Compressive Strength of Ice and Rock at Low Temperatures. J. Atkinson, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA.

Introduction: Recently, water has become a focus for in situ space resource extraction. In addition to being a necessity for sustainable human development off-planet and for processing of extraterrestrial ores, water ice (frozen within soils and rocks) has been identified as one of the most likely substrates in which to find evidence of extraterrestrial life. Much work has been done in identifying potential issues with extraterrestrial drilling/extraction [1, 2, 3, 4], and has been focused on the energy requirement for drilling into permanently frozen extraterrestrial soils. However, little is currently known about the behavior of ice-saturated consolidated rocks at extreme low temperatures as one may encounter in our solar system. Previous laboratory work [5, 6, 7] shows conflicting results, often due to the inherent difficulty in using equipment at such temperature extremes. Using a unique cryogenic axial press at MIT, an experiment was designed to observe the effect of ice saturation at low temperatures on the strength of a porous limestone. This will help to determine the energy needs of drilling into more competent ice-saturated extraterrestrial material.

Background: The unconfined compressive strength (UCS) of a material is the capacity of that material to withstand an axial load in the absence of confining pressure. UCS is an important property and is used in calculating the specific energy (Fig.1) of a material, that is the energy required to drill a hole into the material per unit volume [2]. In order to determine the UCS of an ice-saturated limestone at low temperatures (150K – 78K), an axial press normally reserved for ice/rock aggregate deformation at MIT was used. The machine has a maximum axial load capacity of 200 MPa.

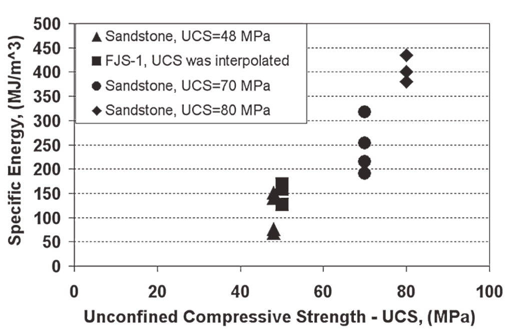

Figure 1. The relation between specific energy and unconfined compressive strength for various substrates [1].

Similar work was done by Mellor in 1971 [5], where he showed an increase in UCS in a limestone with decreasing temperature (Fig. 2). However, at extremely low temperatures (78K), a decrease in UCS was observed, though difficulty in performing the experiment at that temperature was noted.

Using the cryogenic press, an experiment was designed to avoid the difficulties encountered by Mellor and obtain observational evidence of the decrease in UCS from 150K to 78K.

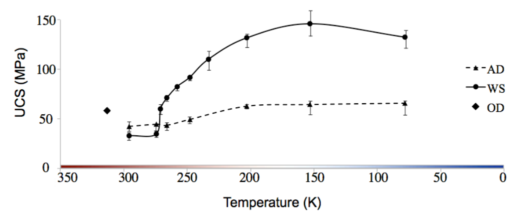

Figure 2. UCS of limestone as a function of temperature (data from [5]). Samples are oven-dried (OD), air-dried (AD), or water-saturated (WS). Note the decrease in strength from 150K to 78K in the saturated samples.

Experiment: Six samples of Indiana Limestone were obtained, with an average porosity of 15% (within range of expected extraterrestrial porosities). Limestone has a UCS at room temperature (295K) of ~45 MPa, therefore increases due to ice saturation were expected to be within capacity of the machine (Fig. 2).

Due to frictional forces within the cryogenic press, unconfined experiments were not possible and a minimal confining pressure of 5 MPa was used. Conversion of this confined strength to UCS was done using Linear Mohr-Coulomb theory.

Results: At both 78K and at 150K, the strength of the ice-saturated limestone exceeded the maximum load of the machine (Fig. 3). That is, the compressive strength under 5 MPa of confining stress (and converted UCS) is greater than 200 MPa. This represents an increase of more than 4.5 times the strength. Additional tests involved subjecting a saturated sample to a freeze-thaw cycle (to weaken the parent rock), which enabled failure at ~184 MPa , as well as obtaining the UCS of oven-dried samples (values ranging from 50-60 MPa at various temperatures) (Fig. 3).

