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Mechanical properties of Enceladus' icy plume deposit analogs

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Objectives: Ice plume deposit regions on Ocean Worlds would be prime landing target locations, however a critical lack of understanding of the mechanical properties of these terrains hinders the development of landing and sampling systems. This research aims at 1) developing a fundamental understanding of the mechanical behavior of porous fine-grained ice as it sinters via a combination of experimental measurements and modeling, and 2) advancing our predictive capabilities of the mechanical properties of plume deposits as a function of emplacement age on Europa and Enceladus.

Background: The poor knowledge of the mechanical properties of plume deposit regions is a source of unknown risk to landed elements and sampling systems. Experiments on the cone penetration resistance of plume deposits as function of time and temperature (Choukroun et al., 2020; Choukroun et al., 2021 [Publication A]) provided new insights on the expected state of consolidation of plume deposits as function of location and age. However, cone penetration resistance alone does not inform on all aspects of mechanical properties that are needed to achieve a fundamental understanding of the mechanics of these materials and their microstructure under all applicable types of loading conditions (quasi-static and dynamic loading).

Approach and Result: The approach for this project is to conduct systematic measurements of mechanical properties and modeling of sintering ice samples.

1) Ice plume deposit analogs are prepared in the form of microspheres with mean radius close to Enceladus plume particles and sintered into bulk form at various temperatures.
2) At regular intervals in time, samples were tested for uniaxial compressive strength (Figure 1), and planned for flexural strength and fracture toughness testing.
3) The evolution in grain size distribution and relative neck size was studied by cryogenic optical microscopy at JPL (Figure 2).
4) The microstructure, porosity, and packing arrangement are examined using the Dartmouth College Ice Research Laboratory's micro-computed tomography instrument (Figure 3).
5) A Discrete Element Modeling effort took place early on; a follow-on was planned for FY22 but had to be descoped owing to time constraints.

Significance/Benefits to JPL and NASA: This research has direct and immediate implications for ongoing (and possibly future) mission concepts in development, such as the Enceladus Orbi-Lander Mission Concept recommended by the latest Planetary Science and Astrobiology Decadal Survey, and a JPL study for a New Frontiers Enceladus lander concept, as it seeks to better understand the mechanical properties of ice plume deposits under the surface conditions of Enceladus.

