Stolle, Assistant Director of the Midwest Roadside Safety Facility, mentioned that researchers at the facility are working on a new barrier system designed to accommodate a wider range of vehicles [3]. Additionally, Mick Syslo, Deputy Director at the Nebraska Department of Transportation, noted that "thousands of miles" of guardrails and barriers may need to be replaced to meet evolving safety requirements [4].**

   In our project, we aim to utilize 3D printing technology and bio-inspired design principles to enhance the energy absorption capacity of concrete barriers, thereby improving their ability to ensure future roadway safety. We have demonstrated the ability to make concrete barriers both stronger and more energy-absorbing under impact conditions— a breakthrough achieved by combining innovative architectures, inspired by the adaptations of extreme animals in nature, with 3D concrete printing technology.

Fig-1. A 7,000-pound Rivian R1T truck crushed and tore through concrete barriers commonly used as freeway median barriers or to shield highway construction workers from ongoing traffic, with minimal deceleration, posing significant risks to both passengers and infrastructure [1][2].

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

Task 1: Fabrication

Task 1.1: Develop a specialized printing head for accurate deposition of concrete in a layer-by-layer fashion, optimizing for strength, durability, and high-strength structures for Large Area Lab Scale (LALS) and Large-Scale Robotic ARM (LSRA) printers.

Task 1.2: Design and fabricate a printing head for extruding polymeric material, strategically integrating it into the biomimetic Jersey barrier design to create energy-absorbing weak interfaces. During our first year, we will implement this in our LALS printer and will plan our implementation for the LSRA printer in subsequent years.

Task 2: Architected Material Designs

Task 2.1: Develop biomimetic architectures inspired by nature to optimize energy dissipation in the Jersey barriers, incorporating weak interfaces, cellular structures, and geometric patterns using both LALS and LSRA printers.

Task 2.2: Study and develop architected materials specifically tailored for acoustic barriers, aiming to mitigate road/traffic noise and the use of shape-shifting materials for reconfigurable barriers that can adapt to different noise patterns and frequency spectra variations.

Task 3: Material Characterization and Testing

Tasks 3.1: Conduct comprehensive material characterization and testing of the 3D printed biomimetic Jersey barriers, including mechanical tests to assess strength, deformation behavior, and energy absorption capacity under quasi-static conditions. Additionally, perform dynamic (drop-tower) impact tests to evaluate performance in simulated collision scenarios.

Tasks 3.2: Evaluate efficiency of reconfigurable traffic noise barriers based on shape-shifting materials using low-cost impedance tube testing to measure sound absorption and transmission loss of the barriers in a controlled environment.

Project Milestones (assuming August 1 Start Date and a 12 month project)		2023-2024											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Task 1.1 (100% completed)												
2	Tasks 1.2(100% completed)												
3	Task 2.1(100% completed)												
4	Task 2.2(100% completed)												
5	Task 3.1(100% completed)												
6	Task 3.2(100% completed)												
4	PI Submits Final DRAFT report to TRANS-IPIC for editing and publication (waiting for TRANS-IPIC to send the final report formant)												
5	Report Posted to TRANS-IPIC website												

Project Progress:

3. Progress for each research task

Task 1: Fabrication

Task 1.1: 100% completed- please reference to previous quarterly reports

Task 1.2: 100% completed

In this task, we aimed to explore the fabrication method for co-printing cement paste and polymer materials to create functional composite materials. This involved designing and adding silicon delivery printing head (syringe) to the small scale printer which was already equipped with the cement paste syringe (Fig. 2a and 2b). The silicone used exhibited suitable rheological properties for extrusion, though there were some challenges with its buildability. To address this issue, we designed a toolpath geometry that allowed for installing the silicone layer between cement paste filaments in a way that allowed for deposition of the second layer of cement paste without squeezing out the silicon (Fig. 2(a) and (b)). The cement paste-silicone composite material was designed to create hard-soft material interfaces to optimize energy absorption capacity. Mechanical performance of this composite was evaluated through three-point bending flexural tests. As shown in Fig. 2c, the 3D-printed cement paste samples exhibited brittle failure upon reaching peak load, while the composite samples, consisting of both cement paste and silicone, displayed multiple small load drops in the load-displacement curves. This behavior suggests the formation of multiple cracks rather than a single catastrophic failure. Fig. 2d presents the fracture pattern of the composite sample, which shows multiple cracks formation as well as strong stretch-recovery behavior due to the presence of silicone. The results demonstrate that by combining polymer with cement paste, a highly stretchable composite with enhanced energy absorption capacity can be created, outperforming samples prepared from paste with no silicon addition,

This achievement is significant for the continuation of the project. Future efforts should focus on enhancing the rheological properties of the polymer, possibly through polymer synthesis or increasing solid content. The ability to print both polymer and cement paste opens opportunities to optimize energy absorption in materials for roadside barriers. In nature, hard-soft interfaces are used to dissipate energy effectively. For example, the integration of flexible polymeric nanofibers with rigid mineral components results in a periodic variation in stiffness [9]. When this feature is combined with the helicoidal (Bouligand) architecture, it promotes crack twisting, thereby increasing the material's ability to resist fracture and absorb more energy [9].

Now, with the capability to 3D print two materials, we could incorporate soft polymers into cement paste during the printing process, mimicking nature's hard-soft material combinations. This could further optimize energy absorption properties. Furthermore, 3D printing with polymer-cement materials offers the potential to develop phase-transforming cellular materials with reconfigurable properties for the reconfigurable noise barrier proposed in this project. These materials could function as actuators, dynamically adjusting the periodic arrangement of phononic crystal structures to optimize noise mitigation based on varying conditions such as vehicle type, speed, and construction activities.

