ADDITIVE MANUFACTURING OF HIGH-PERFORMANCE ICE COMPOSITES

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U.S. ARMY
US Army Corps of Engineers®
ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER
CRREL

ERDC Locations

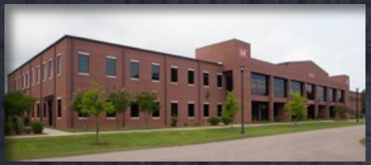
SEVEN LABORATORIES MAKING AN IMPACT ON THE NATION AND WARFIGHTERS

ERDC Laboratories

ERDC Headquarters
Vicksburg, Mississippi

Coastal and Hydraulics Laboratory (CHL)

Environmental Laboratory (EL)



Geotechnical and Structures Laboratory (GSL)

Information Technology Laboratory (ITL)

Cold Regions Research and Engineering Laboratory (CRREL)
Hanover, New Hampshire

Geospatial Research Laboratory (GRL)
Alexandria, Virginia

Construction Engineering Research Laboratory (CERL)
Champaign, Illinois

Field Offices

Permafrost Tunnel Research Facility
Fox, Alaska

Alaska Research Office
Fairbanks, Alaska

Lewisville Aquatic Ecosystem Research Facility
Lewisville, Texas

Contingency Base Integration Technology Evaluation Center (CBITEC)
Fort Leonard Wood, Missouri

Field Research Facility
Duck, North Carolina

Corbin Field Station
Woodford, Virginia

Extreme Exposure Station
Treat Island, Maine

ERDC International Research Office
London, England

Cold Regions Research & Engineering Laboratory

The nations only dedicated cold regions research facility with the most unique cold regions test facilities in the world.

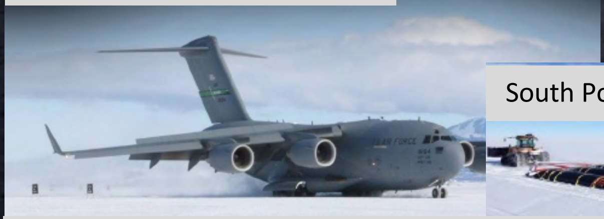
MOBILITY STUDIES IN COLD & EXTREME COLD ENVIRONMENTS

Developing and test new tracks to improve functionality in snow covered terrain.

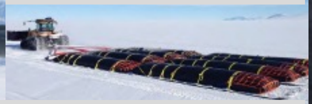
Increasing the speed and accuracy of mobility analyses, enabling short-term forecast capabilities

ENGINEERING FOR POLAR OPERATIONS, LOGISTICS &

Phoenix Deep Snow Runway



South Pole Traverse

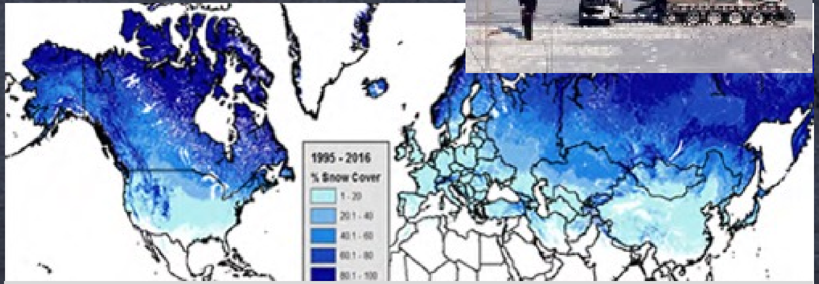


Provide an interdisciplinary approach to understanding and solving unique cold regions challenges

Core Competencies

- Operational Impacts of Extreme Cold Weather Environments
- Performance Predictions of Critical Infrastructure in Cold Regions
- Ice, Snow, and Soil Properties, Behavior, Mechanics and Distribution
- Geotechnical/Permafrost Engineering
- Material Engineering for Cold Regions

Crevasse detection



Transitioned snow assessment capabilities and remote sensing methodologies

ENHANCED COLD REGIONS DOMAIN AWARENESS

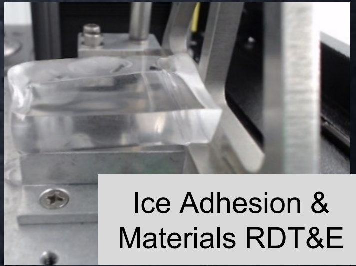
PERMAFROST RESEARCH

Newly excavated ERDC permafrost research tunnel showing a large ice wedge

Evolving infrastructure and capabilities consistent with changing conditions

INNOVATIVE MATERIALS FOR EXTREME COLD WEATHER

Cold weather concrete



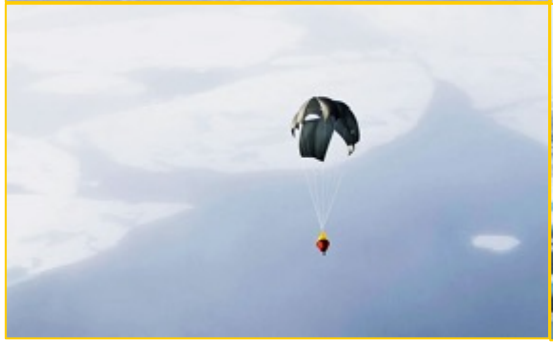
Ice Adhesion & Materials RDT&E

Providing unique capabilities to solve specific customer-driven problems and conduct innovative, state-of-the-art research

