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# Developing Lightweight and High-Performance Metamaterial Concrete


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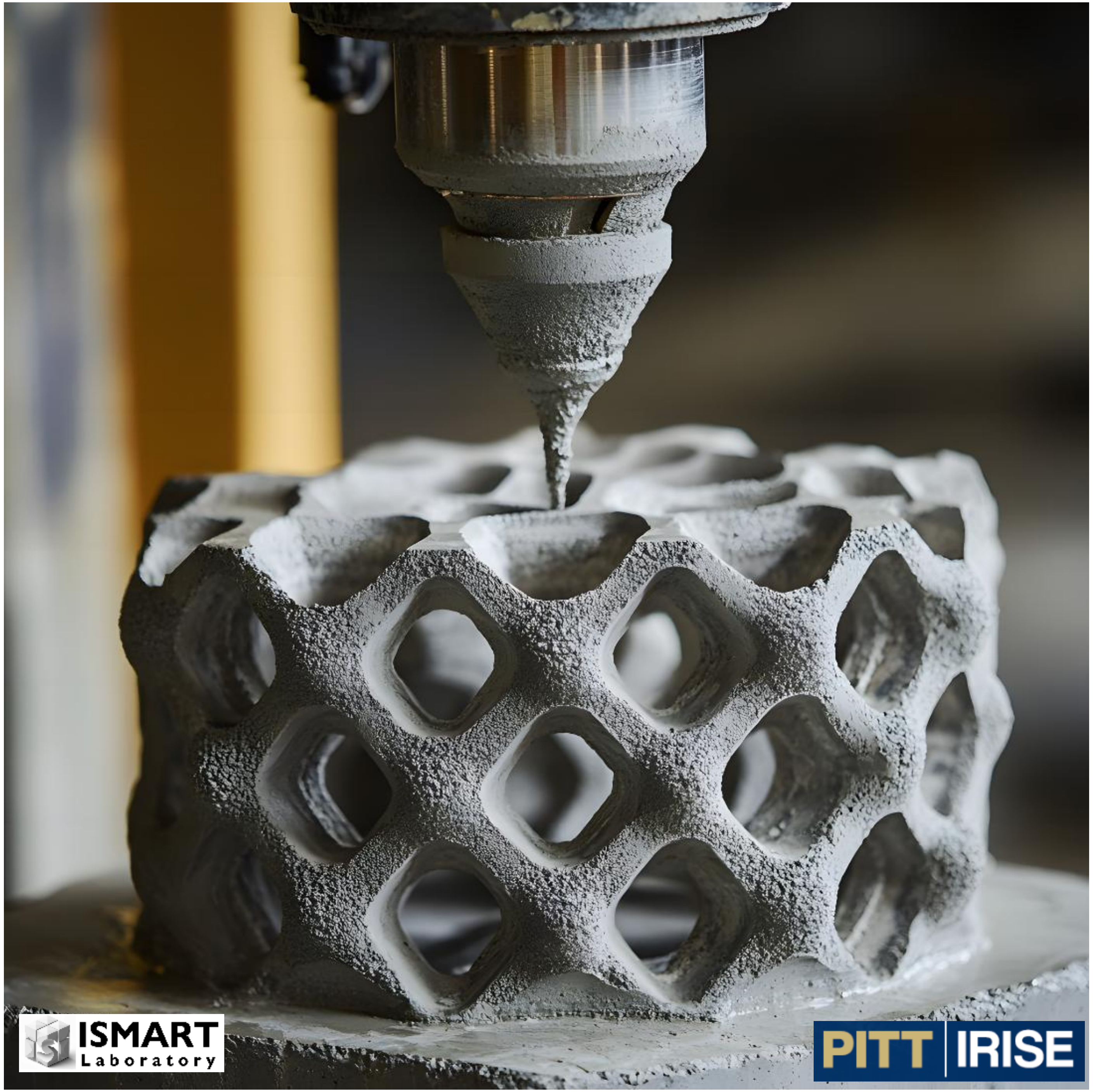
**University of Pittsburgh**


pennsylvania DEPARTMENT OF TRANSPORTATION | ALLEGHENY COUNTY | CDR MAGUIRE ENGINEERING | PENNA TURNPIKE | Michael Baker INTERNATIONAL | CAWP | GOLDEN TRIANGLE CONSTRUCTION GENERAL CONTRACTORS



# Research Problem

For more than a century, concrete technology advances rely mainly on modifying mix compositions