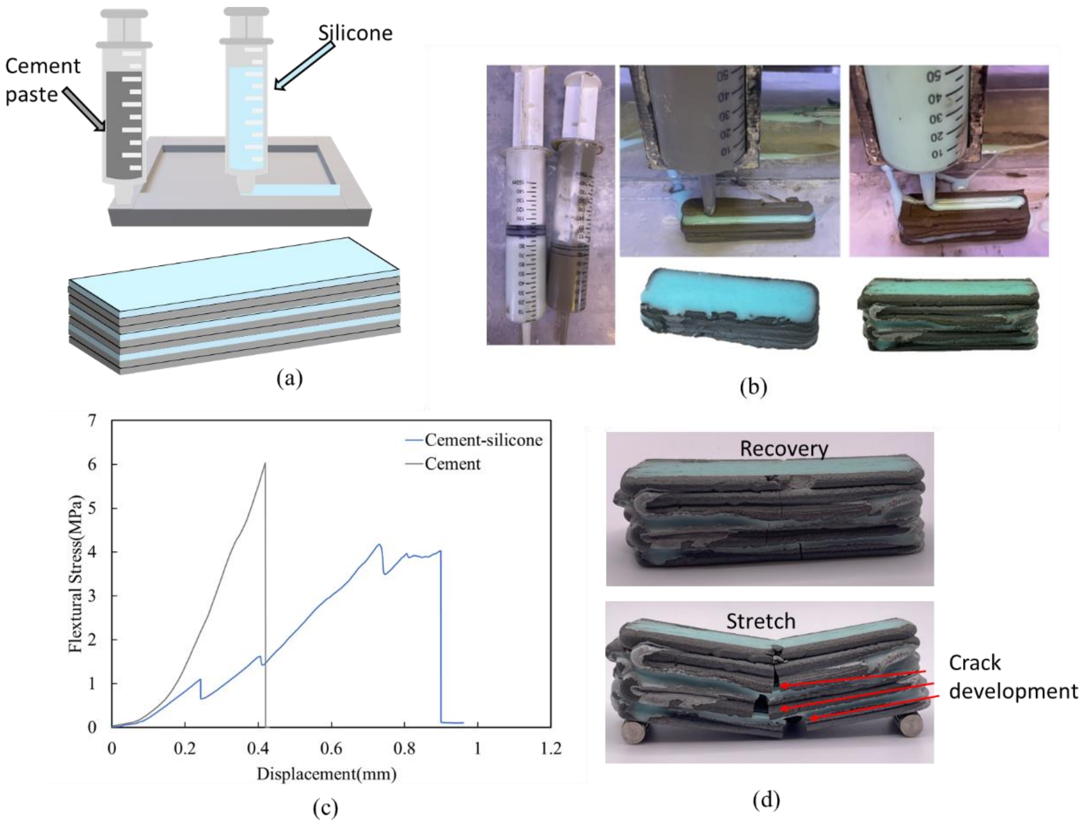


Fig-2. (a) Schematic illustrated 3D printing of cement paste and silicone using syringe extrusion. (b) Examples of cement-silicone composite samples fabricated by small scale 3D printer(c) Load-displacement curve from the three-point bending test for 3D-printed samples: cement paste -only and cement paste-silicone composite (d) fractured sample showing high stretch recovery behavior

Task 2: Architected Material Designs

<u>Task 2.1</u>: 100% completed- please reference to previous quarterly reports

<u>Task 2.2</u>: 100% completed

Noise is pervasive in various environments, originating from sources like rooms, industries, roads, airports, and other forms of transportation. Traffic noise frequencies fluctuate based on factors such as vehicle types, weather, road conditions, and traffic flow. Studies have shown that these variations in traffic conditions can cause the dominant noise frequencies to shift between 500 and 1200 Hz [6][7]. Traditional barriers, such as vertical walls, have several drawbacks. Firstly, they are heavy and can impose significant loads and moments on their foundations. Secondly, when oblique sound waves strike these barriers, they often cause increased diffraction at the top edge, allowing more noise to propagate beyond the barrier. This diffraction reduces the effectiveness of the barriers across different frequencies. Additionally, these designs block airflow and light to adjacent areas, which can negatively impact nearby residents. Therefore, it is crucial to develop novel types of barriers that can address these issues and effectively attenuate the constantly shifting dominant frequencies of traffic noise, thereby reducing the harmful effects of noise pollution.

In this study we developed an adaptive acoustic metamaterial by integrating phononic (or sonic) crystals with phase-transforming cellular materials (PXCMs)(Fig 3). PXCMs are innovative materials that can be designed with a bistable configuration [8], allowing them to reconfigure the periodic arrangement of phononic crystals dynamically. Fig. 3 (c) and (d) presents a schematic of the structure featuring hexagonal lattice patterns in both open and closed configurations. This reconfigurability is essential because it enables the periodic structure of the phononic crystals to adapt to varying traffic noise frequencies, enhancing noise mitigation across a broad spectrum. 3DP cement paste sample with triangle configuration was used as the column elements in the phononic crystals. As illustrated in Figure 3, using PXCM as an actuator allows the arrangement of phononic crystals to be actively modified. The spacing between the columns of these crystals is a key factor that determines the specific frequencies at which noise is mitigated. Adjusting these distances can significantly adapt the spectral properties of the bandgaps, allowing the metamaterial to respond effectively to changes in noise frequency. Research by Thota et al. (2017) has demonstrated that compact hexagonal patterns are particularly effective at mitigating high-frequency noise compared to more loosely arranged hexagonal patterns. This finding underscores the potential of Reconfigurable acoustic metamaterials in applications where adaptive noise control is crucial, such as in urban environments affected by fluctuating traffic noise levels.