THE ARCTIC – THE FROZEN FRONTIER

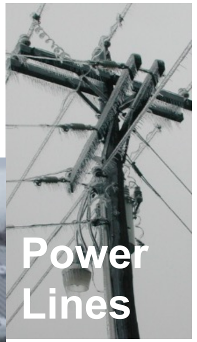
- The Arctic presents enormous logistics and infrastructure challenges
- Equipment never works how you think it should
- Face many challenges familiar to the space resources community in different environmental context






Ice is an Adversary

Utility Systems



Communication/Navigation

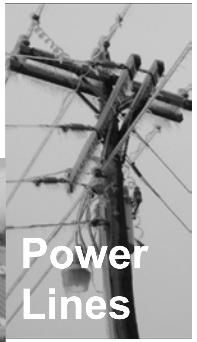
Transportation

Ice is an Adversary

Ice is a Resource

ERDC

Utility Systems



Communication/Navigation

Transportation

Roadways/Runways

Shelters/Structures

ADVANCED MATERIALS TEAM
SCIENCE FOR EXTREME ENVIRONMENTS
CRREL, HANOVER, NH

ICE AS A CONSTRUCTION MATERIAL

In remote cold regions, conventional construction methods can be difficult or impossible to use.

Soldiers reinforcing an ice bridge on the Tanana River, Fort Wainwright, Alaska.

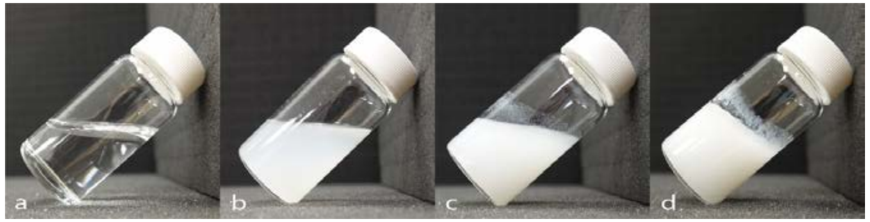
Canadian soldiers constructing igloos out of snow blocks, Nunavut, Canada.

US Air Force plane landing on a snow runway, Phoenix Runway, Antarctica.

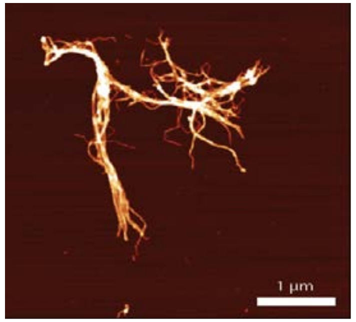
Ice and snow are abundant natural resources to use as unique indigenous construction materials in remote Cold Regions.

REINFORCING ICE WITH CELLULOSE NANOFIBERS

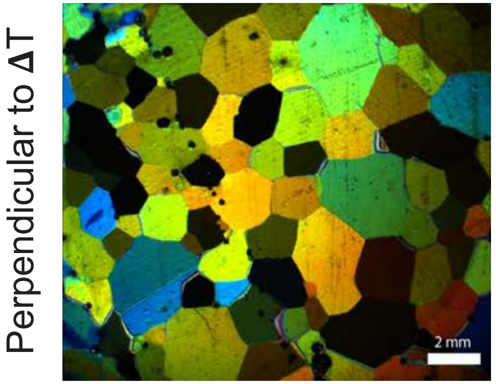
- Cellulose nanofibers (CNFs) are made from milled wood or plant pulp.
  - Biodegradable
- CNFs are a common additive in composites because of their high strength to weight ratio.
- CNFs are bleached white as purchased; when suspended in water they appear white and opaque.
- When frozen in ice, CNFs affect the microstructure of ice bridge across the grain boundaries.
- This results in changes to the macroscopic properties of cellulose reinforced ice.



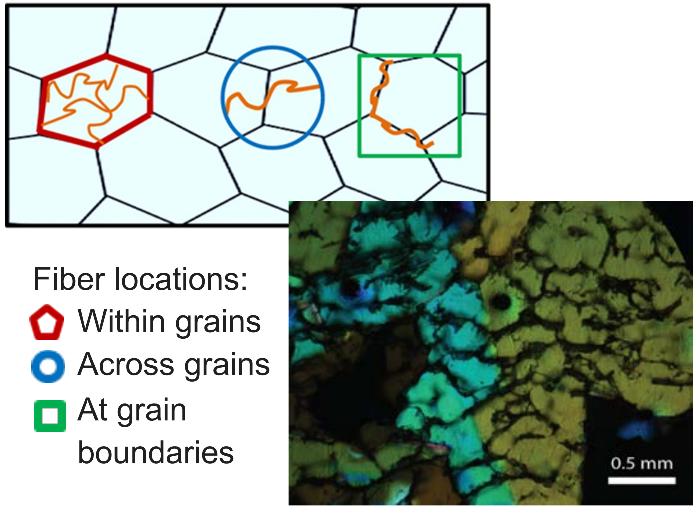
Opacity increases with increasing CNF concentration