Future performance must be reimagined via internal architectural design

Mechanical metamaterials offer a transformative path, geometry over composition

**Reengineering concrete with tunable strength and energy absorption functionalities in a lightweight, structurally efficient form**

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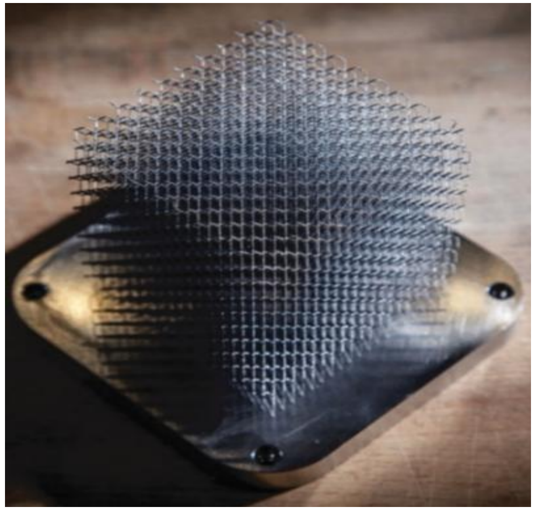
# Mechanical Metamaterials

**Metamaterials**

- Artificial structures
- Often arranged in repeated patterns
- Derive their properties from their designed structure
- Shape, geometry, size, orientation and arrangement

**Metamaterial Types:**

- Electromagnetic Metamaterial
- Photonic or Optical Metamaterial
- Mechanical Metamaterial (MM)
  - Extremal metamaterials
  - Negative metamaterials
  - Ultra-property metamaterials



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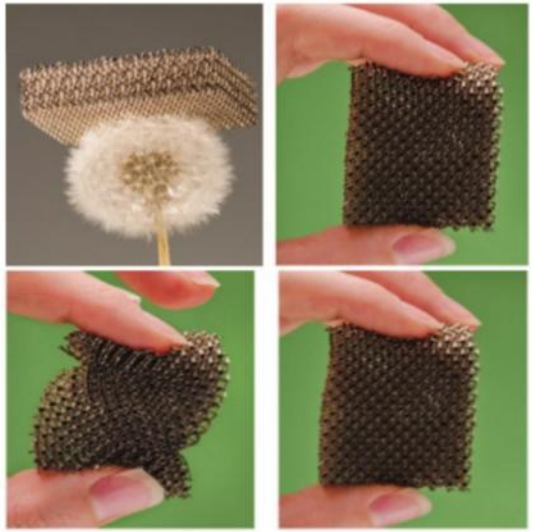

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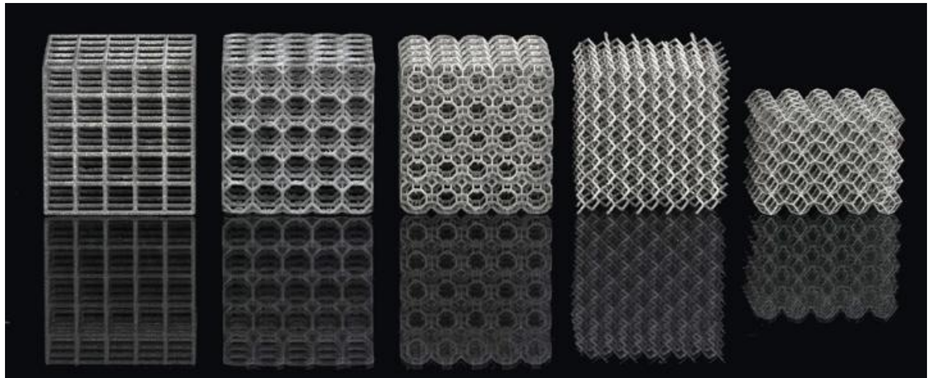