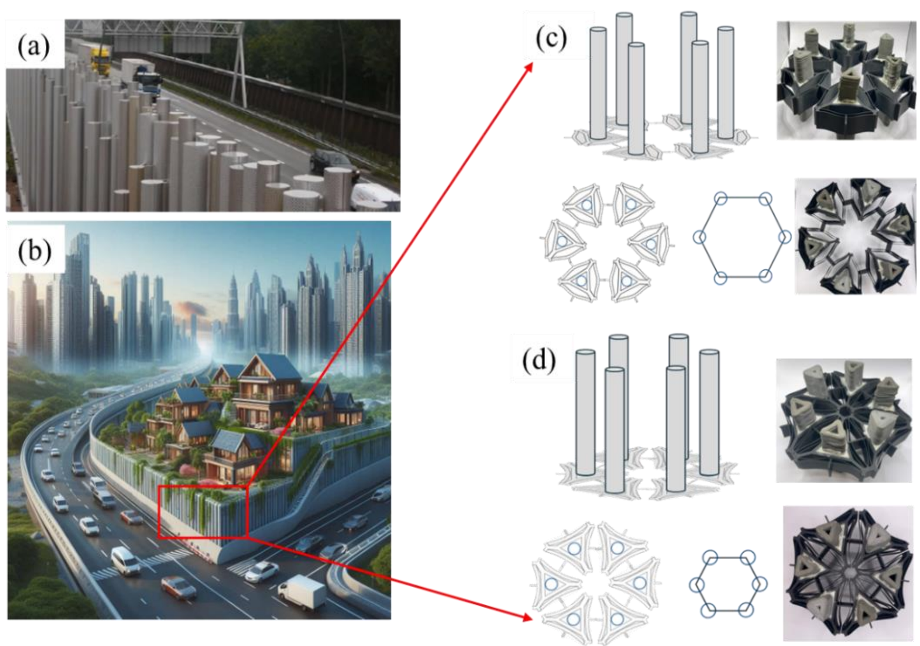


Fig. 3 - (a) Periodic pipe noise barrier on a highway [7]; (b) illustration of the phononic/sonic crystal noise barrier; (c) schematic and specimens developed for reconfigurable phononic/sonic crystals integrated with phase-transforming cellular materials (PXCMs), featuring hexagonal lattice patterns in two configurations: (c) open configuration and (d) closed configuration.

The actuation mechanism is an important aspect for future work. It is preferable for the switch of the bistable material to be operated manually, not with density sensors. In the past, some elements that have been unnecessarily automated in the locks have caused many problems. The simplest solution that achieves the desired results should be the preferred one. There are fairly simple solutions based entirely on mechanical systems. In this regard, we could consider mechanical actuation methods using cables. In some cases, gravity could be harnessed through strategically located weights on the bistable material, offering effective mechanical approaches for the barrier's operation. The actuation mechanisms are discussed below. **Some of those actuation mechanisms are being considered in a patent application as well for another application.**

Actuation Mechanisms for Bistable Unit Cells

The functionality of the Phase Transforming Cellular Materials (PXCMs), whether 1D or 2D, crucially relies on their ability to undergo controlled bistable transformations [10]-[17]. The challenge lies in actuating these individual bistable unit cells efficiently to enable the desired cascade effect for opening and closing the acoustic barrier. Several actuation mechanisms can be employed to achieve this, each offering unique advantages and considerations. Fi. 4 present an example on how the internal forces can be applied at the cell level to induce phase transformation. In other words, these internal forces (that can be actuated remotely), allow the configurations changes from one stable configuration to another stable (or metastable) configuration.

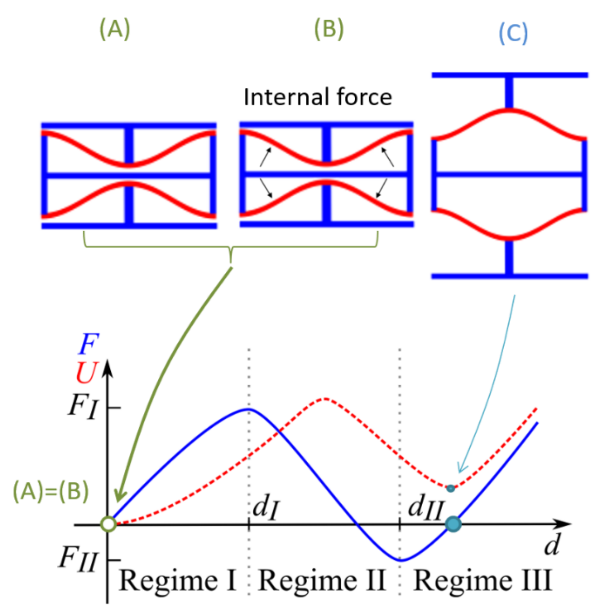


Fig. 4: Principle of hydraulic/pneumatic or mechanical actuation with PXCMS. This schematics shows where the forces should be applied to force once stable configuration to the other stable (or metastable) configuration [12],[13].

Actuation mechanisms for the noise barrier:

1. Hydraulic/Pneumatic Actuation:

Principle: Strategically positioned bladders within key cells can inflate and deflate on demand.

Operation: The inflation and deflation of bladders induce small forces, effectively toggling the bistable unit cells between stable configurations. If the PXCM is bistable, the bladders have to be placed in a way that a certain group of bladders will "close" the cell and the second group will "open". In this way, we ensure the switch from one state to another one remotely by just selectively controlling the pressure of the individual bladders through small hoses. The PXCM does not have to be necesarially bistable. It can also be metastable. Being metastable allows for additional functionality such that there is no need to add additional bladders to switch back to the original configuration.

Advantages: Fluid-based actuation allows for precise control and minimal mechanical wear.

Considerations: Regular inspections are necessary to ensure the integrity of the fluidic system.

2. Mechanical Actuation:

Principle: Actuation through mechanical means, such as bicycle braking cable systems. These cables can be operated remotely via motors, mechanical gear systems, levers, etc.

Operation: A set of actuated cable systems can replicate the effects of hydraulic/pneumatic actuation without relying on fluid presence.

Advantages: Eliminates the need for fluid systems, reducing potential maintenance complexities.

Considerations: Mechanical performance requires careful calibration, and periodic inspections are essential.

3. Smart Materials Actuation:

Options: Utilization of smart materials, including shape memory alloy wires, shape memory alloy devices, piezoelectric elements, etc.

Operation: These materials can undergo controlled shape changes in response to external stimuli, providing an alternative actuation method.

Advantages: Offers diverse options for actuation without the need for elaborate external systems.

Considerations: Calibration and validation are necessary for ensuring reliable performance.

4. Architected Materials Analogous to Shape Memory Alloys (ASMA):

Reference: ASMA concept, as presented by Zavattieri and his group [10], [11], [18]-[23]

Principle: Leveraging architected materials to analogously achieve shape memory alloy-like behavior.

Operation: Mimicking the characteristics of shape memory alloys for controlled actuation of bistable unit cells.

Advantages: Utilizes principles inspired by shape memory alloys while providing additional flexibility in material design.
Considerations: Implementation may require careful material selection and validation. The choice of actuation mechanism depends on specific design considerations, balancing factors such as precision, maintenance requirements, and system robustness.

Fig. 5 presents a schematic view of a modular assembly of the barriers. Depending on the size of the barriers, the number of unit cells can be reduced. Further work on the lattice design will be undertaken to optimize the modular assembly, taking advantage of the proposed lattice's modular nature. Since the horizontal movement of the barrier must be allowed, rolling supports could be used to enable movement and support the barrier's weight. This modular assembly holds the advantage of being lightweight, adaptable, and allowing air and light to pass through.