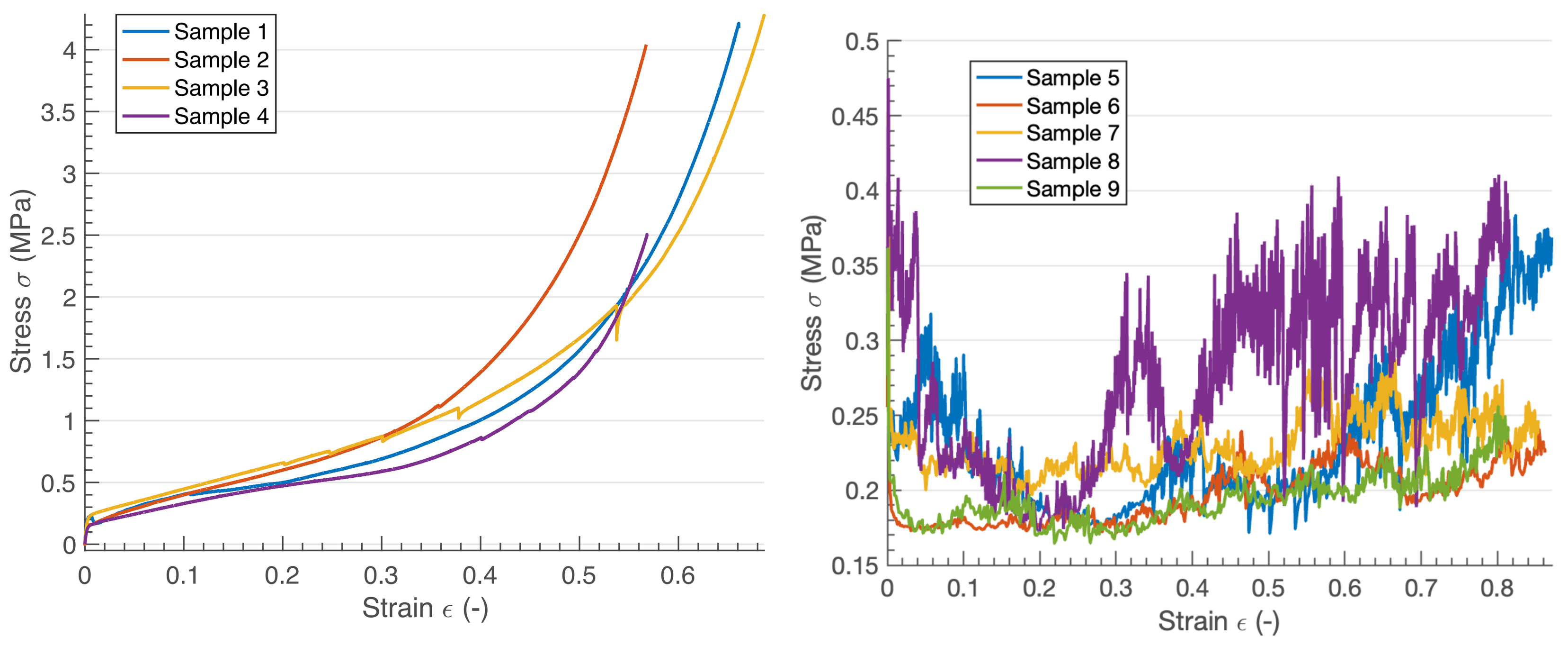

Figure 1. Stress-strain curves obtained on ice samples sintered at -30 °C for 170 days at a loading speed of 0.02 mm/s (strain rate ~ 5x10^{-4} s^{-1}, left) and 0.7 mm/s (strain rate ~ 2x10^{-2} s^{-1}, right) showing ductile and brittle behavior.

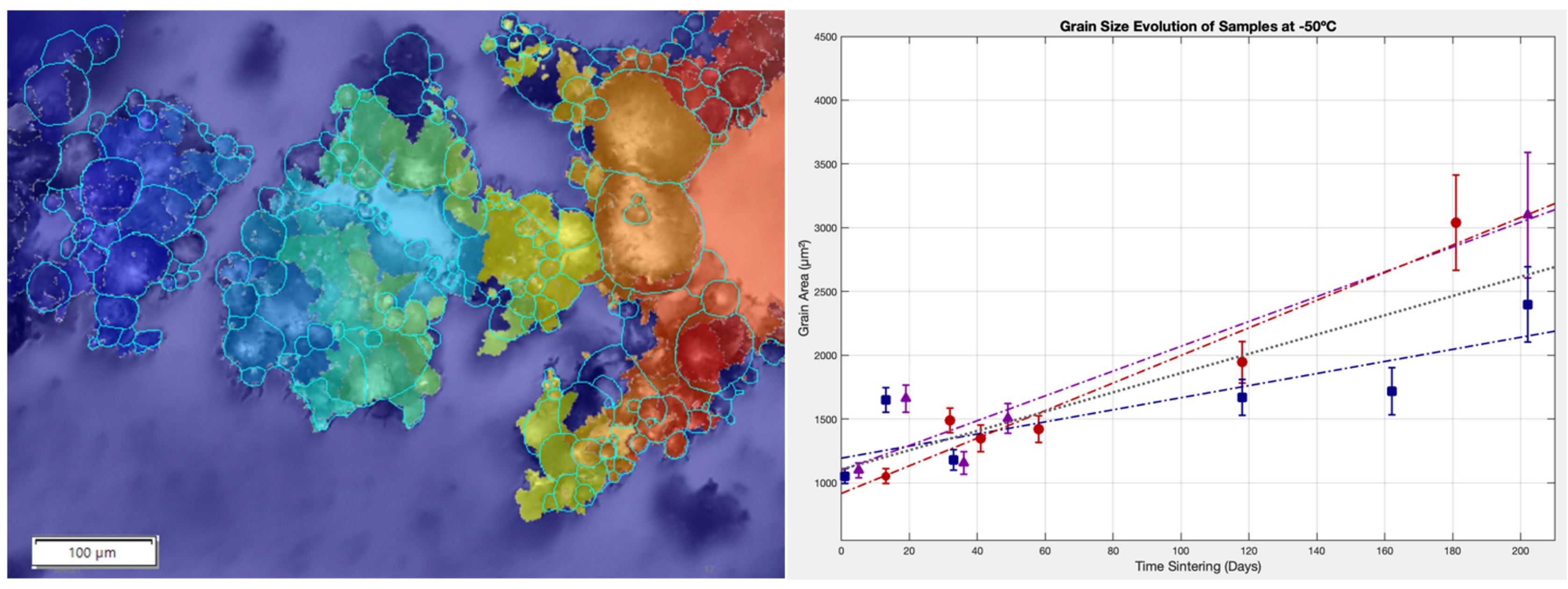

Figure 2. *Left:* Example cryogenic optical microscopy image acquired at -100 °C and processed to extract grain size information. *Right:* Compilation of grain size data from the analysis of 150-300 grains at each sintering time in the -50 °C sintering experiment.