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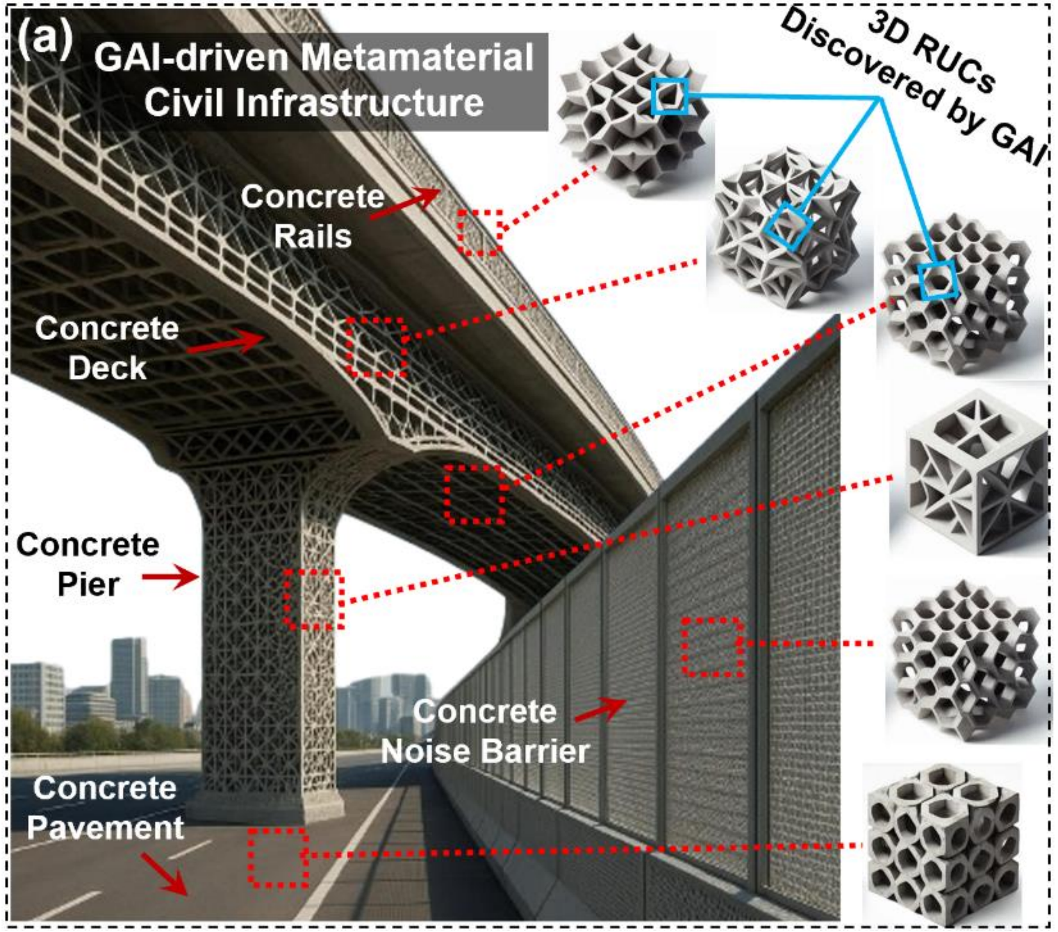
# Vision

A **fundamental shift in the science of concrete design**, and more broadly civil infrastructure materials, from **compositionally** defined to **architecturally** defined




"Structure-specific" metamaterial concrete enables tailored solutions for lightweight and high-strength civil infrastructure systems

# Project Objectives & Approach

## Objectives:

- Developing lightweight and high-performance metamaterial concrete

## Approach:

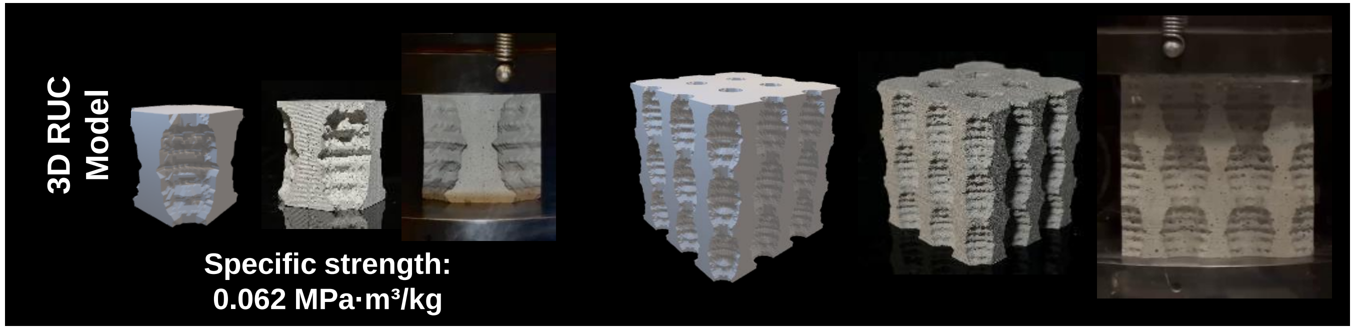
- Mechanical metamaterial design
- Evolutionary generative AI
- Mechanical characterization

