The Brittle-Ductile Transition in Mixtures of Rock and Ice: Experiments at Planetary Conditions.
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Introduction: Mars exhibits a wide variety of landforms that are indicative of ductile flow, ranging from the viscous creep of ice-rich permafrost [1] to the glaciation of thick Martian ice sheets [2] to the surface mobility of thin debris flows [3]. All of these flow features probably contain significant amounts of dust, which for example will likely be present throughout the impact-disrupted subsurface megaregolith [4], within dark bands in the Polar Layered Deposits [2], and inside sublimation lag layers atop ablating near-surface ice [5]. Due to the unknown rheological effects of dust upon water ice undergoing creep, the proportion of ice required to produce such deformation is uncertain.

Mangold et al. [6] attempted to constrain the effects of ice content by conducting constant load triaxial tests at differential stresses of 1.9-8.5 MPa, at confining pressures of 12 MPa and temperatures of 263 K. For ice contents ranging from 25% to 48%, they obtained relative viscosities 10-50 times higher than that of pure ice under the same conditions [6]. Moreover, Mangold et al. [6] concluded that the brittle-ductile transition in ice-rock mixtures occurs at ice fractions lower than 28%; hence, if the upper kilometer of the Martian megaregolith is comprised of ice-rich permafrost undergoing ductile deformation, then this 28% minimum value implies a global equivalent subsurface layer of at least 200 m [6].

We have begun an ongoing investigation into the rheology of ice-rock mixtures at planetary conditions, the main objective of which is to update the 1992 work of Durham et al. [7] in order to assess the effects of particulates upon grain-size sensitive creep of water ice at low temperatures ranging from 77 K to 223 K. As part of this research program, our initial experiments on ice-rock mixtures should provide more detailed constraints on the nature of the brittle-ductile transition at low temperatures—and, by extension, the minimum ice content required for ductile flow on Mars.

The Brittle-Ductile Transition: The maximum particle loading tested in our earlier 1992 work was 56% by volume [7]. At higher loading, conventional testing becomes problematic as the higher differential stresses that must be applied move the deformation regime closer to the brittle-ductile transition, a rather fundamental change in deformation mechanism, with a strong shift in the dependence of viscosity on temperature, pressure, and strain rate. The brittle-ductile transition in all rocks, including ice + rock mixtures, is gradual, with cataclastic fracturing and crushing of grains as one end member behavior [7] and fracture-free flow of the matrix material as the other. In the case of ice mixtures, pressure melting also has been implicated [6,8].

Since Martian strain rates are far slower than practical laboratory strain rates, the wrong deformation mechanism in the lab will extrapolate to an incorrect viscosity for Martian surface materials. Great care must be taken, therefore, to identify the mechanism in the lab. The direct approach of measuring stress vs. strain rate well outside the brittle field is unlikely to succeed, as the required strain rates will be nearly geological. Studies of ice + sand deformation at high sand fraction, with both planetary and terrestrial frozen soil (permafrost) application, show behavior that is either demonstrably brittle or too close for comfort [6,8]. Most testing like this is carried out at high temperatures in an effort to maximize ductility, although the special characteristics of water-ice deformation near the melting point also suggest a different mechanism [8].

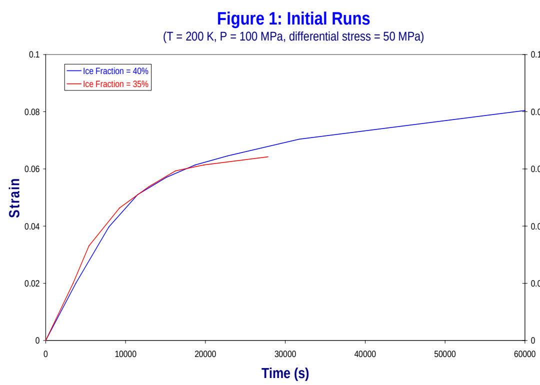
We instead adopt a strategy of differential measurement in an attempt to detect the first effects of ice on the mobility of a sand pack. In brief, we will measure the response of a dry, porous sand to an applied stress, then introduce water into the same sand, freeze it, and measure the response again. Even if the response is a transient one, if it is different for the sand pack dry vs. with ice (and weaker in the latter case), then we can infer the existence of some deformation mechanism related to the presence of ice

Dry sand mixtures of a range of particle sizes (for better packing) will be fabricated in indium jackets using our standard molding tubes, and then vibrated with table shakers to maximize packing density. By mixing grades of sand and silt we hope to be able to attain porosities as low as 25-30%. (For comparison, this is about 10% less than the typical porosities obtained by Mangold et al. [6], who only achieved lower ice contents in their ice-rock mixtures by utilizing less than 100% ice saturation.) By reducing the spread of particle sizes, we should be able to increase porosity in 2-3 steps up to the 44% that we achieve with pure quartz sand (Oklahoma #1), with the most tightly distributed grain sizes of our component sands.