AFM image of a bundle of cellulose nanofibers



Microstructure of pure ice

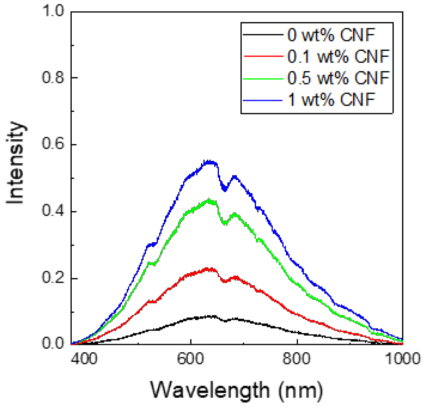


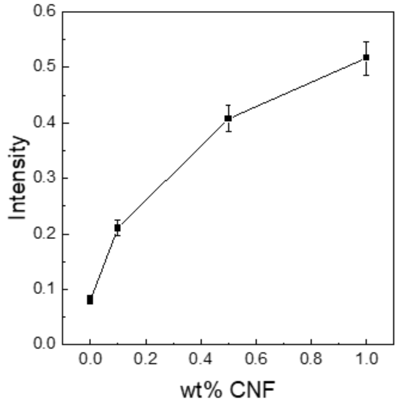
Cellulose fiber location varies in ice microstructure

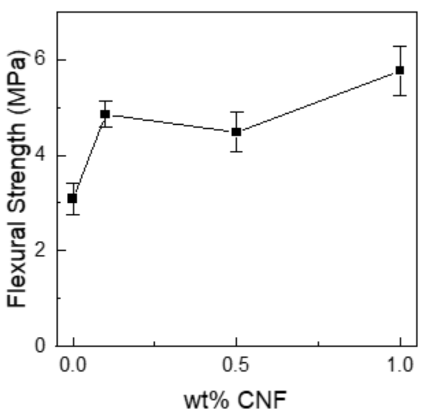
K. Thompson Towell, **E. Asenath-Smith**. Low temperature effects on the rheological properties of aqueous cellulose nanofiber suspensions. 2024, *Cellulose*, 1-14.
E. Asenath-Smith, K. Thompson Towell, M. Fort, and O. Montmayeur. Cellulose nanofibers impart melt resistance to ice through optical and thermal mechanisms. 2025. *Journal of Physical Chemistry C*, 129, 7846-7854.
E. Asenath-Smith, K. Thompson Towell, M. Fort, and N. Wilder. Cellulose nanofibers in ice: microstructural effects on mechanical response. 2026. *Materiala*, 45.

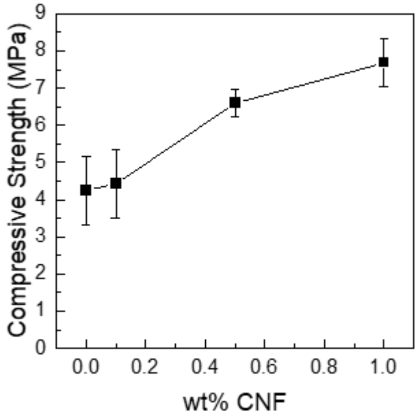
CNF REINFORCED ICE MATERIALS PROPERTIES

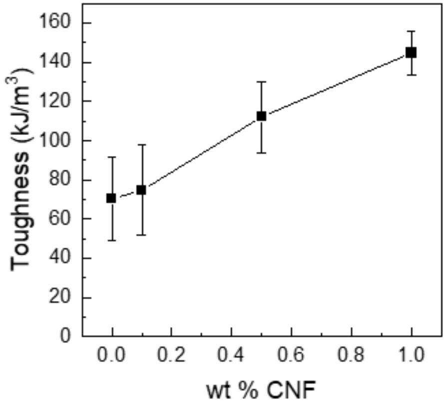
- CNFs increase the reflectivity of ice, decreasing melting from radiative absorption.
- CNFs form an insulating layer on the surface decreasing the melt rate of ice from convection.
- CNFs increase the flexural and compressive strength of ice, as well as the toughness.

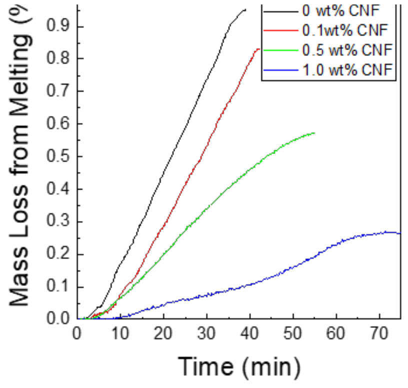


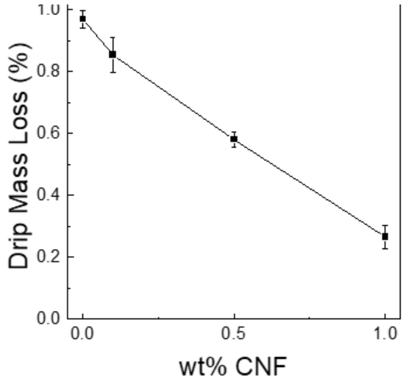












Ice strength and reflectivity increase with CNF concentration, while melt rate decreases

E. Asenath-Smith, K. Thompson Towell, M. Fort, and O. Montmayeur. Cellulose nanofibers impart melt resistance to ice through optical and thermal mechanisms. 2025. *Journal of Physical Chemistry C*, 129, 7846-7854.

E. Asenath-Smith, K. Thompson Towell, M. Fort, and N. Wilder. Cellulose nanofibers in ice: microstructural effects on mechanical response. 2026. *Materiala*, 45.

