BRITTLE AND DUCTILE BEHAVIOR OF ICE/ROCK MIXTURES; W. B. Durham, UCLLNL, Livermore, CA 94550; S. H. Kirby and L. A. Stern, USGS, Menlo Park, CA 94025; K. A. Ragaini, UCSD, La Jolla, CA 92121

As part of an ongoing experimental study of the mechanical behavior of ices under extraterrestrial conditions, we have completed a series of triaxial tests on mixtures of water ice and solid particulates of varying compositions and concentrations. The work applies mainly to the icy Galilean giants Ganymede and Callisto, and possibly to the near surface of Mars. Ganymede and Callisto have bulk water-to-silicate mass ratios on the order of 1:1. Whatever evolutionary scenario one chooses to model, whether the moons accreted as a homogeneous or heterogeneous mix, whether or not differentiation occurred, the mechanical behavior of ice/rock mixtures plays a key role (1).

We have studied the effects of sized particulates of SiC, calcite, and quartz, in volume concentrations ϕ from 0.001 to 0.56, of grain sizes 1 to 150 μm, at temperatures from 77 to 223 K, at confining pressures to 100 MPa, and at strain rates from 3.5×10^{-4} to 3.5×10^{-6} s^{-1}, in an ice matrix of grain size 0.8 to 1.5 mm. To summarize our findings, below $\phi = 0.10$ none of the particulates has a measurable effect (resolution is about ±5%) on the steady-state strength of ice in the so-called ductile field, where plastic flow occurs. At $\phi > 0.10$, the ductile strength of ice increases with increasing particulate concentration. Coarse particulates also toughen ice, that is, they extend its range of ductility and make it less prone to catastrophic brittle failure.

Some of the more important results are shown in Figs. 1 and 2. In Fig. 1 we compare the stress vs strain behavior of pure ice, ice mixed with calcite ($\phi = 0.20$), and ice mixed with quartz sand ($\phi = 0.10$ and 0.56) at conditions of fixed temperature and strain rate. These results are typical for the temperature range 160 to 223 K. One sees subtle differences in the transient portion of the curves (where differential stress changes with shortening). In the steady-state portion, where the curves flatten out, the pure ice samples and SiC-doped samples (not shown in Fig. 1) converge to nearly the same strength. The $\phi = 0.20$ calcite samples are about 10% stronger than the pure ice. For silicate particulates in the ductile field (Figs. 1 and 2), the strength for $\phi = 0.10$ is barely distinguishable from that of pure ice; for $\phi = 0.56$, strength is a factor of 3 higher than for pure ice. The one $\phi = 0.30$ sample tested was stronger than pure ice by a factor of less than 1.5. These strength contrasts are about one-half to one-third those predicted for Newtonian-viscous matrix material (1). Ice is non-Newtonian at the conditions of our experiments (strain rate depends on stress raised to the power n, where n = 4 to 5), and the lower strength contrasts are to be expected.

The data are sparse in the brittle field. Two samples of $\phi = 0.30$ (quartz) failed catastrophically at 77 K and a differential load of 189 and 152 MPa, respectively, vs approximately 170 MPa for pure ice. Four samples of $\phi = 0.30$ and 0.56 at 77 K apparently had jacket leaks, but rather than failing at the 50-MPa level typical of pure ice in the unconfined condition, they failed at 62 to 119 MPa.

The presence of quartz particles (and perhaps SiC and calcite, although it was not investigated) toughens as well as strengthens ice. For example, although the $\phi = 0.10$ ice/quartz mixture has about the same ductile strength as pure ice, the brittle-to-ductile transition occurs at much lower temperatures than for pure ice. Thus, at 143 K and a strain rate of 3.5×10^{-6}, where pure ice fails in a brittle manner, the $\phi = 0.10$ mix flows plastically at 141 MPa. Even at 77 K, the ice/rock samples showed signs of toughening. The higher-than-normal unconfined strengths cited above is one example. The failure that occurred at 77 K was also not as sudden as with pure ice, but was drawn out over a period of 1 or 2 s, or was preceded by behavior reminiscent of yielding. We suggest that the

