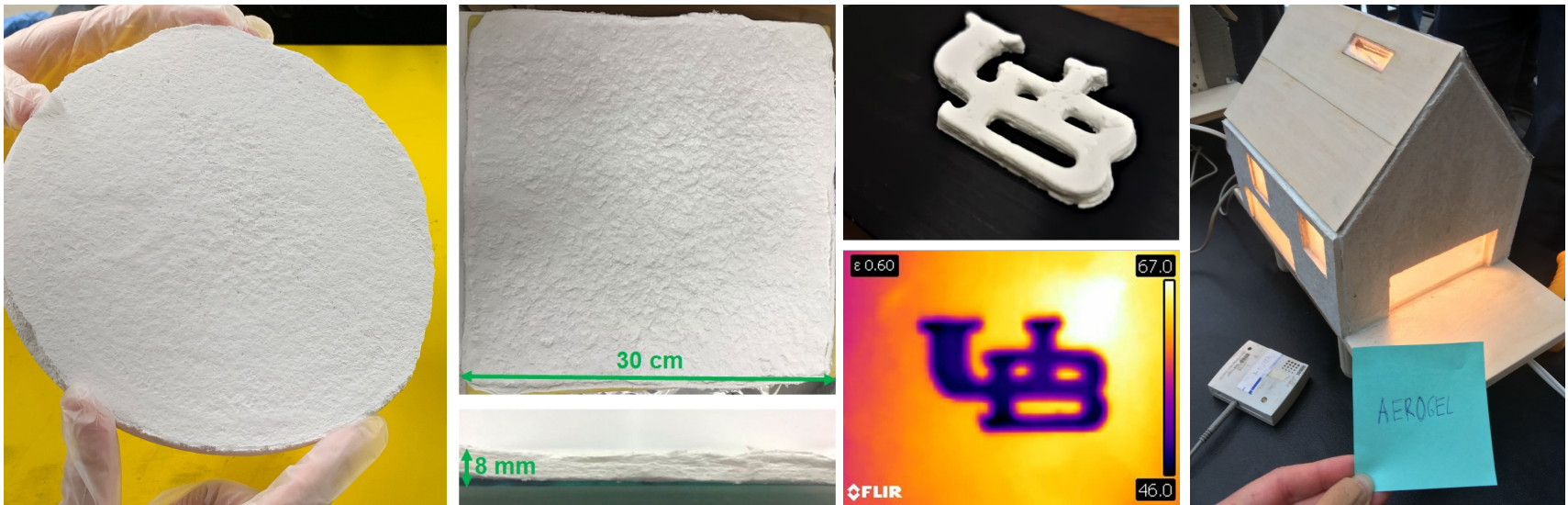


Scalable and Cost-Effective Roll-to-Roll Additive Manufacturing of Highly Durable and Thermal Insulating Silica-Carbon Aerogel



Performing Organization: SUNY University at Buffalo

PI Name and Title: Shenqiang Ren, Professor

PI Tel and/or Email: (716)-645-1431, shenren@buffalo.edu

Project Summary

Timeline:

Start date: 05/01/2019

Planned end date: 04/30/2022

Key Milestones

1. Completed the mechanical and thermal testing for silica aerogels at a thickness of 1 inch with the R-value of R4/in, and compressive Young's modulus of 5 MPa at ambient conditions, 04/30/2020
2. Complete the scalable silica aerogel precursor setup of 50 gram/batch with the throughput of 0.5 kg/day, 4/31/2021
3. Demonstrated the Prototype #4 of 1ft x 1ft silica aerogel blanket with the targeted R-value of R 8/inch, and compressive Young's modulus larger than 5 MPa at a thickness of 1 inch, and achieved the projected target cost of \$1.33/ft2-in, 4/30/2021

Budget:

Total Project \$ to Date:

- DOE: \$1,028,643
- Cost Share: \$257,161

Total Project \$:

- DOE: \$1,500,000
- Cost Share: \$ 375,000

Key Partners:

Unifrax	ORNL
---------	------



Project Outcome:

The project goal is to demonstrate low-cost silica aerogel insulation materials with high R-value, low thermal conductivity and low installed price of R10/inch, and \$0.94/ft2-inch, respectively, which can meet the cost and performance targets of the Department of Energy's 2030 Building Technology Office Emerging Technologies program.

Two journal publications on Y1:

- [Nano Letters, 10.1021/acs.nanolett.9b04411](https://doi.org/10.1021/acs.nanolett.9b04411)
- [Nano Letters, 10.1021/acs.nanolett.0c00917](https://doi.org/10.1021/acs.nanolett.0c00917)

Eight journal publications on Y2:

- [Journal of Materials Chemistry C, 10.1039/d0tc02481c](https://doi.org/10.1039/d0tc02481c)
- [Cell Reports Physical Science, 10.1016/j.xcrp.2020.100140](https://doi.org/10.1016/j.xcrp.2020.100140)
- [Applied Materials Today, 10.1016/j.apmt.2020.100843](https://doi.org/10.1016/j.apmt.2020.100843)
- [Journal of Manufacturing Science and Engineering, 10.1115/1.4048740](https://doi.org/10.1115/1.4048740)
- [Advanced Engineering Materials, 10.1002/adem.202001169, Selected as Front Cover Art.](https://doi.org/10.1002/adem.202001169)
- [Nanoscale Advances, 10.1039/D0NA00655F.](https://doi.org/10.1039/D0NA00655F)
- [ACS Applied Nano Materials, 10.1021/acsanm.1c01280](https://doi.org/10.1021/acsanm.1c01280)
- [ASME Manufacturing Science and Engineering Conference, 10.1115/MSEC2020-8510](https://doi.org/10.1115/MSEC2020-8510)

Team



Team expertise:

- Aerogel chemistry, high-throughput manufacturing and thermal insulation: Ren (UB)
- Nanoporous materials: Swihart (UB)
- Mechanical testing: Armstrong (UB)
- R2R and 3D manufacturing: Zhou (UB)
- R2R manufacturing & thermal insulation: Zhao and Souza (Unifrax)

Aerogel insulation materials chemistry,
mechanical/thermal/soundproof



University at Buffalo
The State University of New York

Thermal insulation R2R manufacturing



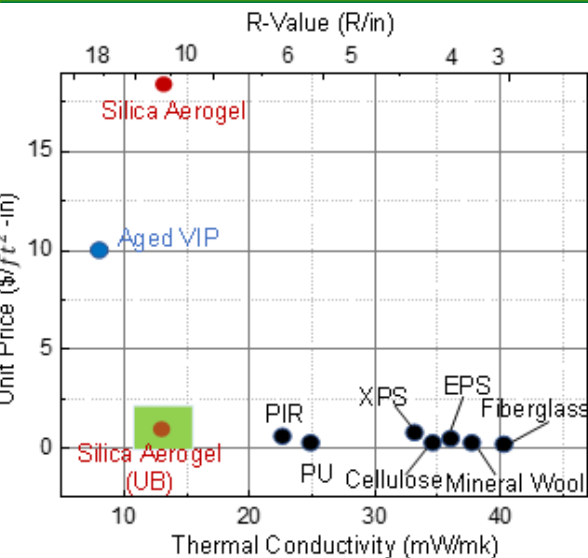
Thermal conductivity measurement
of aerogel insulation materials



Industry Advisory Board



Challenges



About 75% of current buildings will still be standing in 2050 (energy consumption of building envelope: *6% of US energy consumption*). In existing buildings, adding insulation material is often impractical due to high cost and/or space limitations.