All samples will be tested at conditions far from the brittle field. By conservative application of the Goetze rule [9], we will not allow differential stress to exceed half of the confining pressure. We expect that for the highest sand fractions, we will not detect any inelasticity, and the experimental question will become at what sand fraction do we first see an effect of ice. Determining the best sample fabrication method, and confirming the reproducibility of the final product will no doubt require extensive experimental effort and SEM study.

Preliminary Results: Figure 1 shows the initial results of our first two runs, corresponding to samples of Oklahoma #1 quartz sand with ice fractions of 40% and 35%. Both were relatively short-duration exploratory runs, and thus only achieved low permanent strains. However, the sample with less ice does appear to be approaching lower strain rates at the same differential stress. For our impending longer-lasting experimental runs, we will be able to use SEM analysis to determine if brittle fracture has occurred, as evidenced by Figs. 2 and 3, which respectively show SEM images of a 40% ice / 60% quartz mixture before deformation and after 8% strain. Lastly, we will discuss the implications of our laboratory results for the global volatile inventory of Mars.

References: [1] Squyres S. W. (1989) *Icarus, 79,* 229-288. [2] Clifford S. M. et al. (2000) *Icarus, 144,* 210-242. [3] Milliken R. E. (2003) *JGR, 108 (E6)*, 11–1. [4] Clifford S. M. (1993) *JGR*, *98*, 10973-11016. [5] Hofstadter M.D. and B. C. Murray (1990) *Icarus*, *84*, 352-361. [6] Mangold N. P. et al. (2002), *PSS*, *50*, 385-401. [7] Durham W.B. et al. (1992) *JGR*, *97*, 20883-20897. [8] Ma W. (1999) *Cold Regions Sci & Tech., 29,* 1-7. [9] Evans B. and D.L. Kohlstedt (1995), Rheology of rocks, in *Rock Physics and Phase Relations: A Handbook of Physical Constants, Ref. Shelf Vol. 3.*



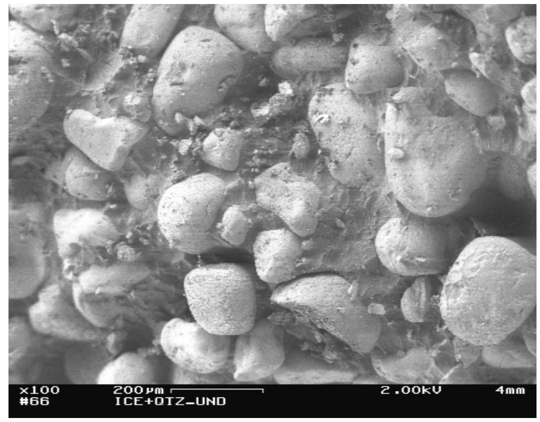


Figure 2: SEM image of undeformed 40% ice-60% sand mixture.

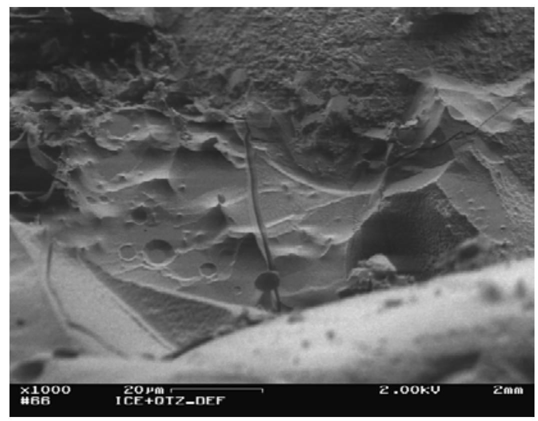


Figure 3: SEM image of deformed 40% ice-60% sand mixture subjected to a total strain of 0.08.