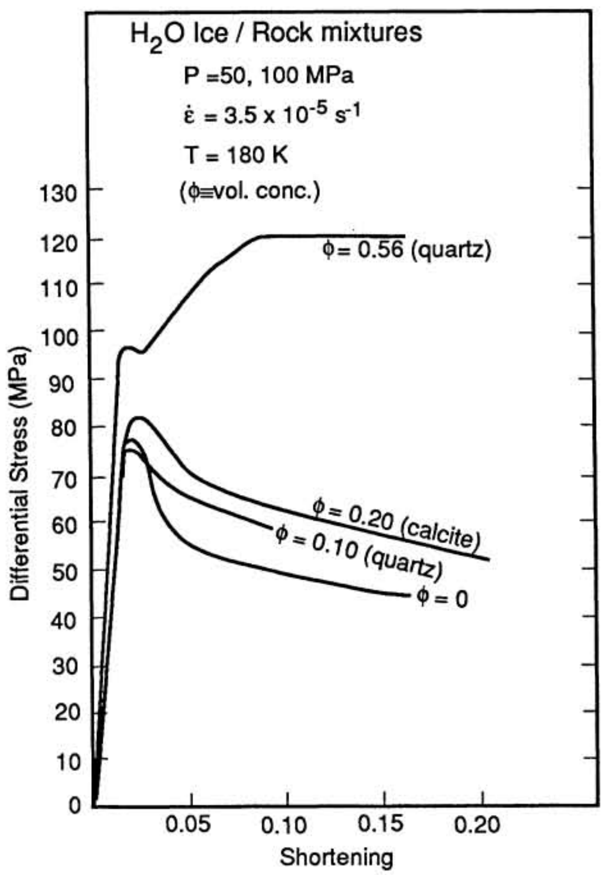

Figure 1. Experimental stress-strain curves for various ice/rock mixtures. Stresses have been corrected for cross-section changes during deformation. Shortening is defined as displacement divided by original sample length.

silicate particles toughen the ice by limiting the flaw (i.e., microcrack) size, either to the size of the particles or to the interparticle spacing.

No evidence for dispersion hardening (dislocation and grain boundary pinning) was observed using SiC and calcite particulates in ice samples, even for grain sizes near 1 μm.

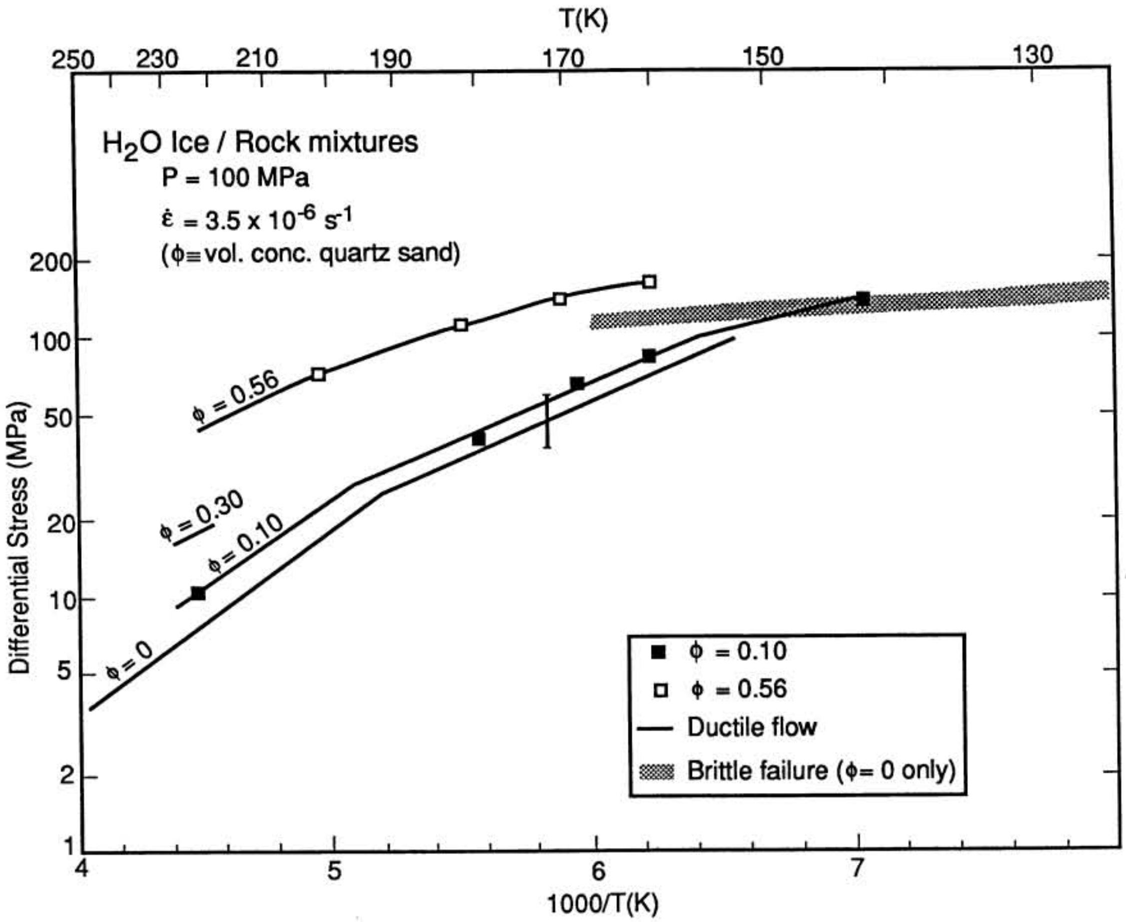

Figure 2. Steady-state flow strengths compared for volume concentrations of quartz sand from $\phi = 0$ to 0.56. The $\phi = 0$ line was taken from earlier work (2) and the error bar encompasses the scatter of experimental data. Solid and open squares represent results from the present study. The curve for $\phi = 0.30$ is derived from measurements (not shown) at higher strain rates.

References

(1) Friedson, A. J. and D. J. Stevenson (1983) *Icarus*, *56*, 1-14.
(2) Kirby, S. H., W. B. Durham, M. L. Beeman, H. C. Heard, and M. A. Daley (1987) *J. Physique*, *48*, supplement (VIIth Symposium on the Physics and Chemistry of Ice), 227-232.