The substantial increase in strength of the ice-saturated samples at 150K and 78K was unexpected, and rendered analysis of the relative strengths at those temperatures impossible with the cryogenic press. However, significant results can still be obtained:

1. Presence of ice in pores at 150K can increase the UCS by more than 4 times (Fig. 4).
2. A small amount of confining pressure can significantly raise the compressive strength of ice-saturated rock (Fig. 3).
3. The UCS of a relatively weak material (limestone) could be greater than 200 MPa if ice-saturated and encountered at appropriately low temperatures (Fig. 4).

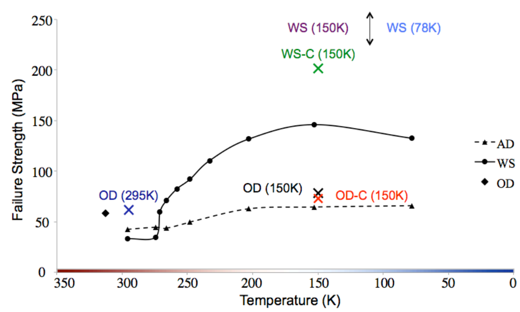

Figure 3. Comparison of compressive strengths of limestone as a function of temperature (confining pressure of 5 MPa). Results from the cryogenic press are shown as coloured x's, where "–C" refers to one freeze-thaw cycle. Note that data from Mellor [5] is unconfined.

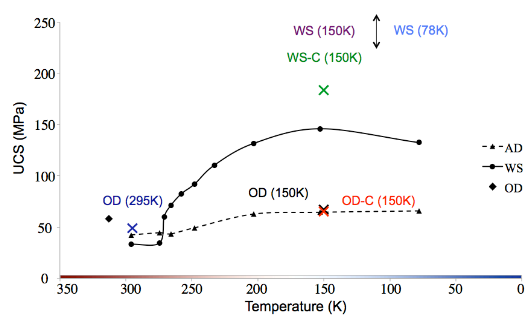

Figure 4. Comparison of compressive strengths of limestone as a function of temperature (converted to UCS).

Discussion: The significant increase in UCS of ice-saturated limestone at low temperatures indicates that the energy required to drill into a saturated, competent extraterrestrial substrate could be quite high. Figure 5 shows two (of many) possible extensions of the relation between specific energy and UCS. If there is no upper bound on the strength, then the energy to drill it becomes unrealistic. Alternatively, at some point there may be a maximum energy requirement reached under which additional material strength may not be important. Much research remains to be done to accurately estimate the amount of energy needed to drill/extract competent extraterrestrial substrate at varying saturations and temperatures.

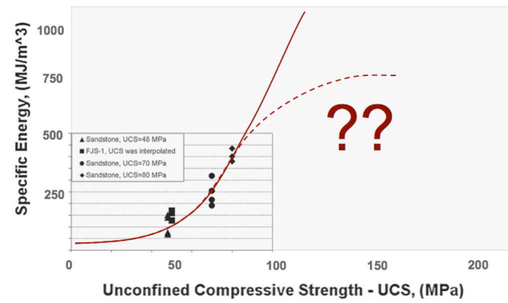

Figure 5. Possible extensions of specific energy requirements to include ice-saturated materials at low temperatures.

References: [1] Zacny, K. et al. (2007) *Space Technology and Application International Forum, Albequerque, NM,* American Institute of Physics. [2] Zacny, K. et al. (2008) *Astrobiology 8, 3,* 665-706. [3] Zacny, K. et al. (2009) AIAA 2009-6431. [4] McKay C. P. et al. (2013) *Astrobiology, 13, 4,* 334-353. [5] M. Mellor (1971) *Cold Regions Research and Engineering Laboratory,* Hanover, NH. [6] A.S. Kurilko and M. D. Novopashin (2005), *Journal of Mining Science, 41, 2,* 119-122. [7] G.E. Monfore and A.E. Lentz (1962), *PCA Research and Development Laboratories.*

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