Opportunities: A cost-effective retrofit insulation provides high R/inch.

- **Low-cost scalable manufacturing:** high-throughput production (high-yield, continuous) at standard temperature, pressure and avoid toxic chemistries.
- **Low-cost and robust installation:** fast and easy installation, and withstand common handling and installation practices.
- **Durability:** fire-retardant, structure, moisture, soundproof requirements.

Silica Aerogel Building Insulation: The major drawback of silica aerogel as building insulation material is high production cost of supercritical drying, and mechanical instability - intrinsically brittle because of 3D pearl neck-like microstructure connected via narrow interparticle necks. This inefficient structure continuity and connection cause aerogel's structural shaping issue, difficulties of machinability, shape fidelity and miniaturization applications.

SUPERCritical DRYING COST

$$PI = A(10 \times VT \times Q)^{0.24}$$

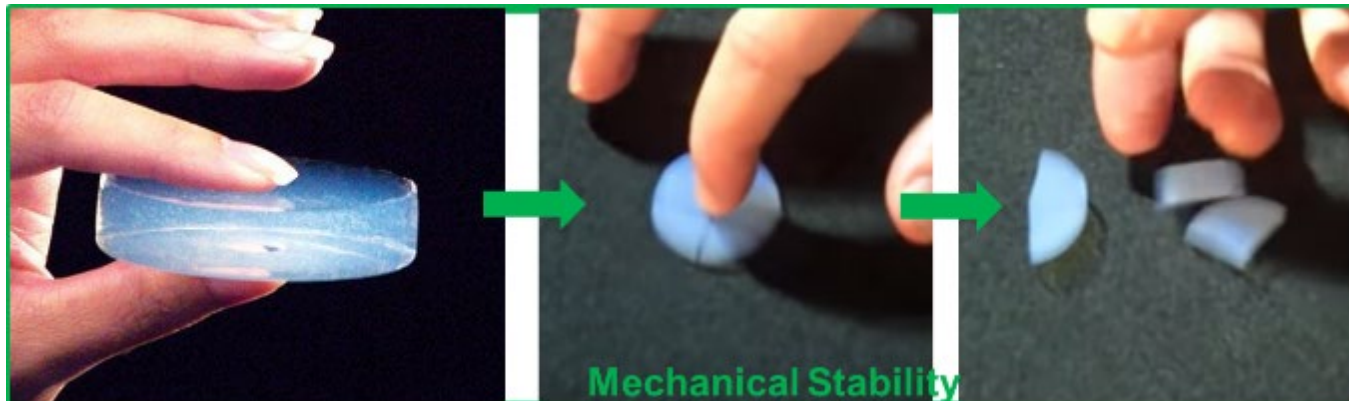
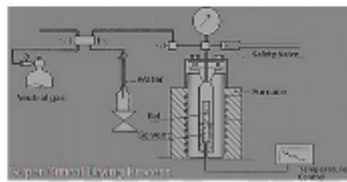
PI: Price Index of Supercritical Drying Process

Q: Solvent Flow Rate

A: Area in contact with the solvent

V: Volume of Supercritical Tank

Future Prospects: With increase in volume of supercritical equipment and increase in solvent flow rate, the cost of supercritical drying decreases exponentially.



Mechanical Stability

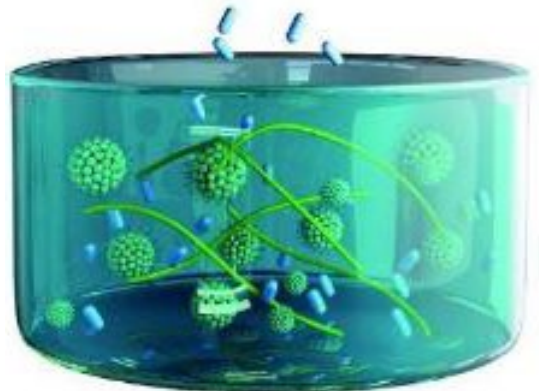
Our Biomimetic Approach for Design and Manufacturing of Insulation Aerogel

How can materials science advance Superinsulation applications?

Fermentation



- In-situ Gas Bubble Formation (Foaming) to Support Pore Gradient

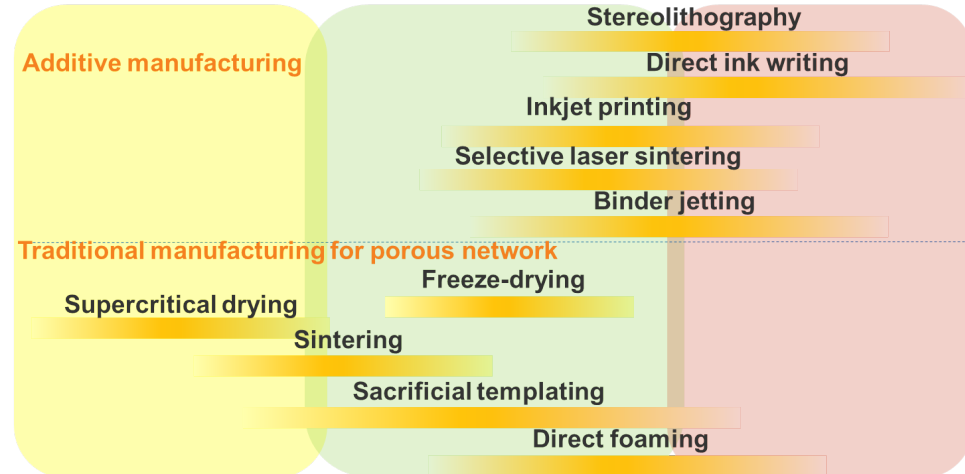
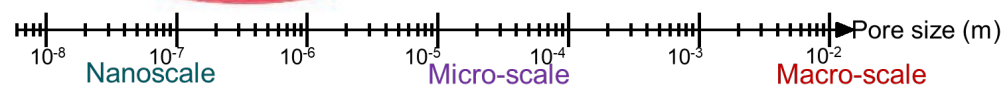