**Define mechanical objectives to achieve high strength-to-density ratio**

$$Objective\ function = -(C^H_{1111} + C^H_{1112} + C^H_{1133} + C^H_{2211} + C^H_{2222} + C^H_{2233} + C^H_{3311} + C^H_{3322} + C^H_{3333})$$

**Explore the design space using evolutionary generative AI**

**Fabricate and test**

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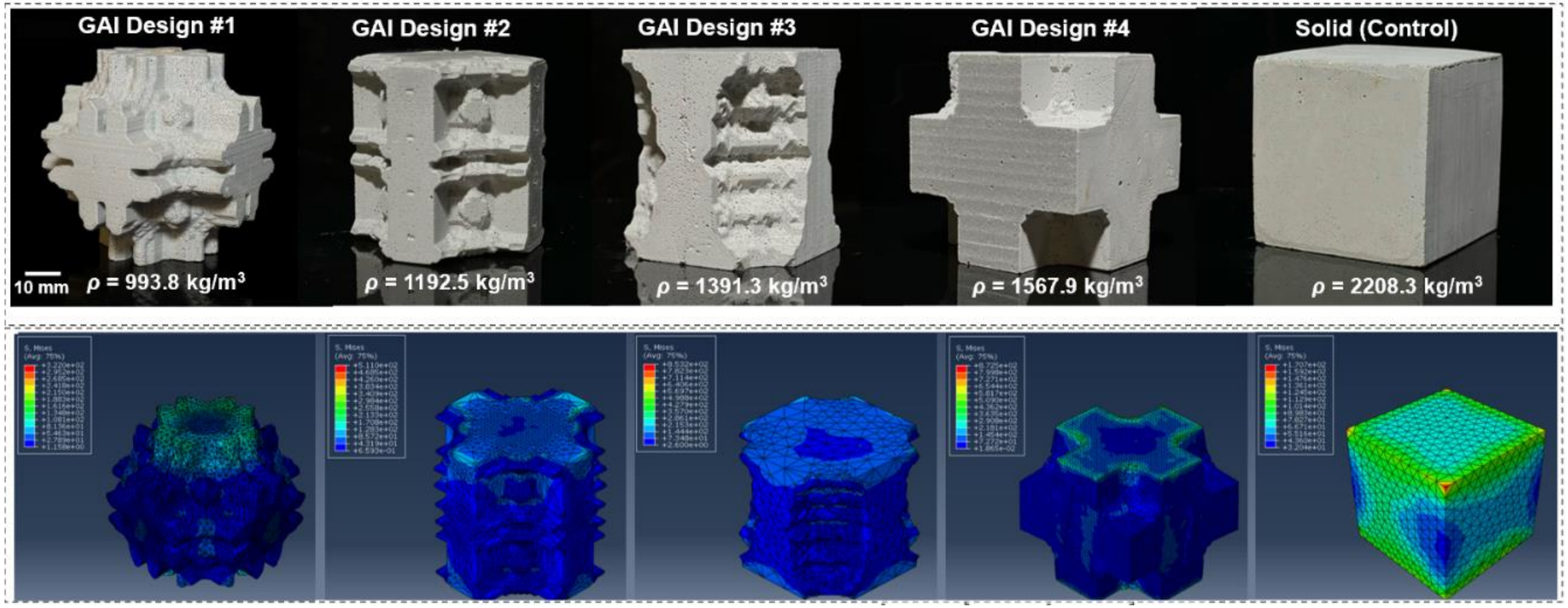
# Optimal Cementitious Designs