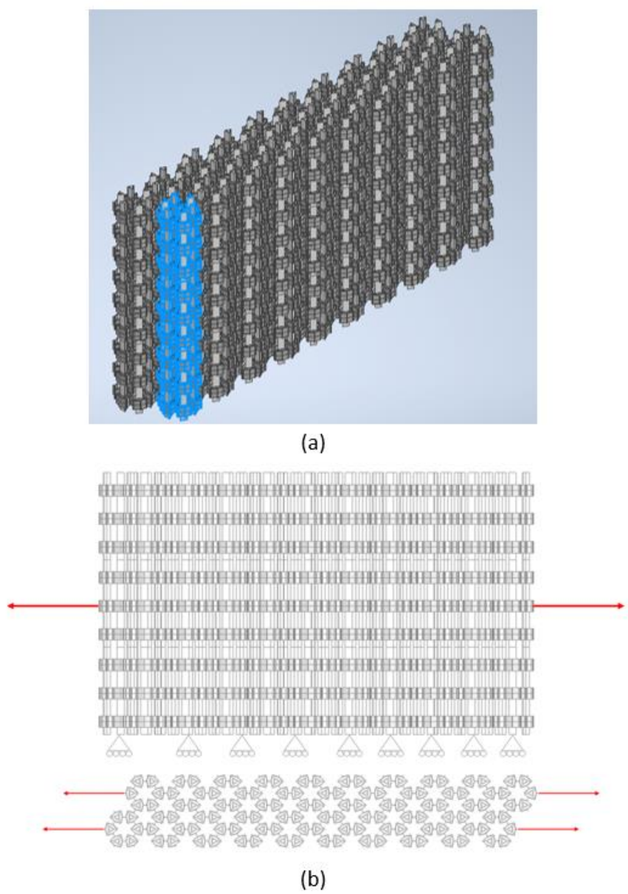


Fig. 5 - (a) Proposed periodic noise barrier with reconfigurable lattice: (b) Supports and forces to be applied to assure barrier reconfiguration.

Task 3: Material Characterization and Testing

<u>Tasks 3.1:</u> 100% complete

The reader is recommended to refer to the previous quarterly report for the results of quasi-static test. In the report we present the result for dynamic (drop-tower) impact tests to evaluate performance of the bio-inspired architectures under impact loading condition. Drop tower impact test was conducted for sample with 3DP and casted fiber reinforced mortar. Five sample configuration was tested including: cast mortar with and without fiber, 3DP sample with Bouligand, sinusoidal Bouligand, and regular straight printing configuration (Fig. 6). The drop was conducted with two impact energy: 56.7J and 70.9J.

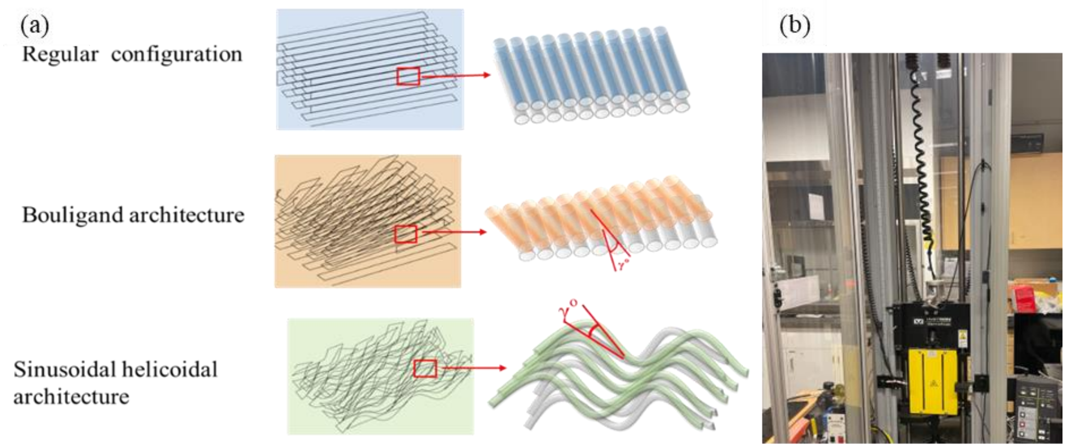


Fig. 6- (a)Schematic showing schematic of 3DP configurations with different architectures including Bouligand, Sinusoidal helicoidal and regular configuration architecture under drop tower impact test (b) Instron drop tower used in this study

Fig. 7 presents the load-deflection results and fracture patterns from the drop tower impact test for cast samples (with and without fiber) and 3D-printed samples using Bouligand, sinusoidal Bouligand, and regular straight filament configurations, subjected to impact energies of (a) 56.7J (drop height of 0.8m) and (b) 70.9J (drop height of 1m). The force-displacement curves highlight the differing abilities of these configurations to respond to dynamic impact loads and absorb energy. The higher peak loads and delayed decline in the curves for the sinusoidal Bouligand and Bouligand samples indicate their enhanced impact resistance at both energy levels. At a drop height of 0.8m(Fig. 7(a)), the sinusoidal Bouligand sample achieved the highest peak force (14,666.4N) and absorbed 56.6J of energy, while the Bouligand sample reached a peak force of 9,968.5N, absorbing 53.6J of energy. The sinusoidal Bouligand sample demonstrated the highest peak load of all samples and exhibited similar energy absorption to the Bouligand sample. The sinusoidal Bouligand design outperformed the other configurations, with a peak load 52.4% higher than the regular 3D-printed samples and 34.8% higher than the cast samples with fiber, while its absorbed impact energy increased by 20.8% and 29.7%, respectively. Compared to the cast sample without fiber, the sinusoidal

Bouligand sample showed a 98.8% increase in peak load and a 102.6% increase in absorbed impact energy.

