THE BRITTLE-TO-DUCTILE TRANSITION OF ICY MATERIALS ON MARS.

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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 which likely contain significant amounts of dust. Since the rheological effects of dust upon water ice undergoing creep are not well known, the proportion of ice required to produce such deformation is uncertain.

Mangold et al. [4] 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 at a temperature of 263 K. For ice contents ranging from 0.25 to 0.48 by volume, they obtained relative viscosities 10-50 times higher than that of pure ice under the same conditions [4]. Moreover, Mangold et al. [4] concluded that the brittle-ductile transition in ice-rock mixtures occurs at ice fractions lower than 0.28, which assuming that the upper kilometer of the Martian megaregolith is comprised of ice-rich permafrost undergoing ductile deformation implies a global equivalent subsurface layer of at least 200 m [4].

However, we have previously demonstrated the importance of conducting deformation experiments involving ice at colder temperatures more relevant to Mars. For example, Durham et al. [5] found that mixtures with 0.44 ice exhibited a relative viscosity nearly 100 times that of pure ice at T = 223 K, which is significantly higher than the maximum value of 50 obtained at T = 263 K by [4]. This suggests that the minimum threshold ice content required for ductile flow on Mars may be significantly greater than 28%.

The Brittle-Ductile Transition: The maximum particle loading tested in our earlier low-temperature work was 0.56 by volume [5]. 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 considering the brittle-ductile transition, it is important to distinguish transient and steady-state deformation. Our view is that in light of the fact that differential stresses in the Martian regolith are probably exceeding low (< 0.1 MPa) except in regions of extreme topographic change, brittle behavior is unlikely to occur in the Martian regolith where rock content exceeds 0.6 – 0.7 by volume. Steady-state deformation in the ductile regime may also require a threshold concentration of ice. Thus if the presence of ice influences the deformation of Martian landforms at high rock content, that influence must be the result of non steady state (transient) ductile deformation.

Experiments: In order to reach higher volume fractions of rock, sand mixtures of a range of particle sizes (for better packing) have been 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 have been able to attain porosities as low as 0.25. For comparison, this is about 0.10 less than the typical porosities obtained by [4], who only achieved lower ice contents in their ice-rock mixtures by utilizing less than 100% ice saturation. We conduct deformation experiments in our cryogenic triaxial gas apparatus under confining pressures sufficient to keep us far from the brittle field. Applying the so-called "Goetze rule" [6] conservatively, we do 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 becomes at what sand fraction do we first see an effect of ice.

The results of 5 initial runs are shown in both Figure 1 and Figure 2. The scale on Figure 1 is expanded to show the influence of ice fraction on the transition from steady-state to transient behavior under laboratory conditions. Figure 2 shows the effects of small changes of ice fraction in the transient region.

Steady-state to transient: The five runs in Figure 1 were carried out under a differential stress of about 31 MPa (under confinement of 60 MPa) and temperatures of 223 and 243 K. The one sample with 0.40 volume concentration of ice I carries to much higher strains than the other four with volume concentrations ≤0.32. An additional difference, not evident on the graph is that the slope of the curve for 0.40 ice becomes straight (this run actually continued to a final strain of 0.23), while the other curves continue to harden to a strain rate below our ability to measure (≤ 5 x 10^{-9} s^{-1} or roughly 1% per 2 weeks). The rheology of the flow in the 0.40 ice sample is consistent with the measurements in [5]. We conclude that somewhere near ice volume fraction 0.35, sand particles form a framework that is essentially undeformable. Consistent with this concept of an undeformable framework is the disappearance of any appreciable temperature effect on strain rate (i.e., the slope of the curves in Figures 1 and 2) at ice fraction ≤0.32. Changing temperature from 243 K to 223 K in the 0.40 ice sample changes the rate of strain by a factor of ten; the same temperature change in the 0.32 ice samples (Figure 2) has some effect at early time, but virtually no effect on the total strain imparted.

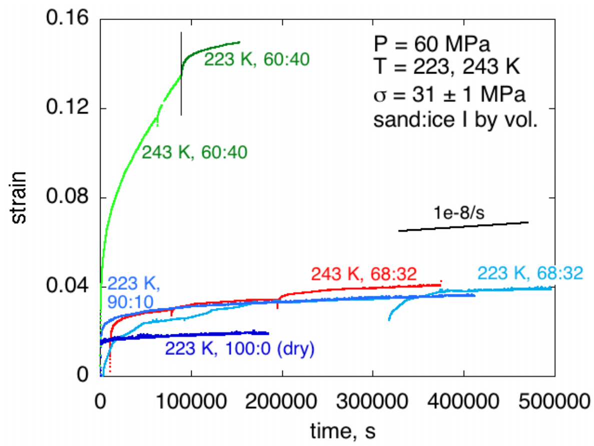

Figure 1 Stress vs plastic strain curves from experimental samples showing the transition from steady-state creep to transient only creep. Curves are labeled according to temperature and volume ratio of rock to ice I. All samples were subjected to the same creep load of 31 MPa. At some volume fraction of ice between 0.40 and 0.32, the sand particles form an undeformable framework.

First mobility: If samples of ice volume fraction ≤0.32 harden to a virtual stop, is there any effect of ice in a regolith if concentrations are below that level? Figure 2 shows that there evidently is, but the effect is far from linear. At ice fraction 0.32 and 0.10 the final strain achieved is virtually identical (at about 0.03). However, in the dry sample, deformation halts at roughly half that strain. Evidently a small amount of ice facilitates a rearrangement of sand particles under differential load. Only when the last of the ice is removed does the mobility disappear.

Further work: We will present the results of additional runs with ice fractions below 0.32 in order to better characterize the onset of transient creep. We will also present the results of runs with ice fractions between 0.32 and 0.40 at low temperatures, which should more firmly constrain the brittle-ductile transition. If we find that steady-state flow only occurs above an ice fraction of 0.35, this would imply that the Martian subsurface has 25% more ice than estimated by [4].

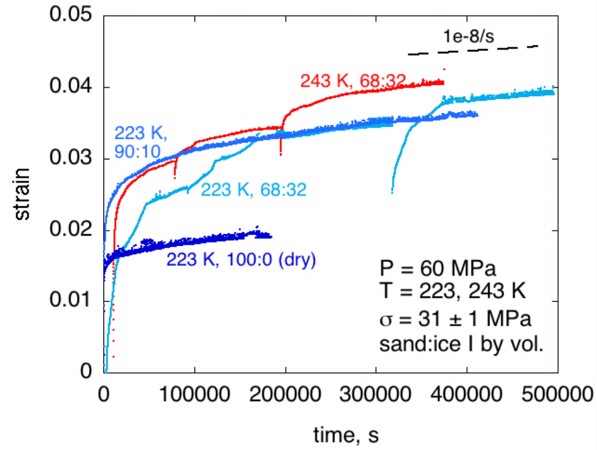

Figure 2. Detail of four of the five curves in figure 1. All curves are trending to a slope below our ability to measure in a reasonable amount of time (the horizontal axis is about 6 days long). The behavior of samples with ice fraction 0.32 and 0.10 is virtually the same. A warmer temperature at ice faction 0.32 (red vs. lightest blue) causes early strain to occur faster. The effect of removing the last 0.10 ice fraction is a dramatic decrease of final strain achieved. The cusps in the lightest blue curves are artifacts of temperature irregularities of 2 -3 K on the measurement system. Three vertical drops in two of the curves (red and lightest blue) mark points of unloading and reloading the creep stress. In all cases this process causes a slight strain enhancement. This is not an artifact.

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