ARCHED CELLULOSE REINFORCED ICE BRIDGE

- We constructed an arched bridge made with cellulose reinforced ice capable of supporting vehicle traverse over a 10 ft span.
- Cellulose increased the strength of ice 3x in flexural loading with only 0.3 wt% CNF.
- The bridge successfully supported multiple crossings of an MRZR and HMWVV with no visible or audible signs of cracking.
- Computational models projected this bridge would support over 16,000 kg.

Thompson Towell et, al. Construction and structural analysis of an arched cellulose reinforced ice bridge for transportation infrastructure in Cold Regions. *Cold Regions Science and Technology*, Vol. 198, Article 103508, June 2022.

Eoghan Matthews (CPT), **Kiera Thompson Towell**, Olivier Montmayeur, and **Emily Asenath-Smith**. Using snow and ice to construct a dry gap crossing. *The Military Engineer*, Vol. 114, No. 72, pp.53-55, November 2022.

ARMY AND ICE 3D PRINTING?

Goal: To support the Army in meeting requirements for Arctic operations by 3D printing expeditionary structures using indigenous ice and snow.

Objective

- Produce an automated construction method for remote cold regions utilizing indigenous materials and document the operating procedures.
- Characterize the mechanical strength and thermal behavior of 3D printed structures.

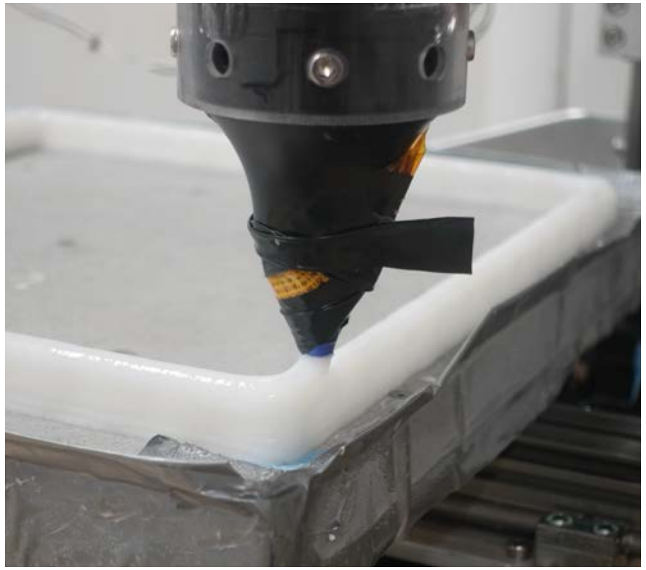
Why

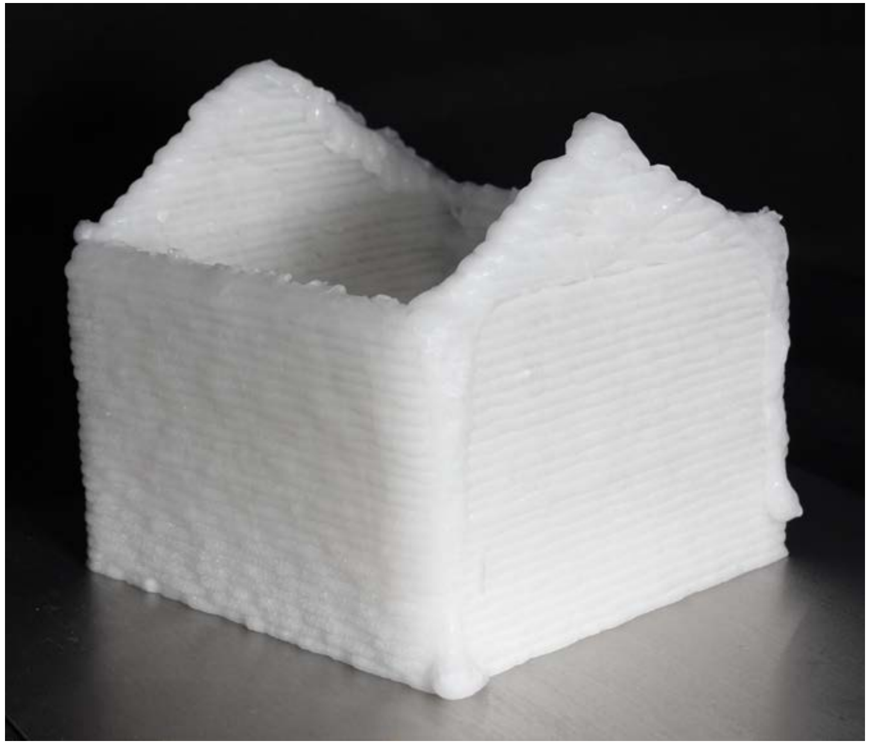
- Cold weather injuries to soldiers during operations at northern latitudes puts these missions at risk. Traditional construction materials (e.g., concrete) do not work at cold temperatures, and expeditionary structures are limited in their configurations and require deconstruction or decommissioning after operations are complete.