As shown in Fig. 7(b), At an increased impact energy of 70.9J (from a drop height of 1m), the sinusoidal Bouligand sample shows peak force of 14,133.8N and absorbed 66.3J of energy, while the Bouligand sample reached a peak force of 12,192.5N, absorbing 68.7J of energy. The cast sample with fibers exhibited a peak load of 8,383.8N and absorbed 44.5J of impact energy. The sinusoidal Bouligand and Bouligand samples surpassed the peak load of the cast sample by 68.6% and 45.4%, respectively, and exceeded its absorbed impact energy by 49.2% and 54.6%. Compared to the results at the drop height of 0.8m, the energy absorbed by the sinusoidal Bouligand and Bouligand samples increased, while the energy absorbed by the cast sample remained similar due to the fatal damage it sustained

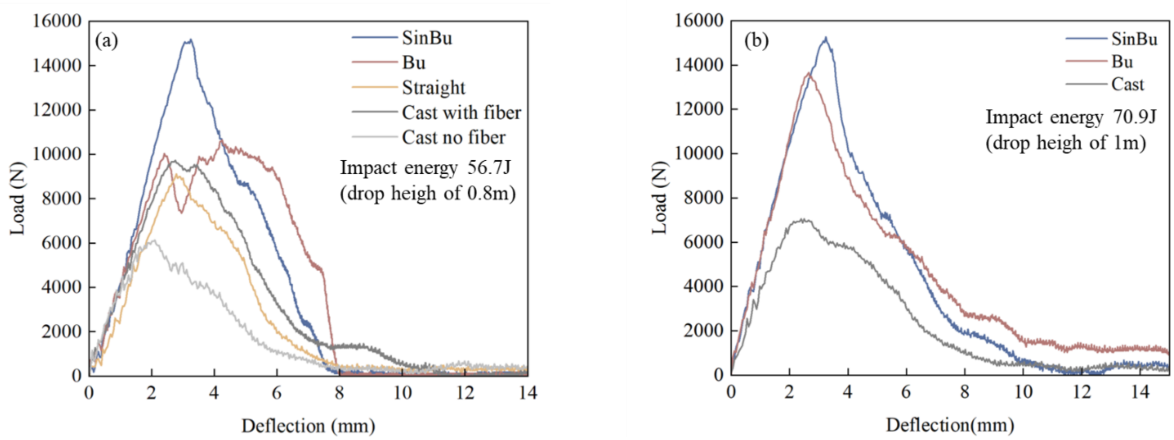


Fig. 6 - Load-deflection results and fracture patterns from the drop tower impact test for cast samples (with and without fiber) and 3D-printed samples with Bouligand, sinusoidal Bouligand, and regular straight filament configurations, subjected to impact energies of (a) 56.7J (drop height of 0.8m) and (b) 70.9J (drop height of 1m).

Fig. 8 (a) compares the fracture patterns and Ashby plot, illustrating the average peak impact load and absorbed energy for different samples under an impact energy of 56.7J (drop height of 0.8m). It is evident that the sinusoidal Bouligand sample exhibits the highest peak load and absorbed energy compared to the other configurations. The Bouligand sample shows a slightly lower peak load but similar absorbed energy compared to the sinusoidal Bouligand. Notably, both the sinusoidal Bouligand and Bouligand samples outperform the cast samples. As seen in the fracture pattern images, these designs demonstrate excellent resistance to crack propagation and maintain their structural integrity. In contrast, the cast samples (with and without fiber) and the regular 3D-printed samples suffer significant structural damage, failing to absorb the full impact energy and and exhibiting severe failure. These results underscore the superior impact resistance of the sinusoidal Bouligand and Bouligand structures. Fig. 8 (b) compares the fracture patterns and Ashby plot, showing the average peak impact load and absorbed energy for different samples under two impact energy levels (56.7J and 70.9J). Both the sinusoidal Bouligand and Bouligand samples exhibit increased energy absorption as the imposed energy rises. These designs are more effective under impact loading conditions compared to the cast samples, owing to their ability to prevent fatal crack development and maintain structural integrity. In contrast, the cast samples fail to absorb higher impact energy due to the extensive damage they sustain under both conditions.