In-situ cross-linking reaction between pre-aerogel precursor and nanofiber

- In-situ Cross-linking Reaction to Reinforce Aerogel Insulation Materials



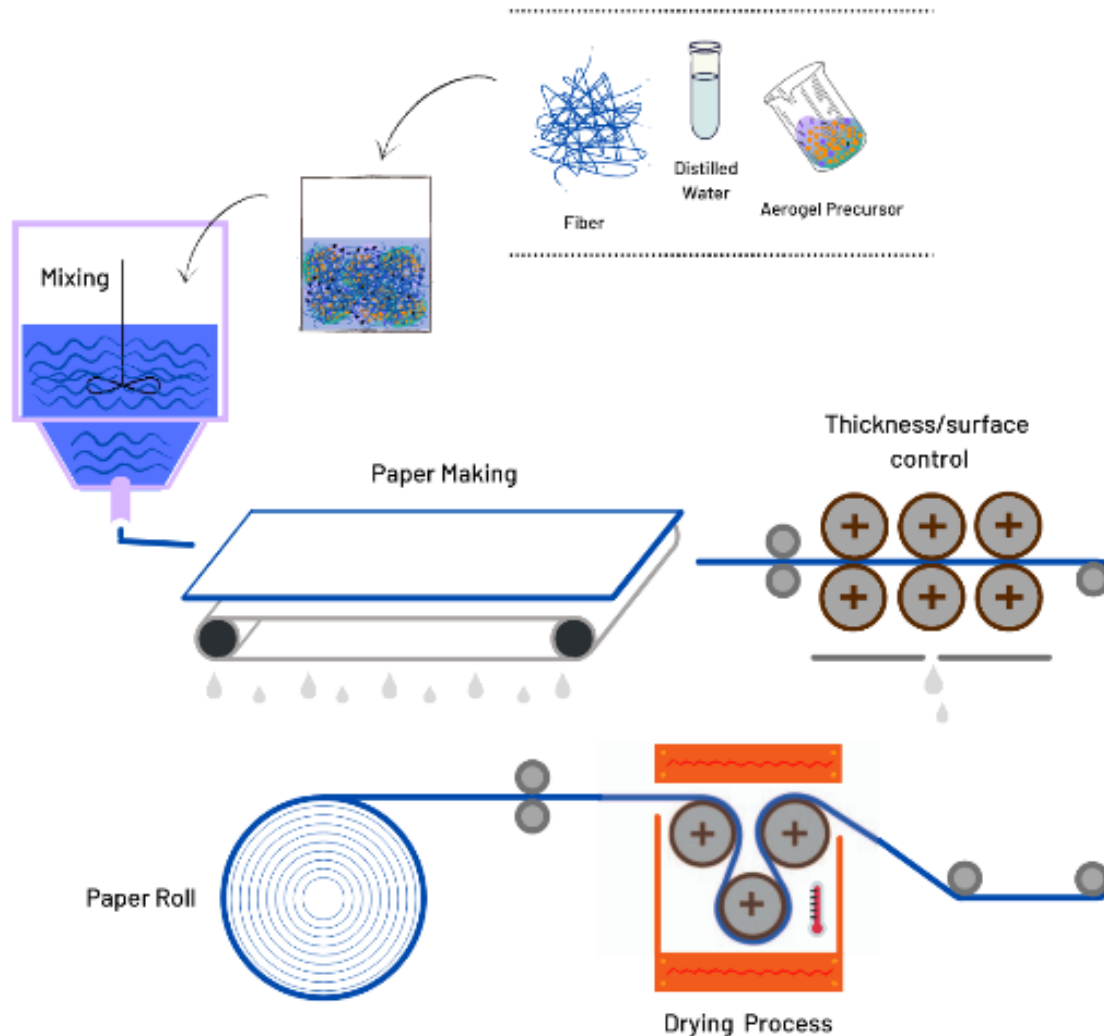
- Pore-Gradient Structures for Thermal Regulation



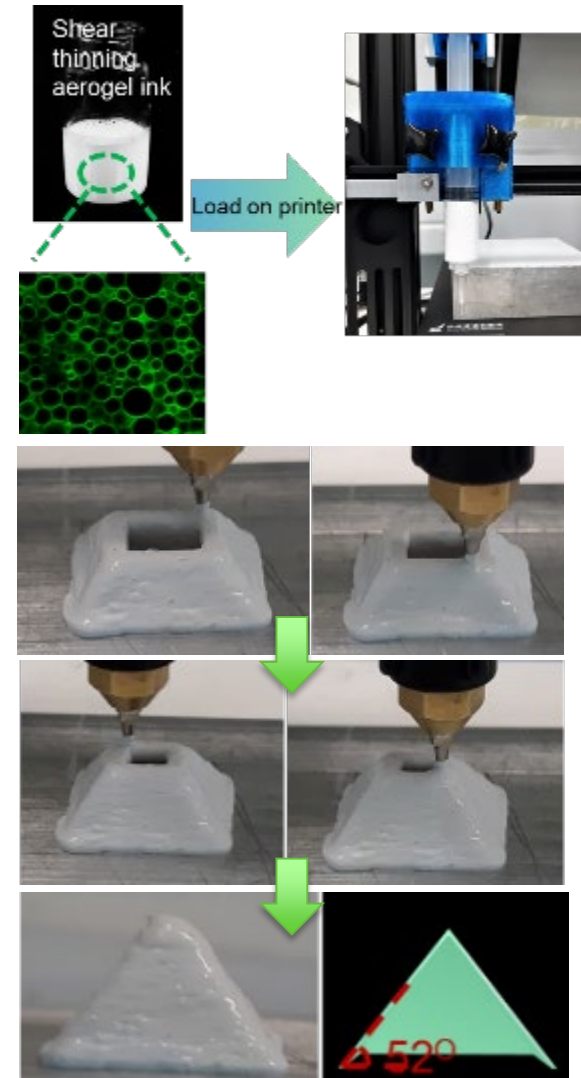
- 3D Printing for Manufacturing Aerogel across Length Scale

Technical Approach: R2R and APD Papermaking for Low-Cost and Mechanical-Robust Silica Aerogel