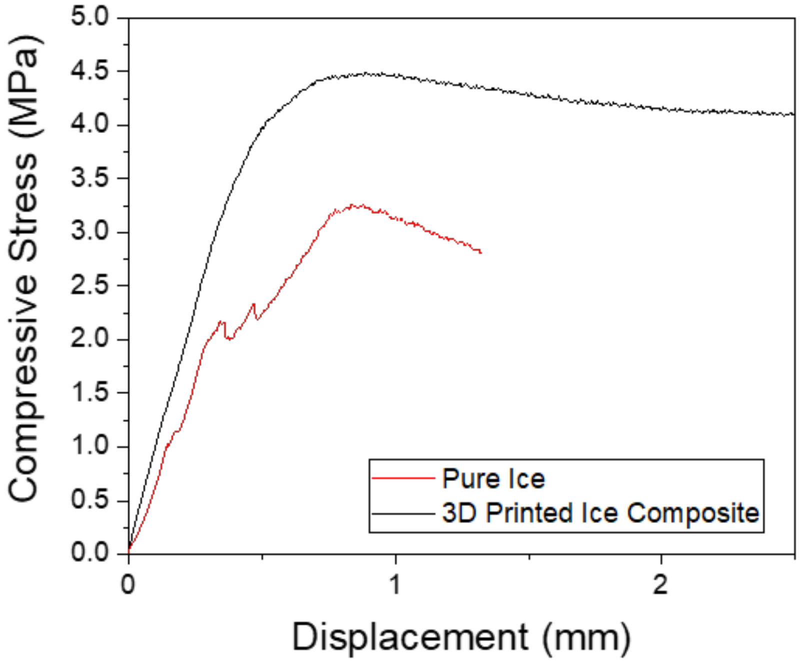
Technology Readiness Level (TRL)	Starting	Current
Ice composite Material for Cast	5	6
Extrudable Ice Composite	3	6
Additive Construction (Printer - Ice)	3	6

3D PRINTING REINFORCED ICE

- We were able to successfully extrude a CNF solution layer by layer to additively construct a 300 mm wide and 150 mm tall dollhouse.
- The 3D printed ice composites demonstrate increased strength under compressive loading and had increased ductility whereas pure ice experienced brittle failure.



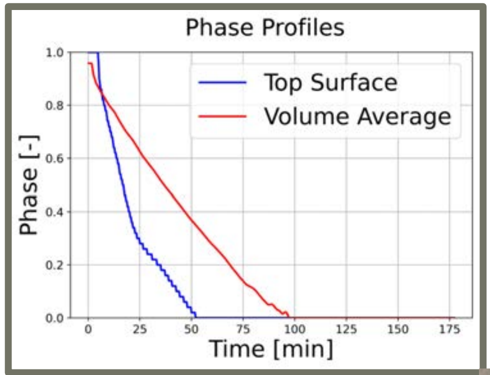


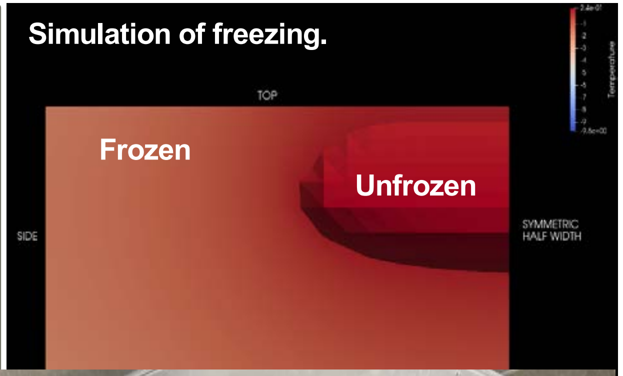


BRIDGING SCALES

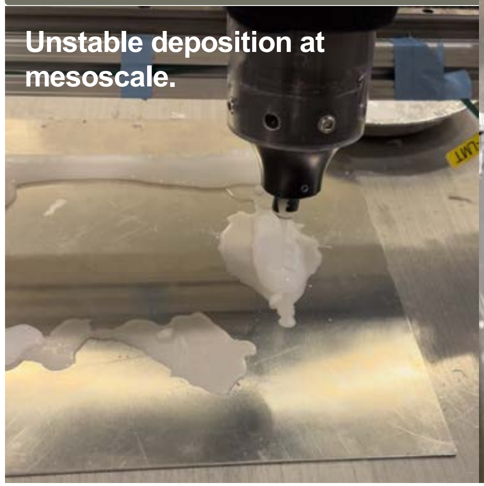
SCALING CHALLENGES

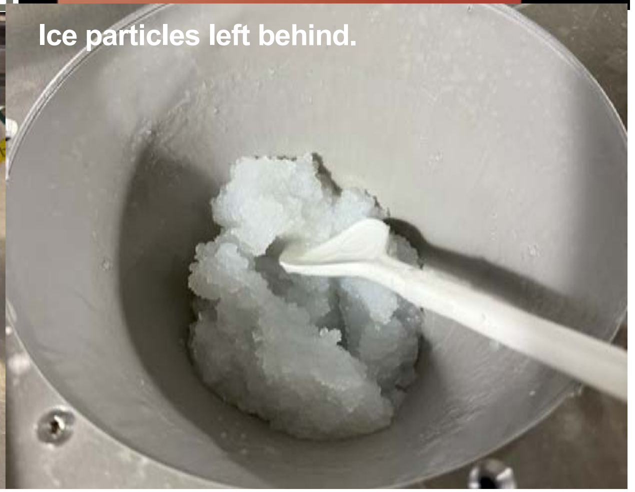
Curing through phase gradients.