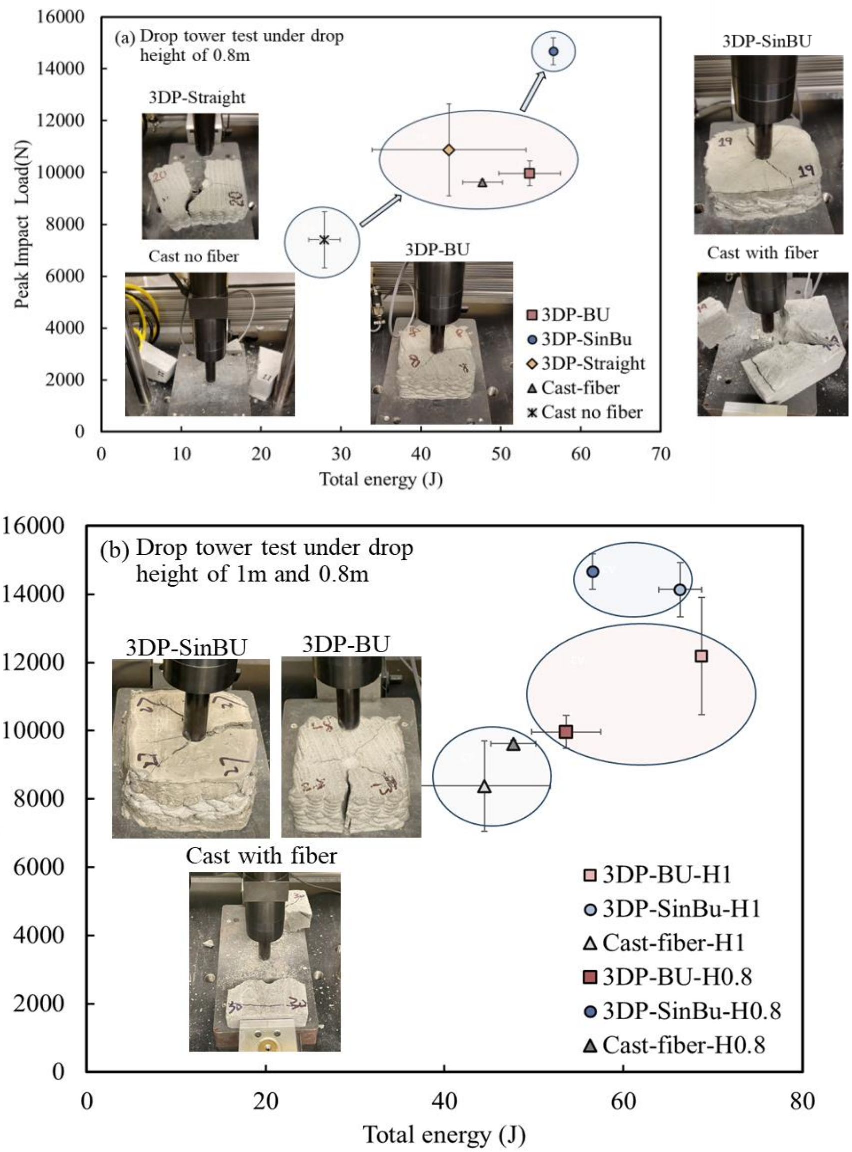


Fig. 8 – Results of drop tower impact test(a) Comparison of fracture patterns and Ashby plot showing the average peak impact load and absorbed energy for different samples under two impact energies: 56.7J (drop height of 0.8m) and 70.9J (drop height of 1m); (b) Comparison of peak impact load and absorbed energy for different samples under an impact energy of 56.7J (drop height of 0.8m)

As mentioned in the project description section, as electric vehicles (EVs) become increasingly prevalent, traditional roadside barriers face significant challenges due to the greater impact forces these heavier vehicles generate. Current designs, optimized for lighter gasoline-powered vehicles, often fail to adequately contain EVs, leading to catastrophic failures during collisions that impact both the infrastructure and the vehicle [1]-[5]. Our research highlights the potential for innovative barrier designs that leverage advancements in materials and engineering, specifically through the use of bio-inspired architectures and 3D printing technology. The results from our dynamic impact tests indicate that the sinusoidal Bouligand and Bouligand configurations significantly enhance energy absorption and impact resistance, making them highly suitable for modern roadside barriers. These designs exhibit a remarkable ability to prevent fatal crack development while maintaining structural integrity, which is critical as the weight of the vehicle fleet continues to evolve. The enhanced energy dissipation capacity of these materials translates into improved deflection during impact, allowing barriers to effectively manage the forces exerted by heavy trucks. This capacity for deflection is particularly important, as it enables the barrier to absorb energy while reducing the velocity of the impacting vehicle. By dissipating energy effectively, these barriers not only minimize damage to themselves but also protect the vehicles involved, enhancing overall safety. This design approach is crucial for preventing heavy trucks from rebounding into traffic or penetrating the barrier, which could have catastrophic consequences for road users. In summary, our findings underscore the necessity of re-evaluating and redesigning roadside barriers in light of the evolving vehicle landscape. By incorporating bio-inspired designs and advanced materials, we can develop barriers that better withstand the challenges posed by modern vehicles, particularly heavier EVs, thereby significantly improving roadway safety.

Tasks 3.2: 100% completed

The purpose of this experiment is to measure the noise absorption ratio of a barrier under two different shape configurations in a controlled environment with noise isolation. The barrier is a shape-shifting structure, and by changing its shape, the distance between the phononic crystals embedded in the barrier varies. The goal is to observe how this change in configuration affects the barrier's ability to absorb sound at different frequencies. Specifically, we aim to determine how efficient the barrier is at absorbing noise in both configurations and how the absorption ratio shifts across the frequency spectrum.

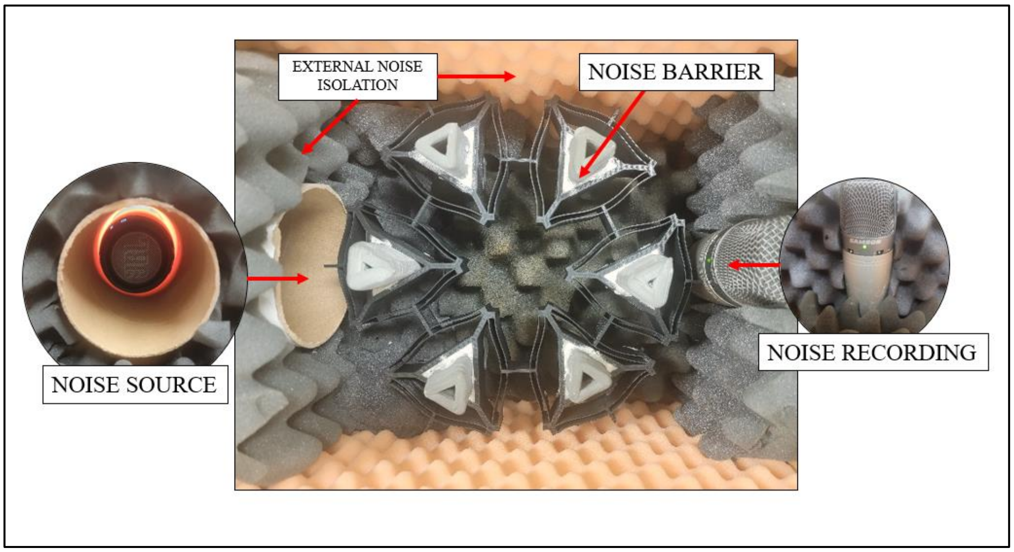


Fig. 9 – Noise absorption experiment set up.

A MATLAB code was implemented to facilitate this experiment by generating sound at various frequencies, playing these frequencies through a speaker on one side of the barrier, and recording the sound on the other side using a microphone. The RMS power of the original signal is compared to that of the recorded signal, and the difference is used to calculate the noise absorption ratio, given by the formula:

$$Absortion\ Ratio = 1 - \frac{\text{RMS of Original Signal}}{\text{RMS of Recorded Signal}}$$

By running the experiment with both barrier configurations, we analyzed the variation in noise absorption ratio across different frequencies, identifying which configuration provided more effective noise absorption at specific frequencies. The plot of absorption ratio vs. frequency reveals how the arrangement of phononic crystals affects sound attenuation in each configuration.

The experiment was conducted using a scaled-down prototype of the proposed barrier, following the scaling method described by Thota and Wang [7]. The noise barrier depicted in Figure 9 is a 1:7 scale model of the barrier intended for roadway use. Since the frequency range of traffic noise typically varies between 350 and 1500 Hz, the frequencies for the experiment were scaled accordingly, and the testing spectrum was set from 2.5 kHz to 10.5 kHz [7].

