ADDITIVE MANUFACTURING OF HIGH PERFORMANCE ICE COMPOSITES.

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Introduction: We present a 'first of its kind' demonstration of additive construction of high strength ice structures reinforced with biopolymers. Developed for expeditionary construction and protection in terrestrial austere and cold environments, the technology may be adaptable as a new kind of in situ resource utilization methodology on the Moon and Mars. We present on our work 3D printing a doghouse-sized ice composite structure, the technology development, and characterization of material properties and processes.

Relevance to Space Resources: Despite the interest of additive construction in space [1] and the interest in utilizing ice as a resource in situ, the use of ice as an additive construction material in extraterrestrial environments is underexplored. Furthermore, for a sustained human presence on the Moon and Mars a circular synthetic bioeconomy is desirable [2] and the use of replenishable biomaterials for printing structures has been proposed [3]. Our technique leverages both ice and biomaterials, making 100 percent of the feedstock available in situ to an established settlement and allow for rapid deployment of expeditionary or more permanent structures to meet operational needs. The method has minimal burden on the synthetic biomaterial supply, requiring only 1.4 wt. % biopolymers and 99.6 wt. % abundant water and ice resources on the Moon [4] and Mars [5]. The final structure is much more durable and stable than natural ice and may provide ultraviolet radiation resistance.

Technical Background: Natural ice in terrestrial environments has an active microstructure, making its utility as a structural material limited due to its tendency to fracture and creep [6]. In the 1940s, the U.S. military discovered that freezing sawdust in ice significantly improved its strength and created a composite material known as pykrete [7]. Modern research has led to the development of high performance ice inspired by pykrete, imparting high aspect ratio cellulose nanofibers (CNFs) that scaffold ice grains and alter the crystallographic texture of the ice microstructure. At CNF mass of only 1 weight percent, this high performance ice has been shown to increase melt resistance through optical and thermal mechanisms [8], increase flexural strength, ductility, compressive strength, and apparent toughness [9], and has been demonstrated to bear the load of military vehicles for gap crossings [10]. Research has not been conducted at Moon and Mars conditions, but lower temperatures likely amplify many of these performance improvements. Figure 1 shows microscopy of the high performance ice composite.

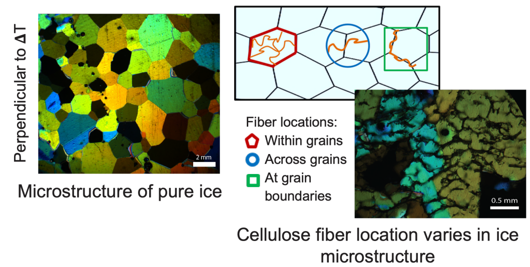

Figure 1: The microstructure of pure ice (left) and CNF reinforced ice (right). The diagram (middle) shows the interpretation of CNF networks in the ice microstructure. Images shown are perpendicular to the temperature gradient during crystal growth.

Most efforts to additively manufacture with ice involve techniques targeting the micro- or nano- scale, suitable for precision manufacturing or material templating and often involving energy input at the nozzle for instantaneous freezing and geometric control (e.g., [11-13]). Additive construction with ice has only been demonstrated with a few techniques [14-15], none of which have resulted in a high performance composite for functional use or been demonstrated at scales where thermal gradients during crystallization are relevant (i.e., structural scale).

Methods: We combined off the shelf mechanical technologies with a novel ice slurry formulation to additively manufacture a meter scale high performance ice composite structure. Using cascaded cold rooms at CRREL to control environmental conditions, the slurry was prepared at -2°C, allowed to mix in a hopper, and pumped to an aluminum deposition platform in -12°C in a process analogous to concrete printing. The deposition was controlled by a custom built triaxial machine that moved the nozzle head around the platform. The slurry was composed of 1 wt. % CNF, 0.4 wt. % other bioadditives, and polydisperse ice particles. The final printed structure included 27 separate layers.

Post construction we corroborated the observed scalability via laboratory experiments and modeling. Fluid properties were characterized with a vane-in-cup rheometer. The morphology of the composite structure was examined using a microscope placed in a cold room. Differential scanning calorimetry (DSC) and phase field modeling were used to study crystallization behavior. Other characterization (e.g., sublimation rates, UV-VIS) are ongoing and omitted here for brevity.

Results: The additively constructed rigid walled structure and print deposition are shown in Figure 2.