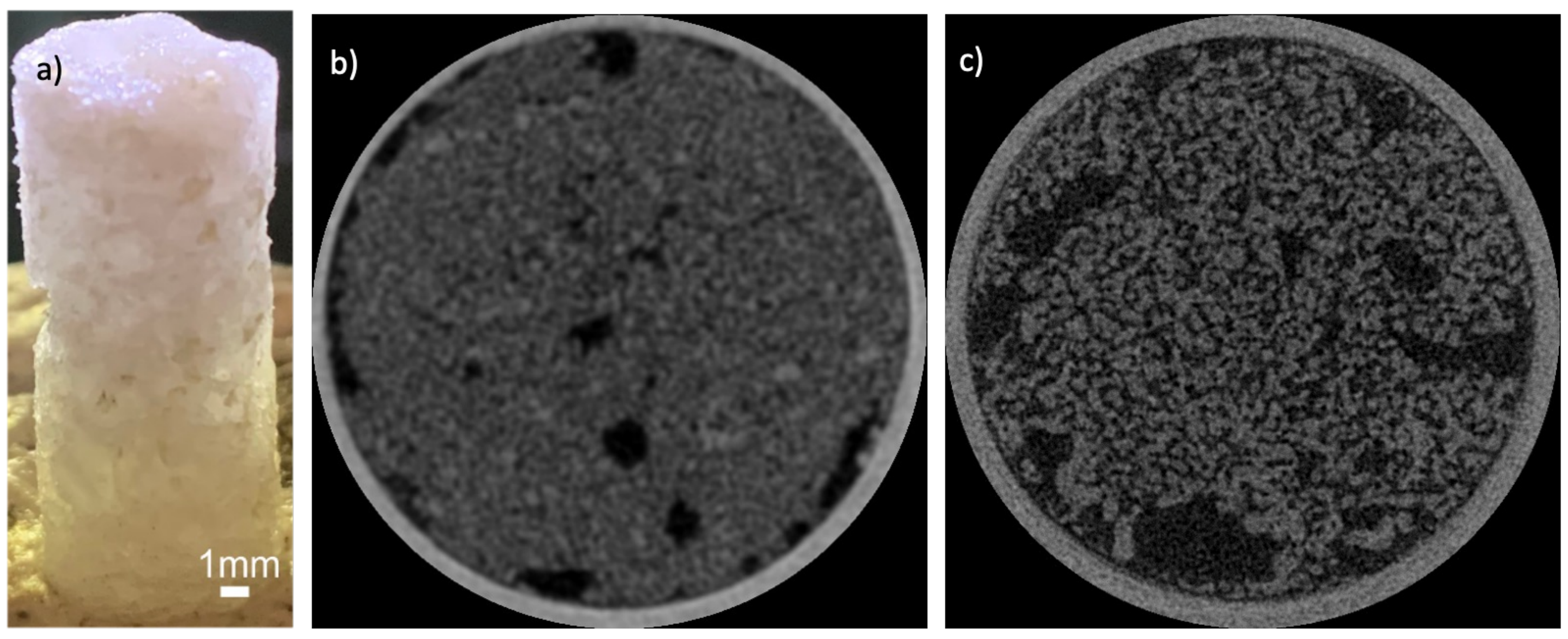

Figure 3. Optical photograph of a cylindrical sample of ice sintered for 2 months at -30 C (a). Horizontal X-ray microtomographic images through the sample after additional sintering of 1 month at -30 °C (b) and of 18 months at -30 °C (c).

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A. Choukroun, M., Backes, P., Cable, M.L., Fayolle, E.C., Hodyss, R., Murdza, A., Schulson, E.M., Badescu, M., Malaska, M.J., Marteau, E. and Molaro, J.L., 2021. Sampling Plume Deposits on Enceladus' Surface to Explore Ocean Materials and Search for Traces of Life or Biosignatures. *The Planetary Science Journal*, 2(3), p.100.

B. Dhaouadi, W., Marteau, E., Kolvenbach, H., Choukroun, M., Molaro, J.L., Hodyss, R., Schulson, E.M., 2022 Discrete Element Modeling of Planetary Ice Analogs: Mechanical Behavior upon Sintering. *Granular Matter*, 24(1), pp.1-20, 2022.

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