A preliminary run of the program was performed to measure the noise absorption of the system depicted in Figure 9 without the noise barrier inside, and the results are shown in Figure 10 (blue). The figure also shows the results for the experiments conducted with the barrier set in the open configuration (red) and closed configuration (green). The frequencies tested during the experiment range from 2.5 kHz to 10.5 kHz, with 10 Hz increments.

In a preliminary run of the experiment, peaks in the noise absorption ratio were detected at 4200 Hz and 9067 Hz, which can be interpreted as system resonance frequencies (without the barrier), where wave cancellation occurs. When the barrier was placed, these resonance frequencies were slightly altered, either increasing the absorption or shifting the peak frequencies. At 4200 Hz, the absorption ratio increased by 10.609% with the barrier in the open configuration and by 26.83% in the closed configuration. The resonance frequency at 9067 Hz shifted to 9183.8 Hz in the open configuration and to 9772 Hz in the closed configuration, with a 10.83% decrease in the absorption ratio.

Changes in noise absorption are evident across the frequency spectrum when switching between configurations. The most significant change occurred at 6150 Hz when transitioning from the open to the closed configuration, where the absorption ratio increased from 0.282 (open configuration) to 0.914 (close configuration). Additionally, for frequencies of 10257Hz, the absorption ratios increase from 0.348 (open configuration) to 0.808 (close configuration). A similar effect can be observed at 3130 Hz, where the absorption ratio increased from 0.188(open configuration) to 0.469 (close configuration). In accordance with the previously described scale factor (based on the literature [7]), the major impacts for real-world applications (1:1 scale) are expected to occur at frequencies around 447.142 Hz, 878.571 Hz and 1428.571 Hz and above.

When switching from the closed to the open configuration, the highest impacts are observed at 5080 Hz, where the absorption ratio increased from 0.421 to 0.914, and at 7120 Hz, where the absorption ratio rose from 0.228 to 0.776. These frequencies correspond to 725.714 Hz and 1017.142 Hz, respectively, for (1:1 scale) [7]. On the other hand, at frequencies near 2760 Hz, 3500 Hz, 3900 Hz, 5570 Hz, 6870 Hz, 7716 Hz, and 8750 Hz, no major changes in the absorption ratio were observed.

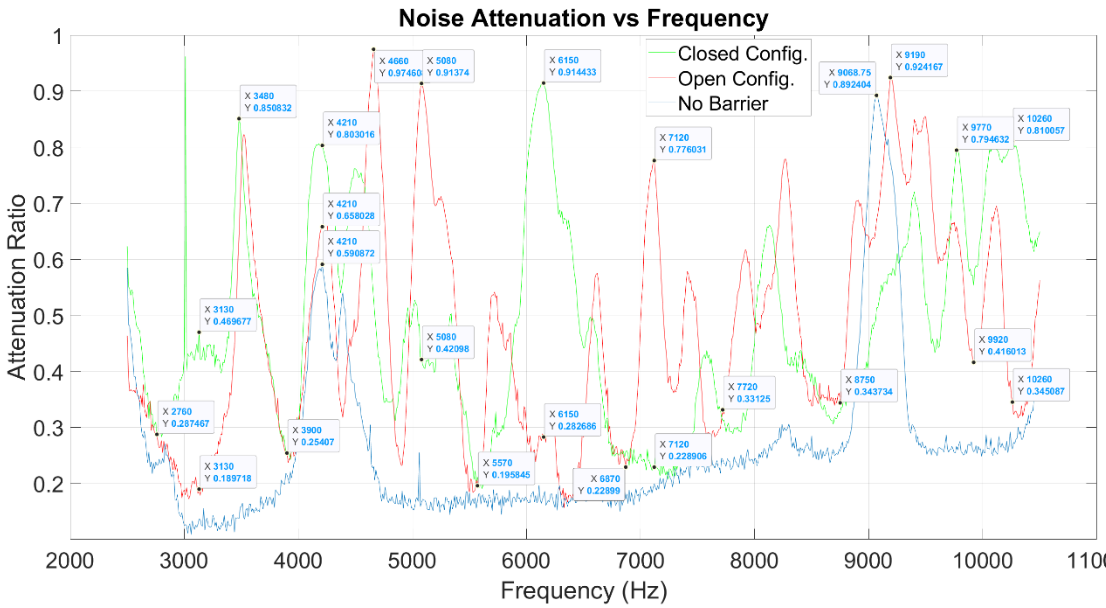


Fig. 10 – Absorption Ratio – Frequency graphic for different shape-shifting barrier configurations.

These low-cost DIY experiments demonstrated the ability to alter the barrier's working frequency intervals, while also emphasizing the need for more advanced data analysis and filtering methods to better understand and mitigate the effects of external noise and system geometry on the results. Future work will focus on increasing noise absorption and stabilizing the effect of barrier configuration changes across the frequency spectrum by modifying the shape-shifting lattice geometry, as well as incorporating other noise-mitigating metamaterials into the barrier to address the frequency ranges where the barrier shows no significant effect on the absorption ratio.

Response to reviewer's comments:

Comments from report in April 1st:

The report lacks a clear connection between the work done and the actual proposed barrier designs or transportation infrastructure in general. It's recommended that the research team establish this connection in future reports and how their technology will improve infrastructure durability. It's not clear whether the stated educational activities are focused on workforce development in the transportation sector.

The authors appreciate the reviewer's comments. The first phase of this project aims to explore the use of 3D printing technology, bio-inspired design, and proper mixture design to enhance the mechanical properties of concrete. These improvements can directly contribute to enhancement of performance of transportation infrastructure, such as roadside barriers. Our results demonstrate that adding cellulose nanofiber to the mixture can significantly enhance the rheological and mechanical properties of 3D-printed concrete. Additionally, we found that filament architectures significantly influence mechanical properties.

3D-printed specimens with regular filament configurations exhibit weakened compressive strength when tested in different directions compared to cast specimens. However, by using a sinusoidal helicoidal architecture, both the compressive strength and work of failure of the 3D-printed samples are improved, surpassing those of the cast specimens. From the drop tower test, we have demonstrated the ability to make concrete barriers both stronger and more energy-absorbing under impact conditions. This enhancement is crucial for applications like roadside barriers, which are often subjected to high impact loads and must possess superior mechanical strength and energy dissipation capacity. Additionally, we evaluated the efficiency of reconfigurable traffic noise barrier design based on shape-shifting materials. These innovative noise barrier designs optimize noise mitigation according to varying conditions, such as vehicle type, speed, and construction activities.