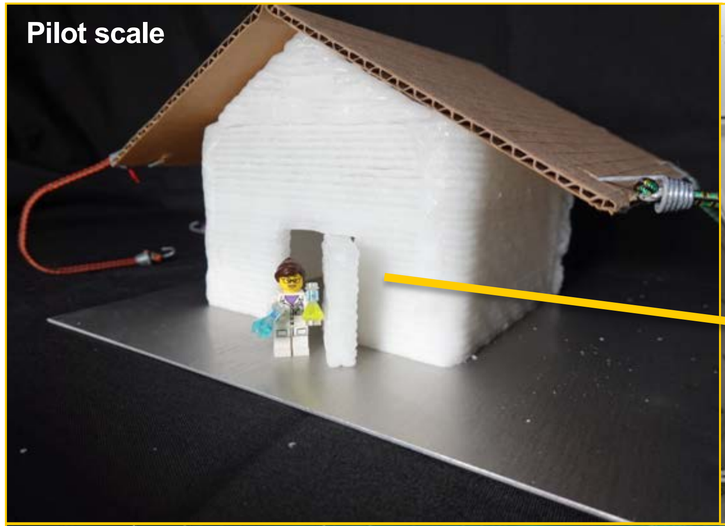




Flow control and phase separation.



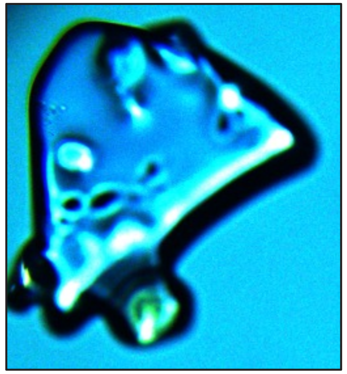




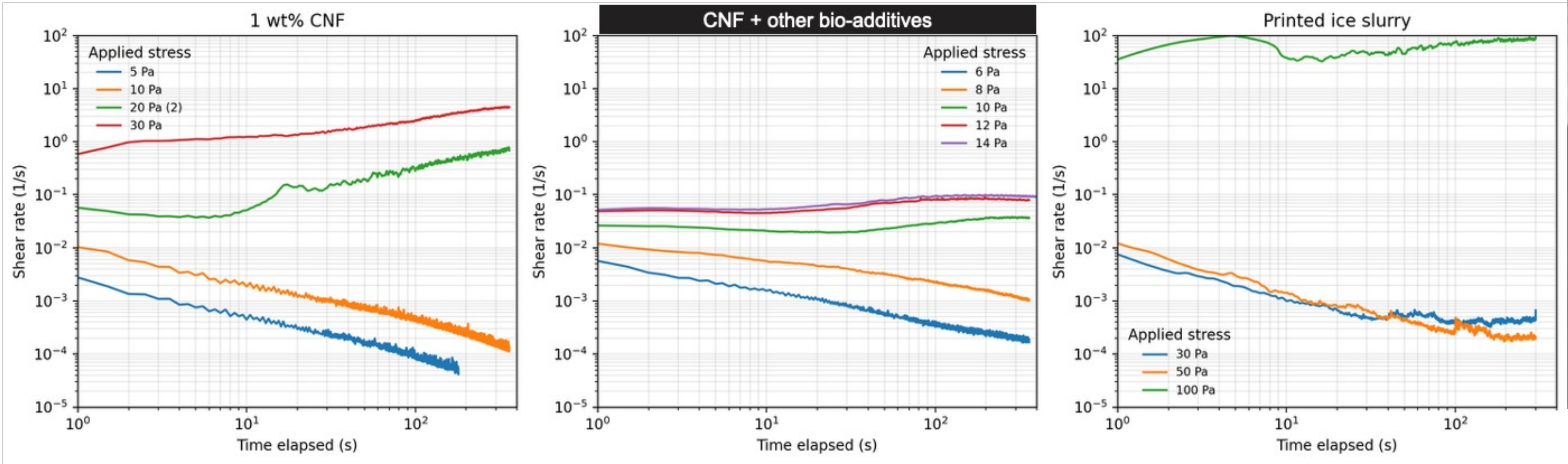
IMPROVING FLOW CONTROL

Maximum Particle Size (mm)	2	1	0.6	0.425
Fraction Passed	1.000±0.000	0.612±0.003	0.374±0.002	0.302±0.004

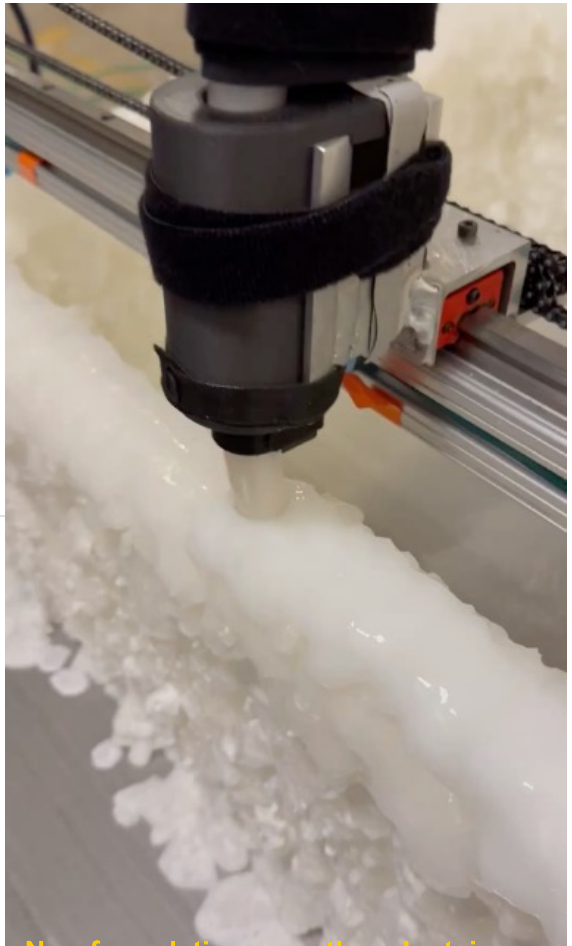
Polydisperse ice roughly bimodal between coarse and fines.