R2R Papermaking of Silica Aerogel

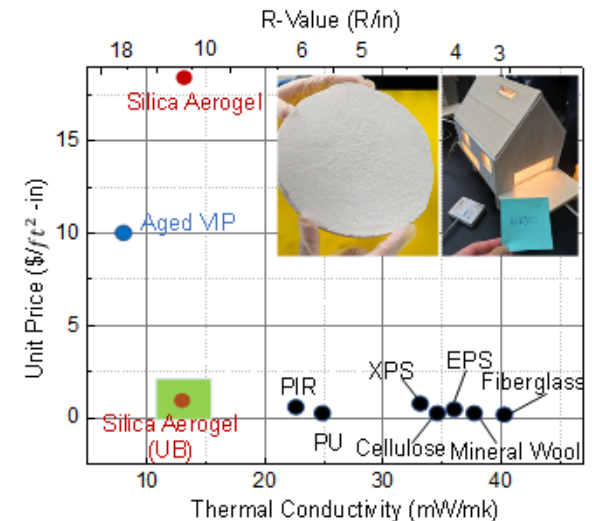


3D Printing of Silica Aerogel

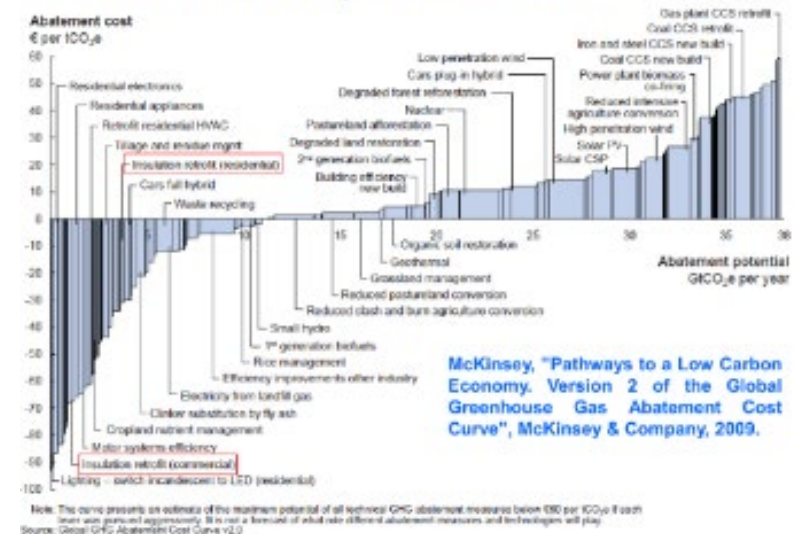


Impact

- 1) **Low-cost and Mechanical-Robust Aerogel Building Insulation Material:** A low-cost silica aerogel insulation could reduce the unit price by 90% (project target: ~\$240/kg, or \$0.94/ft²-inch), meeting DOE's cost target, while having low-cost high-R insulation materials can reduce energy costs of existing buildings (easier to retrofit) and make new construction higher performing.
- 2) **R2R Manufacturing:** R2R manufacturing with ambient-pressure drying is the main contributor to the reduced production and installation cost of silica aerogel. R2R manufacturing can reduce energy costs by 50% and material costs by 90%. Because R2R manufacturing eliminates tooling, a product may be manufactured on the same day that the design is completed; lead time constraints are eliminated. An aerogel insulation material through near-net-shape manufacturing, meets health safety and durability (fire, structure, moisture and acoustic code) requirements.

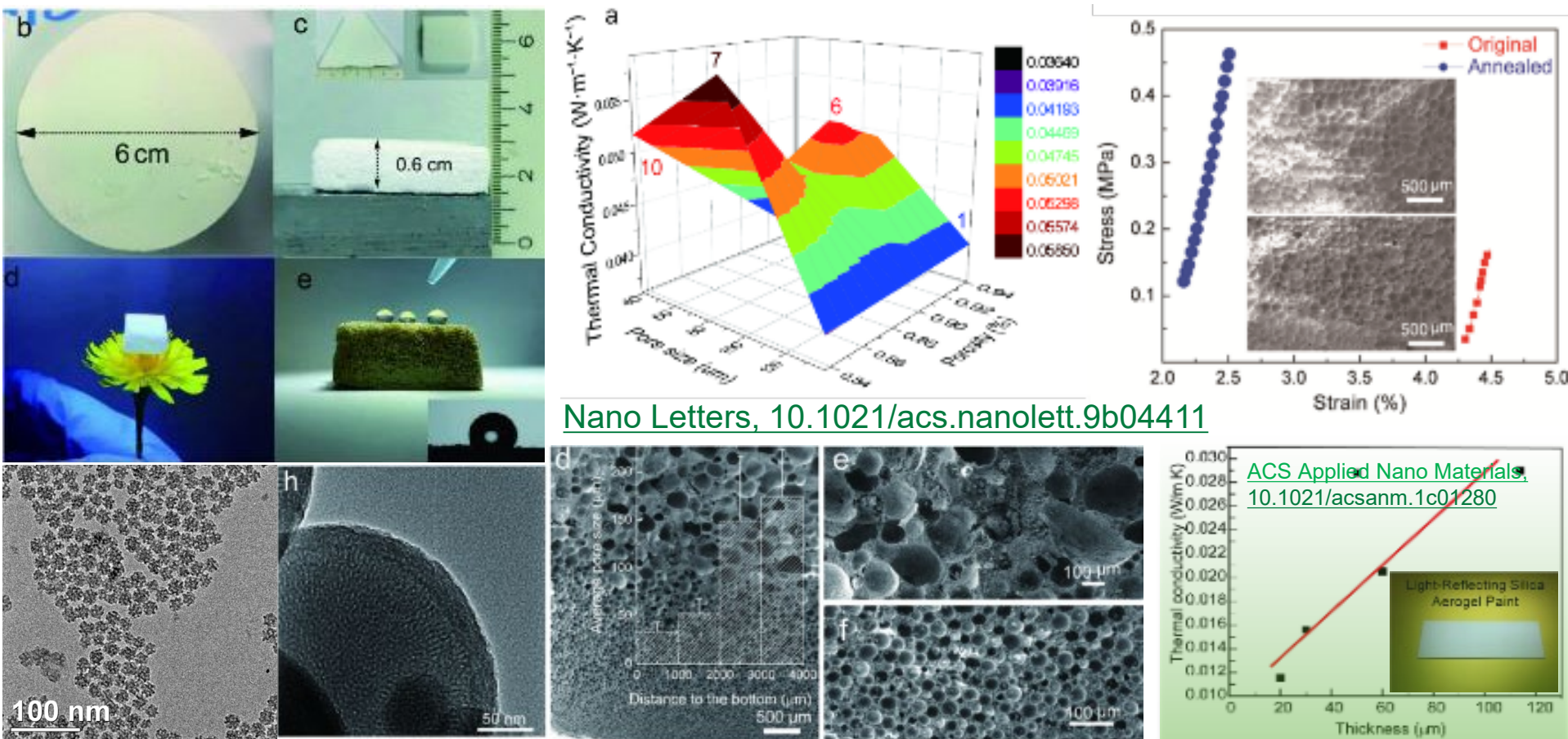


Global GHG abatement cost curve beyond business-as-usual – 2030

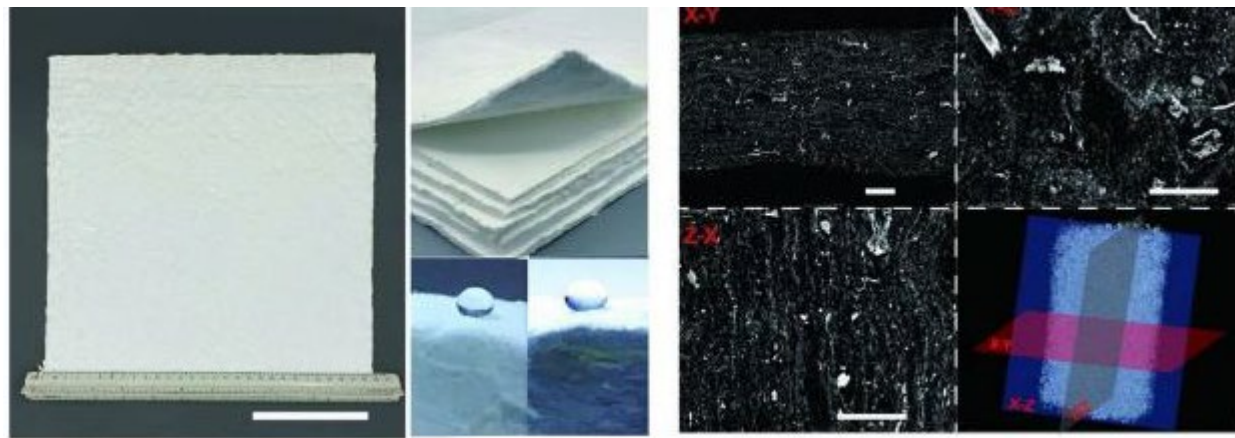
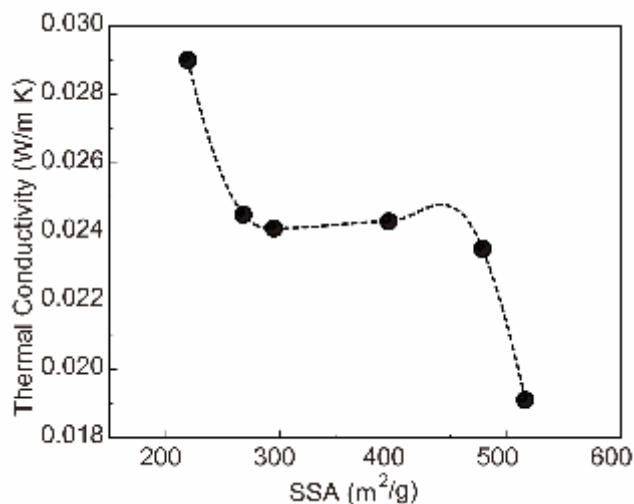