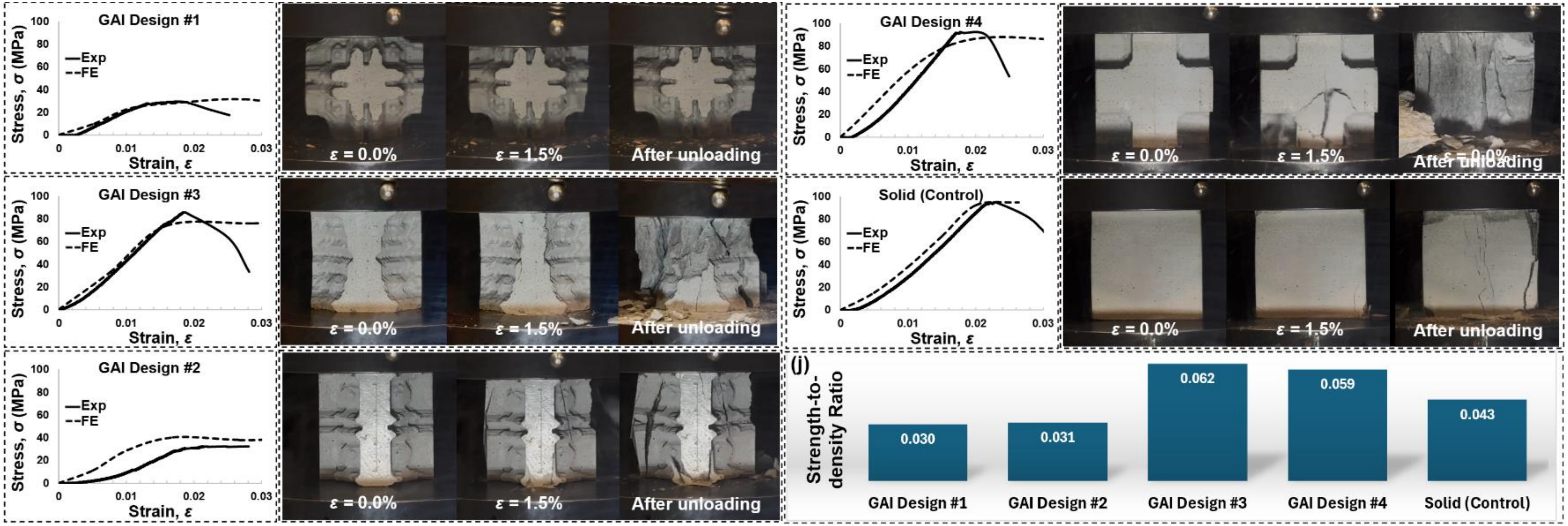
Four representative designs based on their K values, VF, and manufacturability

