The mechanical properties of water ice play an important role in physical processes, both past and present, on icy bodies in the solar system. The two largest, the Galilean satellites Ganymede and Callisto, are well over half \( \text{H}_2\text{O} \) by volume. Those bodies are also of particular interest because of their considerable size, chemical similarity and dissimilarity of surface morphology. \( \text{H}_2\text{O} \) exists in those bodies in several high pressure phases and may or may not be contaminated with dissolved impurities (such as \( \text{NH}_3 \) or \( \text{CH}_3 \)) or particulate impurities.

Recently, we began conducting laboratory deformation experiments on pure polycrystalline \( \text{H}_2\text{O} \) ice at elevated pressures and low temperatures \([1]\). At present we have achieved a nearly complete characterization of the flow of ice \( \text{I}_h \) at pressures \((P)\) throughout its stability field to temperatures \((T)\) as low as 77 K and for strain rates \((\dot{\varepsilon})\) \(3.5 \times 10^{-4} \text{s}^{-1}\) to \(3.5 \times 10^{-6} \text{s}^{-1}\). We have also conducted tests in the ice II and III stability fields and have made significant progress toward understanding the plastic flow of those phases.

A standard creep relation of the form

\[
\dot{\varepsilon} = A\dot{\varepsilon}^n \exp \left(\frac{-H^*}{RT}\right), \quad H^* = E^* + PV^*
\]

where \(\dot{\varepsilon}\) is the differential stress, \(R\) is the gas constant, and \(A\), \(n\), \(E^*\), and \(V^*\) are material constants has been adequate to describe all of the ductile results we have gathered thus far. Flow of ice \( \text{I}_h \) under the conditions tested here has indicated that, depending on \(T\) and \(\dot{\varepsilon}\), three different sets of material constants are needed to describe flow. Thus, three different flow mechanisms exist. The constants \(H^*\) and \(n\) for the three mechanisms are given in Figure 1. We have confirmed the preliminary indications of a decreased temperature sensitivity for creep at \(T < 195 \text{ K}\), supporting the notion that the surface viscosity of a pure ice body may be insufficient to support the topography which exists on Ganymede and Callisto.

Regarding brittle fracture, our recent results indicate that fracture
strength at $P < 50$ MPa has a positive dependence on pressure, making ice like most other rocks in the brittle field. The transition between the "normal" low pressure behavior and the anomalous pressure-insensitive regime described in [1] is $50 \pm 10$ MPa at $T = 77$ K. The volume-independent failure mechanism operative at $P > 50$ MPa may involve local phase change. It is still under investigation.

The flow of ices II and III at $\dot{\varepsilon} = 4 \times 10^{-4}$s$^{-1}$ is compared to that of ice Ih in Figure 2. The rheologies of ices II and III are distinctly different, with III being more temperature sensitive than either Ih or II. We have made measurements at $\dot{\varepsilon} = 4 \times 10^{-4}$s$^{-1}$ comparing strengths of the phases at common pressures (i.e. transition pressures) and found that ice II is roughly 30% stronger than ice Ih, with the difference not strongly dependent on temperature. The relative strengths of ices Ih and III are very temperature sensitive, as can be inferred from Figure 2. At 244 K, ice III has 40% the strength of ice Ih; at 248 K, ice III has barely 20% the strength of ice Ih. The pressure and stress sensitivity of flow rate of ices II and III are currently under investigation.


Figure 2. Ductile flow of ices II and III at $P=250$ MPa compared to the flow of ice Ih at $P=50$ MPa, all at $\dot{\varepsilon} = 4 \times 10^{-4}$s$^{-1}$. Circles represent experimental data on ices II and III and the squares represent data (not plotted in Figure 1) on ice Ih. Phase identification is inferred from position in the phase field and metastability information from Bridgman[2]. The data point at $T = 230$ K is suspected to pertain to ice III existing metastably in the ice II field. At $P = 250$ MPa the ice II-III boundary occurs at $T = 240$ K.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.