Progress I: Functional-Gradient Mechanical-Robust Silica Insulation

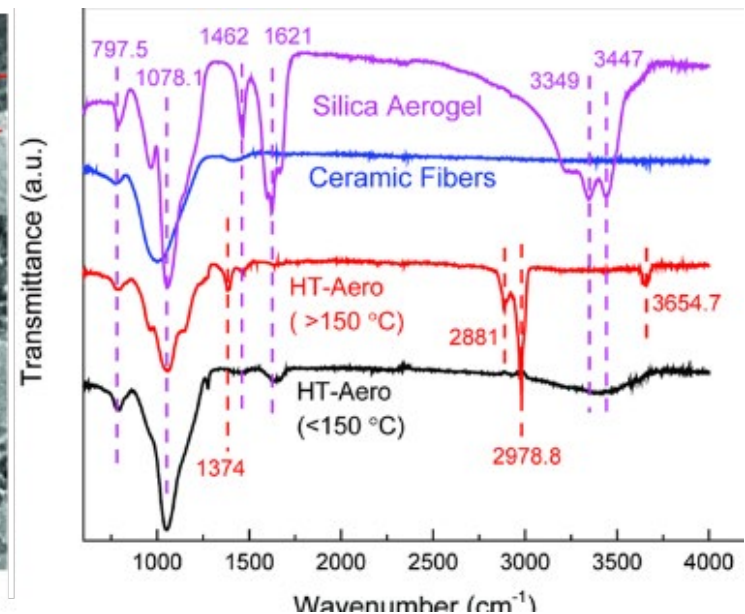
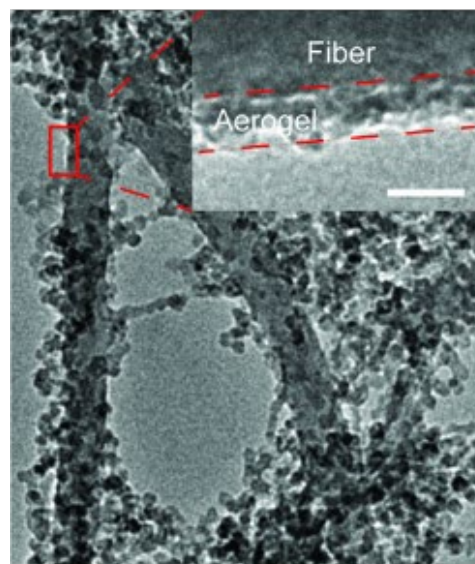
- Mechanically-robust, lightweight, monolithic silica aerogel, with thermal conductivity of $0.036 \text{ W m}^{-1} \text{ K}^{-1}$ and a compressive strength of 100.56 MPa (Machinable).
- Hierarchical hollow structures with gradient macroscale pores and mesoporous silica networks.
- A soundproof performance by sound reduction of 28.3 %, or 22.3 dB at a thickness of 15 mm, over the reference insulating foam.