Ice particles have high angularity.



Constant shear stress rheology tests above and below the yield stress.

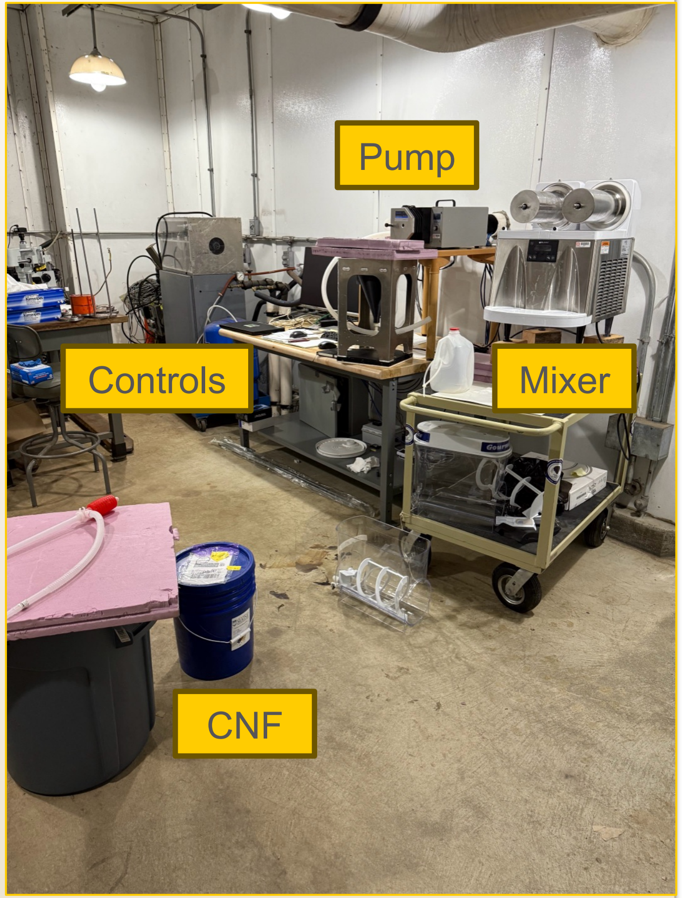


New formulation smooth and retains shape.

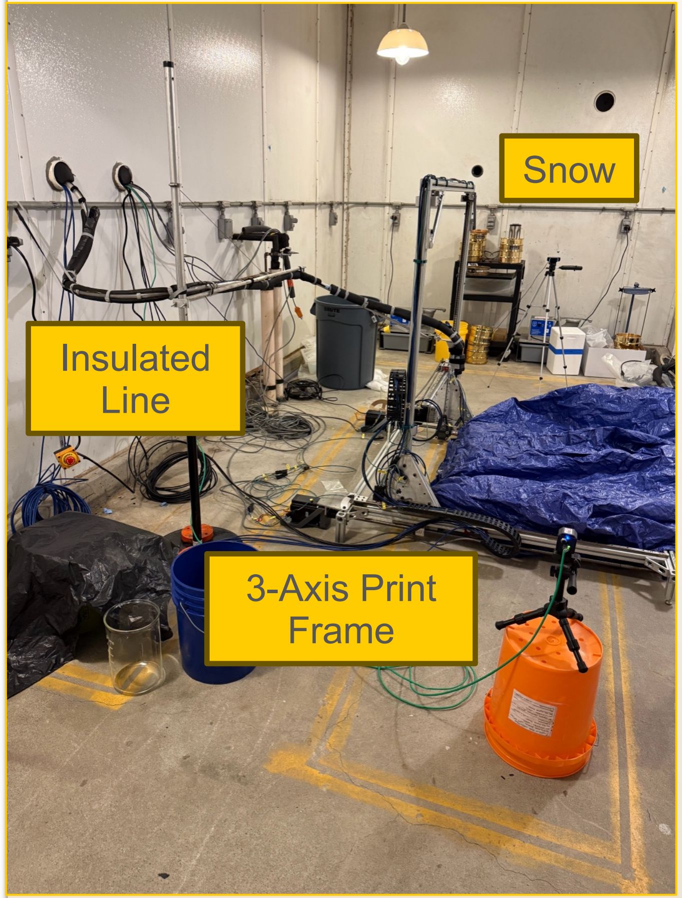
INTERMEDIATE SCALE OPERATION

Command Side Room

T = 28 F (-2.2 C)