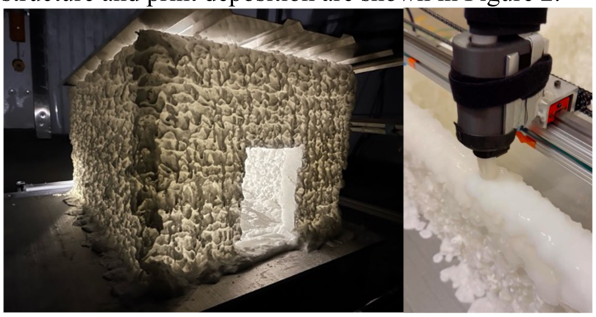

Figure 2: The final printed rigid walled structure made of high performance ice composite (left). The structure was arbitrarily completed at approximately 3'x'2'x2' dimensions. A line of ice slurry deposited during operations (right).

Our experimental results corroborate the observed scalability of our methodology. Shear rate sweeps and constant shear stress tests show our carrier fluid (1 wt. % CNF + bioadditives) has less time dependent flow behavior than pure CNF dispersion, and adding ice particles increases the yield stress to the point where the fluid retains its shape at deposition. Microscopy confirms our modified fluid and freezing methodology retains fiber networks interacting with ice grains. DSC anlaysis confirms that the CNF acts as a nucleator in this formulation, aiding the phase transformation of water to ice. Simulations show the methodology should be able to construct functional structures within days and still deposit and cure at much larger construction length scales. Figure 3 shows a sampling of experimental results.

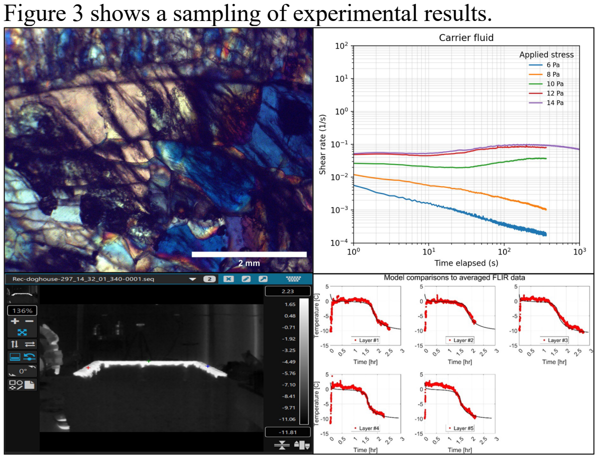

Figure 3: Microscopy of the printed composite (TL). Constant shear stress tests of the fluid carrying the ice particles display near model yield stress fluid behavior (TR). Thermal imaging of a curing layer (BL). Model calibration comparing temperature predictions to average values observed by the thermal camera (BR).

Qualitatively, we have observed noticeable reductions in sublimation rate and light obscuration for the printed ice compared to clear ice, further lending credence to this technology as an enabler for a sustained presence in space.

Conclusions: This work demonstrates the value of technology transfer between polar research and space science. It is the first step towards a new class of additively manufactured high performance ice structures that may be relevant to a sustained presence on the Moon and Mars. The technology will need retrofit for extraterrestrial environments – for example, the need for liquid water in the slurry and stabilization of the slurry prior to deposition will be engineering challenges in extraterrestrial conditions. Nonetheless, it is a promising technology that may be useful for expeditionary ventures on other worlds from a primary staging area, like in terrestrial environments on Earth, and is fully compatible with the circular economy required for sustained human presence.

References: [1] Mueller R. P. et al. (2016) *ASCE Earth and Space*, Orlando, FL. [2] Averesch N. J. H. et al. (2023) *Nature Communications*, 14, 2311. [3] Wordsworth R. W. et al. (2025) *Science Advances*, 11. [4] Spudis P.D. et al. (2013) *Journal of Geophysical Research: Planets*, 118, 2016-2029. [5] Morgan G.A. et al. (2021) *Nature Astronomy*, 5, 230-236. [6] Vasiliev N.K. et al. (2015) *Cold Regions Science and Technology*, 115, 56-63. [7] Perutz M. F. (1948) *Journal of Glaciology*, 1, 2, 95-104. [8] Asenath-Smith A. et al. (2025) *Journal of Physical Chemistry C*, 129, 7846-7854. [9] Asenath-Smith A. et al. (2026) *Materialia*, 45, 102633. [10] Thompson Towell K. L. et al. (2022) *Cold Regions Science and Technology*, 198, 103508. [11] Garg A. et al. (2024) *PNAS Applied Physical Sciences*, 121, 30. [12] Deville S. et al.. (2006) *Science*, 311, 515-518. [13] Zheng F. et al. (2020) *Nature Microsystems and Nanoengineering*, 6, 89. [14] Barnett E. et al. (2009) *IEEE International Conference on Robotics and Automation*, Kobe, Japan. [15] Demmenie M. et al. (2025) *ArXiv Physics Fluid Dynamics*, 1512.14580.