Progress II: R2R Papermaking of Silica Aerogel

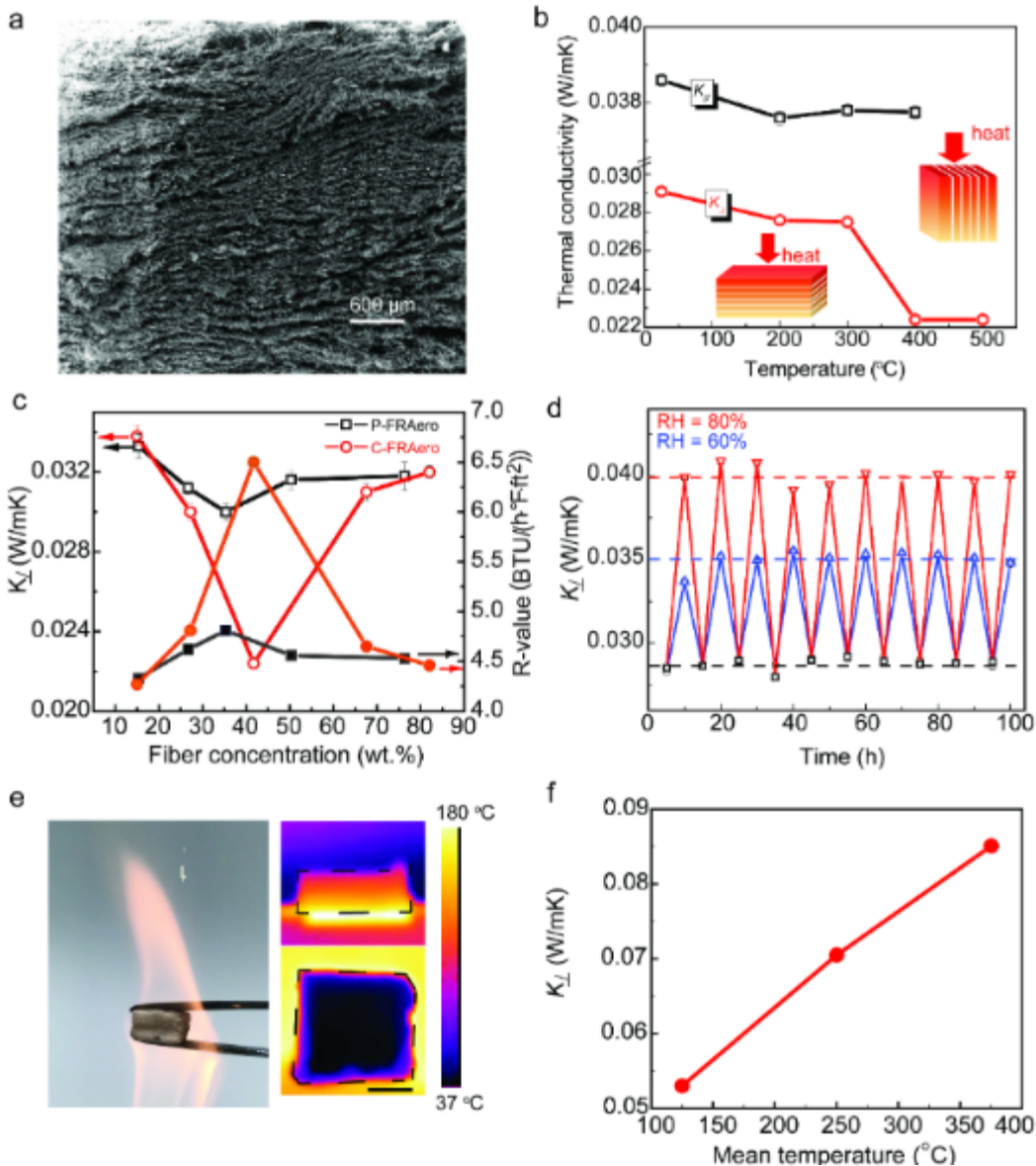


- The resulting ultralight aerogel composite exhibits a density of 0.05 g/cm³, large strain recovery (over 50%), and its hydrophobicity with the water contact angle of 135°.
- Interfacial cross-linking between fiber and silica aerogel.



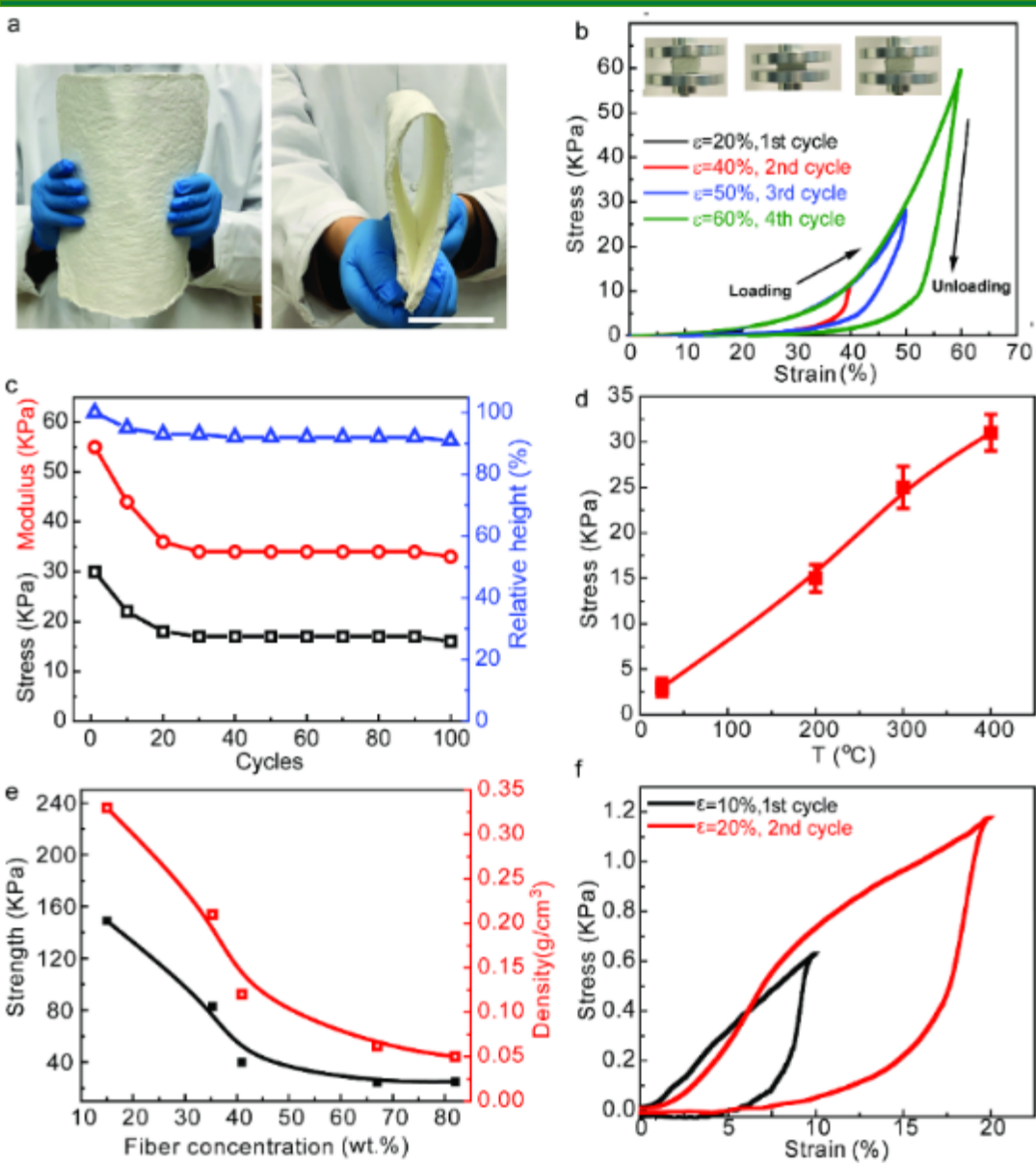
[Nano Letters, 10.1021/acs.nanolett.0c00917](https://doi.org/10.1021/acs.nanolett.0c00917)

Progress II: Anisotropic Thermal Insulation of Silica Aerogel

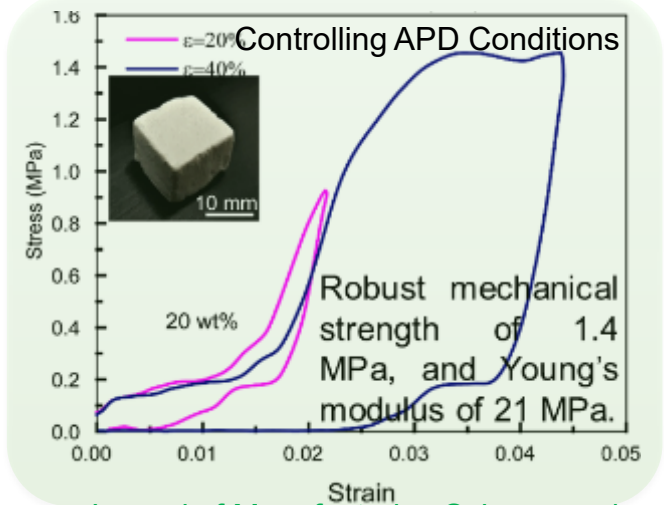


- The resulting ceramic aerogel composites demonstrate an anisotropic thermal insulation performance, with a low thermal conductivity of 0.0224 W/m.K (R-value of 6.5).
- The anisotropic thermal insulation from its nanolayered structure, exhibiting in-plane thermal conductivity $K_{//}$ of 0.0367 W/m.K with an anisotropy factor of 1.63, suggesting this material to prevent heat localization and reduce heat flow for the improved thermal insulation.