Ultra-high-performance concrete (UHPC) mix as the parent/bulk material




The density reduction is independent of the type of cementitious bulk materials

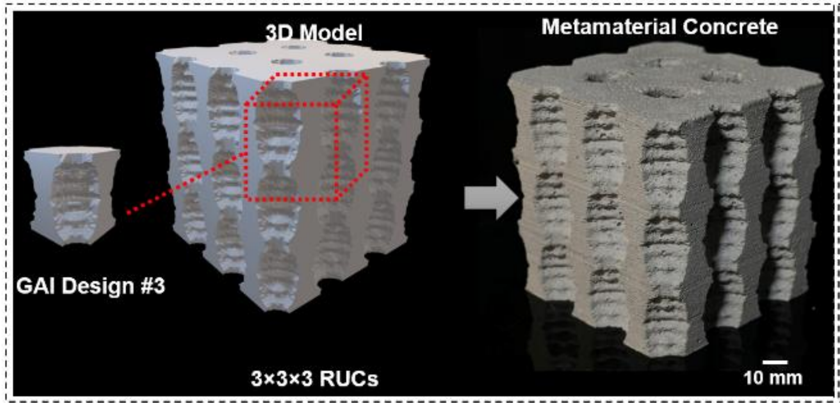
# Results

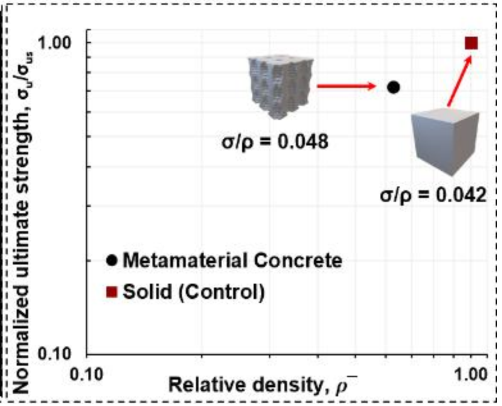


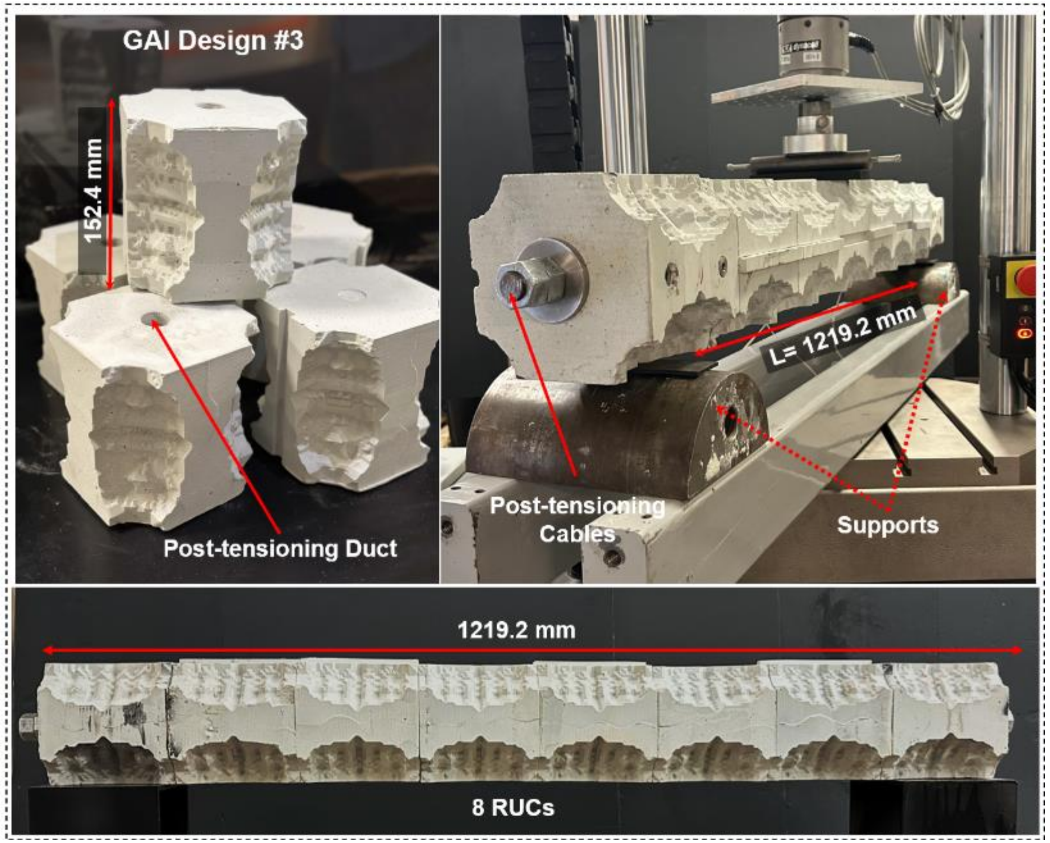

Mild steel (~0.027 MPa·m³/kg), structural steel (e.g., ASTM A36 ~0.025-0.035 MPa·m³/kg), high-strength low-alloy steel (e.g., ASTM A992 ~0.030-0.045 MPa·m³/kg), and common construction aluminum alloys (e.g., 6061-T6 ~0.040-0.065 MPa·m³/kg)

# Large-scale implementation

The transition from laboratory-scale research to large-scale implementation is a crucial step



# Impact

**Engaging students in hands-on projects with advanced materials inspires** broader interest in the future of civil infrastructure design

• Our Pitt ASCE Student Chapter developed bridge prototypes using GAI-designed metamaterials

• Achievements in the 2025 ASCE Mid-Atlantic East & West Student Symposium at Penn State:

- 2nd place in structural efficiency & stiffness (Steel Bridge)
- 1st place in structural efficiency (3D Printed Bridge)

• First-ever academic use of mechanical metamaterials in a civil engineering competition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# Conclusion & Further Works

- **Demonstrated Feasibility:** Successfully validated GAI-driven structure-specific metamaterial concrete as a strong, lightweight alternative to conventional concrete
- **Enhanced Performance:** Showed significant improvements in strength-to-weight ratio with metamaterial concrete
- **Future Directions:**
  - ✓ Clear protocols for material selection, 3D printing, and modular prefabrication ensure their efficiently into construction workflows
  - ✓ Flexural performance can be improved using strategies like post-tensioning, external reinforcements, and grout encapsulation tailored to their geometry
  - ✓ Field testing and regulatory code development are critical for scaling structure-specific metamaterial concrete in bridges, pavements, and modular infrastructure

# Acknowledgement

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## Undergraduate students

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Sophia Roa
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# Thank You

ISMART Laboratory

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We are the "Intelligent Structures and Architected Materials Research and Testing (ISMART)" Laboratory at the University of Pittsburgh