Additionally, the primary objective of this phase was not to investigate the durability performance of 3D-printed concrete. The durability aspects of our design, such as resistance to freezing and thawing and chloride exposure from deicing salt, will be evaluated in future phases.

The educational activities conducted by the research team provide students with knowledge of 3D printing technology, cementitious materials, and basic mechanics. These activities introduce students to fundamental concepts, advanced materials, and technologies relevant to transportation infrastructures.

Comments from report in July 1st:

(1) *The tasks mentioned in the report are different from those proposed (please refer to original proposal). It is recommended that the research team report on the originally proposed tasks (including the subtasks). If necessary, a request should be submitted to the TRANS-IPIC management team to modify the scope of the work from the original plan.*
    Thank you for your comments. In the original proposal, this section presented a revised budget justification (narrative task). Therefore, the report followed the narrative task. However, after communicating with the TRANS-IPIC management team, we have now aligned with and completed the original task outlined in the proposal within this report.
(2) *No mention of plans for testing actual bio-inspired 3D printed barriers under flexure and impact loads as stated in the proposal.*

    Thank you for the comments. The flexural test was presented in the previous report submitted in July, while the drop tower test was performed this quarter.

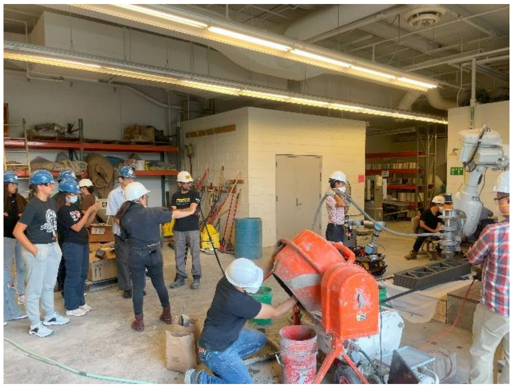
4. Percent of research project completed
   100%

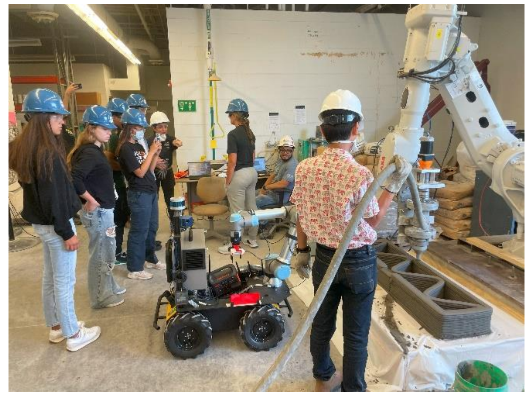
5. Expected progress for next quarter
   This phase one project is 100% completed.

   If year 2 funding is awarded, we will work on the work Task 1 of the proposal submitted in September 2024. In task 1 of the new proposal, we will focus on designing bioinspired architected materials based on the promising results from Phase 1, where small-scale prototypes exhibited superior strength, toughness, and energy absorption capabilities. Building on these findings, we will develop scalable designs that can be applied to full-size roadside barriers.

   In addition, once we receive the template, we will work on preparing the final report.

6. Educational outreach and workforce development
   - During the summer of 2024 (06/2024-08/2024), the research team is collaborating with two Purdue Summer Undergraduate Research Fellows and industry partner Terran Robotics on projects focusing on sustainable earth-based materials and additive manufacturing technology. This research project enables students to explore the impact of novel materials and technologies on the development of general and transportation infrastructures.
   - This summer, our lab had the pleasure of hosting two enthusiastic groups of undergraduate students from Purdue University's 'Summer College for High School Students' and the 'Gifted Education Research and Resource Institute'. These students were eager to learn about 3D printing concrete, and they sought out our lab at Purdue University because of our leading-edge research in this area. We delivered a lecture covering the fundamentals of 3D printing technology. We provided an overview of various 3D printing systems, with a particular focus on their applications in cementitious materials. This lecture aimed to provide students with a understanding of the principles and innovations driving 3D printing technology. Students also participated in lab demonstrations focused on 3D printing concrete. The visit featured notable demonstrations using both a small-scale gantry system and a large-scale robotic arm system. The lab demonstrations highlighted the precision and versatility of the 3D printing equipment in creating intricate designs, and also showcased the technology's ability to manage larger projects and its practical applications in real-world construction scenarios. Another part of the visit was dedicated to demonstrating the compressive testing of 3D printed samples. This test provided insight into the mechanical properties of the printed structures. Additionally, we demonstrated the use of digital image correlation (DIC) to track strain and crack development in the 3D printed samples. This technique allowed students to observe how strain and crack propagation are monitored and analyzed in real time, adding a valuable dimension to their understanding of material performance. Throughout the visit, the students were actively engaged, asking insightful questions and displaying a keen interest in the advanced applications of 3D printing technology. The combination of lectures, hands-on demonstrations, and practical testing provided them with a comprehensive and engaging experience






Questions?
TRANS-IPIC

7. Technology Transfer

Patent submitted under review:

- 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*, under review
- Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Energy-Absorbing Roadside Barriers Using Bio-Inspired Architecture and 3D Concrete Printing
- Zavattieri, P. D., Youngblood, J. P., Olek, J., Wang, Y., Cubillos, L. David, Reconfigurable acoustic metamaterials for traffic noise reduction
- Zavattieri, P. D., Olek, J., Marika Santagata, Youngblood, J. P., Wang, Y., Hygrolock-reinforcement for building blocks made of earth materials

Research Contribution:

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

Two papers under preparation, will include TRANS-IPIC UTC in the acknowledgments section:

- Y. Wang, J. Olek, J. Youngblood, P. Zavattieri, Biomimetic Sinusoidal Helicoidal Architectures Enhance Strength and Impact Resistance of Additively Manufactured fiber reinforced cementitious composite.
- Y. Wang, A. Douba, J. Olek, J. Youngblood, P. Zavattieri, Sustainable Cementitious Composite Containing Cellulose Nano Fiber and Limestone Filler for Concrete 3D-Printing.

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

- Present poster in Purdue Civil and Construction Engineering Research Showcase

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.
No to date

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