Progress II: Flexible and Recoverable Silica Aerogel

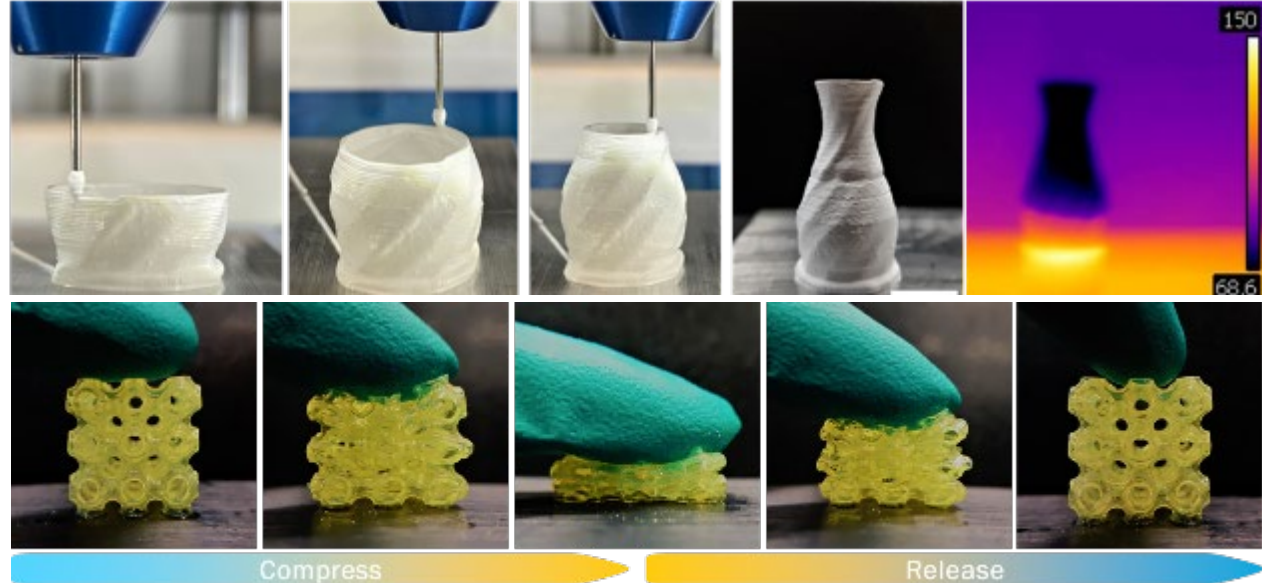
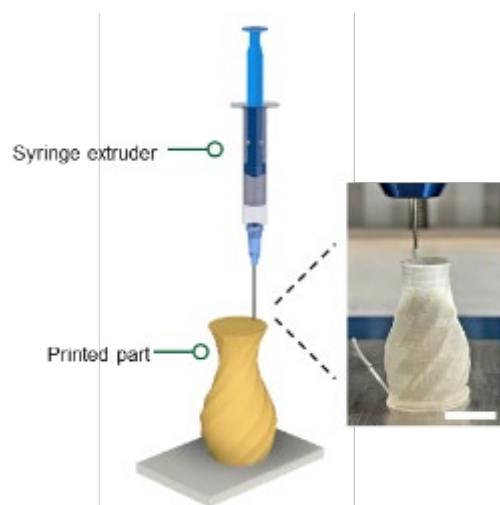


- Large strain recoverable compressibility (>50%) and excellent fatigue resistance (hundred cycles with a set strain of 50%), in addition to its flexibility, mechanical anisotropy and a large recoverable compression behavior.
- The ultimate stress and Young's modulus reach their equilibrium states with 17 KPa and 37 KPa.
- The mechanical behavior is related to the density ρ of aerogel composites with the $E \sim \rho^n$ ($n=2.0\sim3.8$), indicating the efficient load transfer to fibrous layer structures.

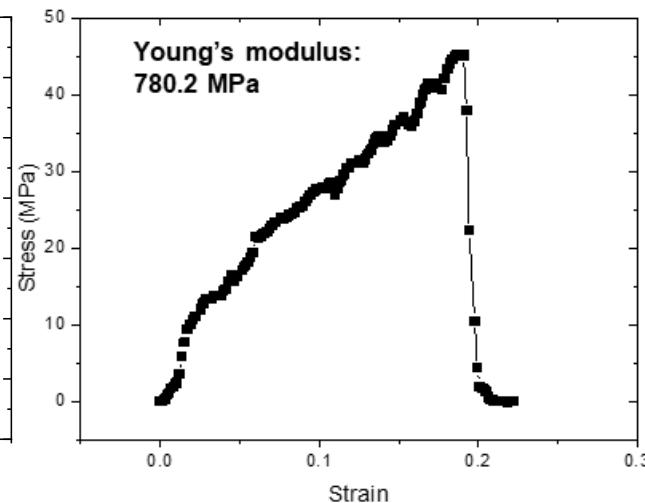
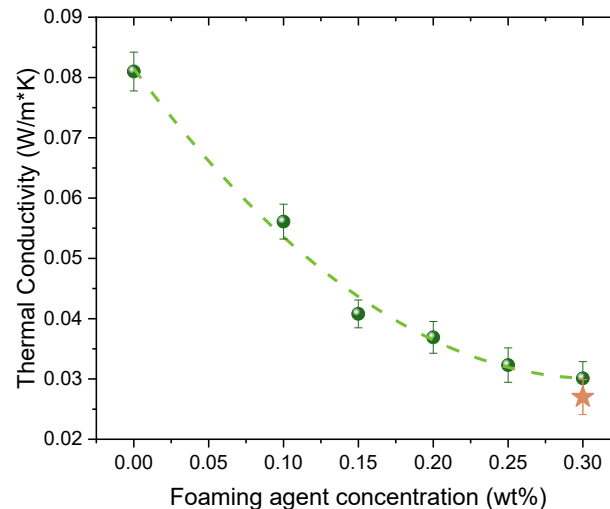
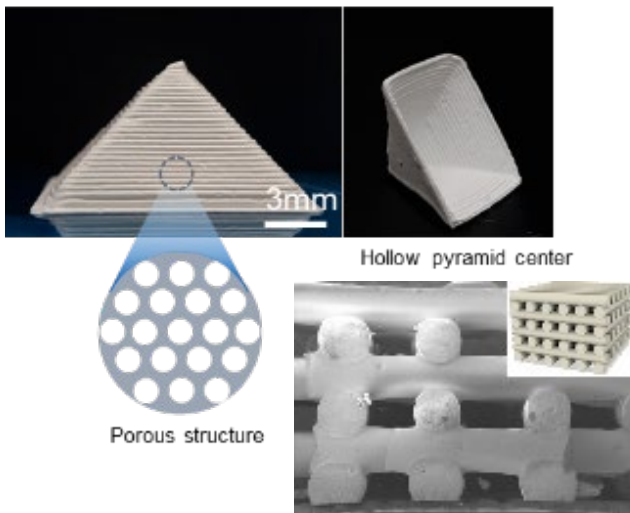


[Journal of Manufacturing Science and Engineering, 10.1115/1.4048740](#)