Print Side Room



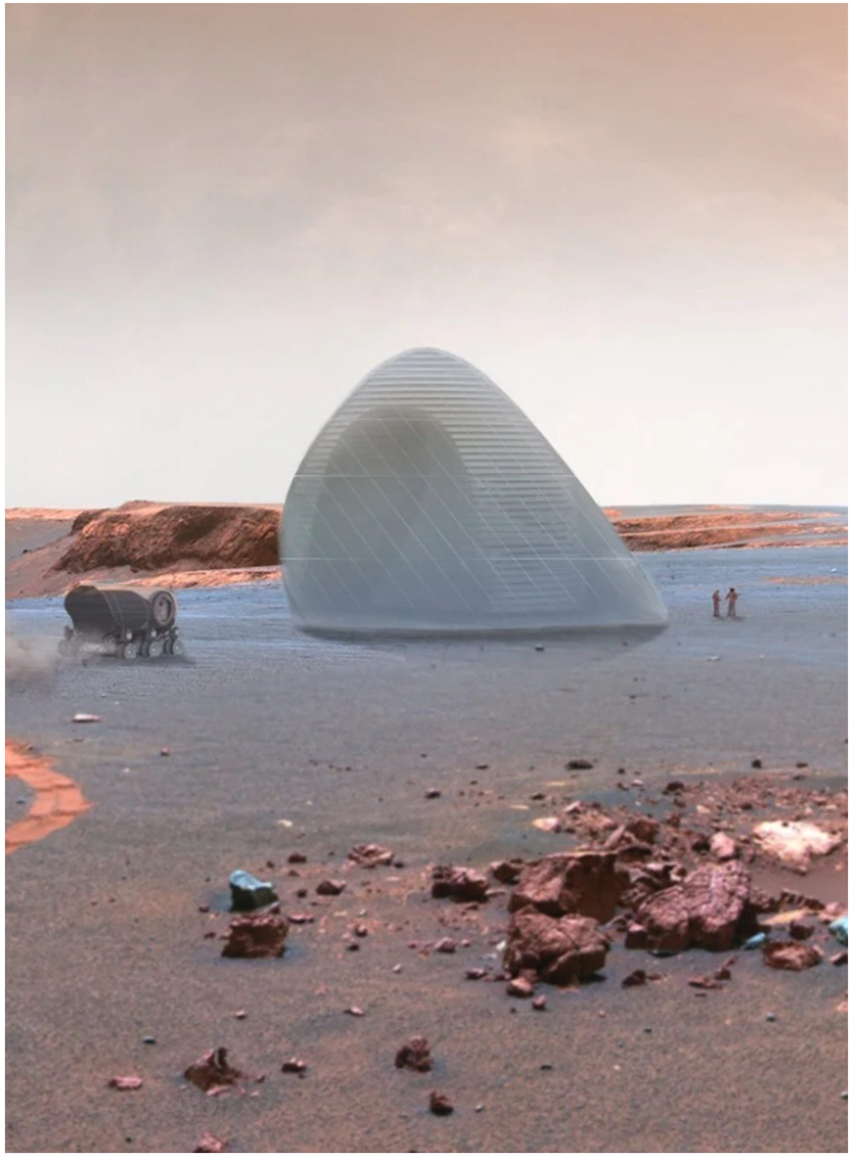
T = 5 F (-15 C)

FINAL PRODUCT

- 28” by 33” by 21.5” rectangular structure with 2-2.5” wall thickness.
- Conservative time to print without sleeping – 27 layers x 1 hour/layer cure = 27 hours.
- FOB can have rigid structures within a day.

RELEVANCE TO SPACE RESOURCES?

- Additive construction necessary for sustained presence
- Use of abundant water ice as a resource proposed on Moon and Mars, but less explored as a construction material
- High performance ice enabled by small percentage of bio-additives, which is compatible with necessary synthetic bioeconomy necessary for a sustained presence
- Composite ice is sublimation resistant and blocks more radiation than pure ice
- Like on Earth, additive construction with ice may be an ideal methodology for expeditionary constructions in new domains and staging areas while more permanent settlements are developed
- 3D printing with ice may be an additional construction technique in the toolbox for a sustained presence in space



Credit: Mars Ice House (https://www.marsicehouse.com/building-on-mars)

FINAL NOTES

- First of its kind demonstration at construction scale! Please watch for our paper.
- This work is enabled by cold facilities of unique scale at CRREL. Ask me about our facilities brochure!
- Long history of high-performance ice construction at CRREL. Ask me for those papers!
- Ask me about our other Advanced Materials Team programs such as ice adhesion and biomacromolecular interactions with ice!

CONNECT WITH US

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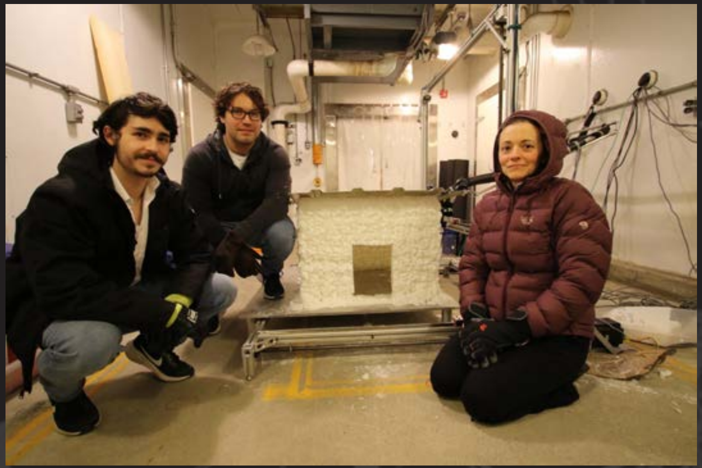

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DISCOVER DEVELOP DELIVER
POWER OF ERDC PODCAST

BEYOND the GATES
How ERDC makes the difference

U.S. ARMY

US Army Corps of Engineers

ERDC

CRREL