Mechanical properties of ice-silica mixtures: Fracture toughness and elastic moduli

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Ductile-to-brittle (D/B) transition is a key rheological property to determine the tectonic style (flow features and fracture patterns) on the surfaces of icy bodies in the solar system such as Earth, Mars and icy satellites and it has been studied by numerical models, laboratory experiments, and field observations. The theoretical model of D/B transition indicates that the transitional strain rate is controlled by some factors; for example, a power law relationship between stress and strain rate in a ductile behavior, $d\varepsilon/dt = B\sigma^n$ ($d\varepsilon/dt$ is the strain rate and σ is the stress), fracture toughness, and coefficient of friction [Schulson, 1990; Renshaw and Schulson, 2001]. Particularly, fracture toughness is one of the most important factor to determine the critical strain rate corresponding to the D/B transition. The fracture toughness of water ice has been studied by laboratory experiments and depends on temperature, porosity, ice grain size, etc. For example, the K_{Ic} of non-porous fresh water ice is about 100 kPa $m^{1/2}$ at -10° C [e.g., Nixon and Schulson, 1987]. The tectonic features found on Mars and icy satellites has a rocky component with various contents in water ice. Thus, the fracture toughness of ice-rock mixtures is important to determine the tectonic style on icy bodies but it remains unclear. In this study, we measured the fracture toughness of ice-rock mixtures and examined the effect of rock content on fracture toughness. Furthermore, we also measured elastic moduli, Young's modulus and Poisson's ratio, which are closely related to fracture toughness.

The samples were prepared by mixing ice seeds with a diameter smaller than 850 μm, amorphous silica beads with a diameter of 0.25 μm, and distilled water at 0° C to fill spaces among the ice seeds and/or silica beads. The samples which had a cylindrical shape with a diameter of 30 mm and a height of 60 mm were frozen in a cold room at -10° C for more than one day. The specimens for the measurements of fracture toughness were shaped by cutting original cylindrical sample to a rectangular parallelepiped shape and the notch was made by cutting at the center of basal surface. We made samples with silica volume fraction, *f*, of 0, 0.06, 0.12, 0.18 and 0.34. Fracture toughness was measured using the method of three-point bending in a cold room at -10° C at Ice Research Laboratory, Dartmouth College. The elastic moduli were determined by measuring the ultrasonic velocity of both longitudinal and shear waves. After the measurements, the microstructure of recovered specimens were observed using a cryo-SEM.

The fracture toughness, K_{Ic}, for pure ice was 99.8 ±18.5 kPa $m^{1/2}$, close to those of fresh-water ice obtained in previous studies at -10° C [e.g., Nixon & Schulson, 1987]. The values of K_{Ic} for each ice-silica mixture varied more than that of pure ice yet the fracture toughness increased with increasing silica volume fraction and scaled as the square root of silica volume fraction; i.e., $K_{Ic} \propto f^{0.5}$. Young's modulus, *Y*, increased linearly with increasing silica volume fraction over the range of silica volume fraction explored in this study. On the other hand, Poisson's ratio, ν, of pure ice and ice-silica mixtures were almost the same, irrespective of silica volume fraction. The average value was 0.33, consistent with that of polycrystalline granular ice at -5° C [Schulson and Duval, 2009]. Fracture toughness is related to Young's modulus and Poisson's ratio as $K_{Ic}=\sqrt{G_c}(Y/1-\nu^2)$, where G_c is the critical value of the crack-extension force. In our experiments, we found that the increase in fracture toughness with silica volume fraction primarily resulted from the linear increase in Young's modulus with silica volume fraction given assuming the crack-extension force G_c was independent of silica volume fraction over the range of silica volume

fraction explored in this study.

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