Progress III: 3D Printing of Silica Aerogel



High resolution printing and shape fidelity

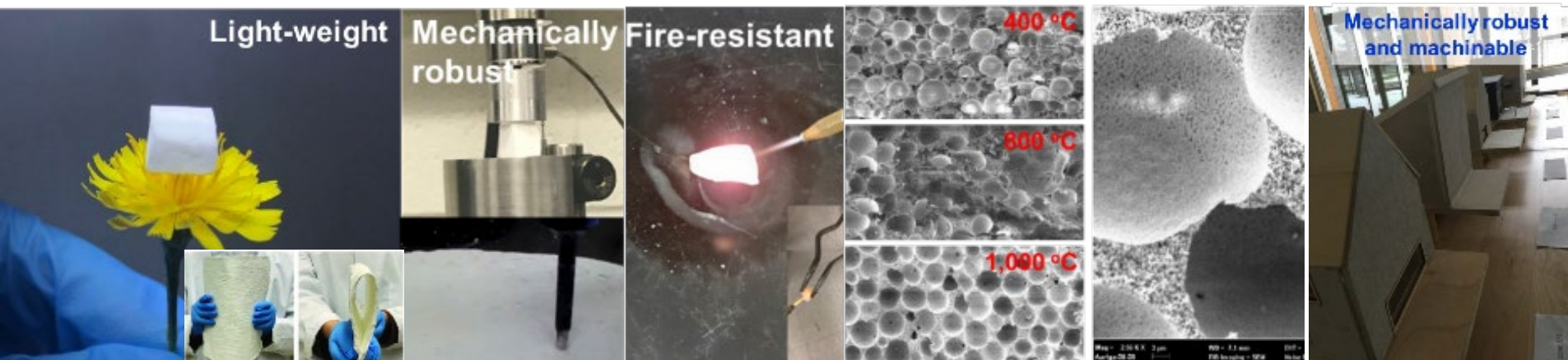


Ensure the integrity of structure; Aesthetic and customized geometry

Summary of Silica Aerogel Materials @ UB

Materials Characteristics

Materials	SiO ₂
Thickness(mm)	6
Density (g/cm ³)	0.05
Thermal conductivity (W/m.K)	0.018
R-value (ft ² ·°F·h/BTU)	8
Modulus	Papersheet: 37 KPa ~ 21 MPa Monolith: 100 MPa
Maximum recoverable strain (%)	Papersheet: 50
Soundproof reduction (dB.%) under 2,000Hz	16.7



Stakeholder Engagement

Building insulation and construction partners for commercialization and R&D collaboration

- Meeting with over 10 industry partners with non-disclosure agreements on low-cost mechanical robust aerogel insulation
- Materials transfer agreement with 3 partners for the aerogel sample evaluation
- Commercialization with one industry partner



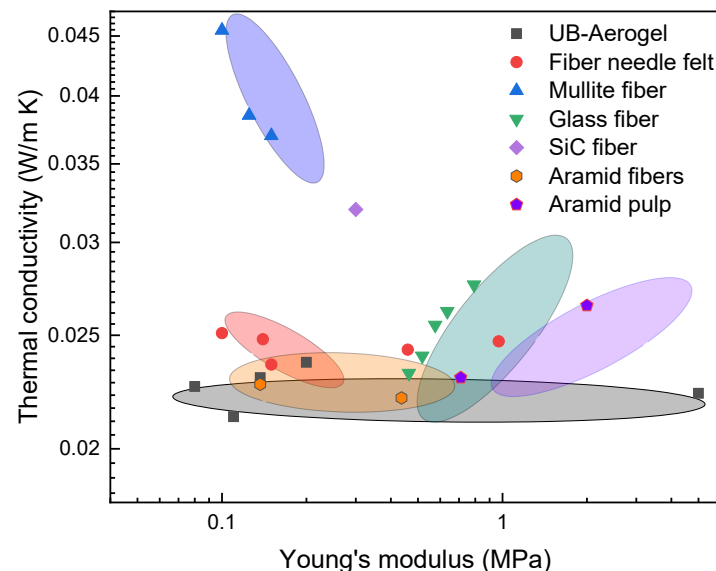
Sampling of Stakeholder Engagement

Organization	Industry	Interaction summary
Owens Corning	Building insulation	Low-cost and high performance aerogel-fiberglass composite insulation
Kingspan	Building insulation	Low-cost aerogel chemistry
Aspen Aerogel	Aerogel insulation	Mechanical strong aerogel
Unifrax	Thermal insulation	Low-cost aerogel and fiber insulation
Rodriguez Construction Group	Construction (new and retrofitting)	Drywall-like insulation

Remaining Project Work

Project Stage: Y3 (FY21)

1. Fabricated TEOS-based silica aerogel (95% porosity) at 100 gram/batch with the pilot-scale throughput of 1.5 kg/day.
2. Fabricated hydrophobic waterglass-based silica aerogel at 20 gram with the scalable cost analysis from the waterglass raw material.
3. Established the flammability and flexibility tests of silica aerogel samples.
4. Produced 15' x 17" (1 inch thickness) hydrophobic aerogel with the targeted R-value of R 10/inch and compressive Young's modulus larger than 5 MPa at ambient conditions at a thickness of 1 inch, with the projected cost \$0.94/ft²-in.
5. Completed long-term aging test based on 10 of aerogel samples for the robust aerogel insulation composite.



Thank You

Performing Organization(s): SUNY University at Buffalo

PI Name and Title: Shenqiang Ren, Professor

PI Tel and/or Email: (716)-645-1431, shenren@buffalo.edu

REFERENCE SLIDES

Project Budget

Project Budget: \$1,500,000 (DOE) and \$375,000 (Cost-share)

Variances: N/A

Cost to Date: DOE: \$1,028,643; Cost Share: \$257,161

Additional Funding: N/A

Budget History					
05/01/2019- FY 2020 (past)		FY 2021 (current)		FY 2022 - 04/20/2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
\$532,010	\$133,003	\$496,633	\$124,158	\$471,357	\$117,839

Project Plan and Schedule

Project Schedule															
Project Start: 05/01/2019		Completed Work													
Projected End: 04/30/2021		Active Task (in progress work)													
	◆	Milestone/Deliverable (Originally Planned)													
	◆	Milestone/Deliverable (Actual)													
	FY 2019				FY2020				FY2021				FY2022		
Task	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)		
Past Work															
Q2 Milestone: Produce 10 g aerogel ink from TEOS	◆														
Q2 Milestone: Produce 5 gram silica aerogel		◆													
Q4 Milestone: Complete scalable aerogel reaction			◆												
Q2 Milestone: Produce 1 in ² (at a thickness of 1 inch) surface-modified silica aerogel sheets				◆											
Q2 Milestone: Prototype #2 produced				◆											
Current/Future Work															
Q3 Milestone: Complete the scalable silica aerogel precursor setup of 50 gram/batch				◆											
Q4 Milestone: Fabricate a 10 gram silica aerogel through the waterglass approach				◆											
Q1 Milestone: Establish the porosity (93%) control of silica aerogel								◆							
Q2 Milestone: Complete the temperature-dependent (0, 24, 40°C) thermal conductivity mechanical performance								◆							
Q2 Milestone: Established the scalable extrusion printer									◆						
Q4 Milestone: Determine the hydrophobic silica aerogel sheet thickness															
Q2 Milestone: Produce the Prototype #6 of 15' x 17" (1" thick)															