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Rate-dependent strength of porous ice–silica mixtures and its implications for the shape of small to middle-sized icy satellites

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ABSTRACT

Porosity is one of the most important physical properties in the rheology of small icy satellites composed of ice–silicate mixtures. Deformation experiments involving ice and 1 μm silica bead mixtures were conducted to clarify the effect of porosity on the flow law of ice–silica mixtures. Mixtures with silica mass contents of 0, 30, and 50 wt.% were used for the experiments, and the porosity was changed from 0% to 25% in each mixture. The temperature ranged from −10 to −20 °C, and the strain rate was changed from 1.2×10^{-6} to $4.2 \times 10^{-4}\ \mathrm{s}^{-1}$. As a result, it was found that the ice–silica mixtures deformed plastically, and that the relationship between the maximum stress, $\sigma_{\max}$, on the stress–strain curve and the applied strain rate, $\dot{\varepsilon}$, could be described by the following flow law: $\dot{\varepsilon} = A_0 \exp(-Q/RT) \cdot \sigma_{\max}^n$. The mixture became softer as the porosity or silica mass content increased, and the stress exponent n and activation energy Q were independent of porosity, depending only on the silica mass content. Furthermore, the parameter A_0 could be written as $A_0 = B(1-\phi)^{-\alpha}$, where ϕ is the porosity. The constants B and α also depended only on the silica mass content, and they increased with the increase in this content. The Maxwell relaxation time was calculated in order to estimate the conditions for topographic relaxation of icy satellites, and it was found that topographic relaxation occurred at temperatures higher than 160 K in the case of icy satellites with mean radii of 200 km.

1. Introduction

Recent explorations by spacecraft and ground-based observations have shown that icy bodies such as the jovian and saturnian satellites and Kuiper Belt Objects have various shapes. In particular, icy satellites with mean radii smaller than 200 km are irregular in shape and are generally referred to as "potato-shaped", while those with radii larger than 200 km are nearly spherical. The shapes of asteroids such as Ceres and comets are also recognized to be irregular or spherical (Thomas, 1989). It is believed that icy satellites having an irregular shape might be reaccreted fragments produced by the disruption of a larger proto-satellite or remnant planetesimals. As such, icy satellites have preserved substantial information regarding the processes involved in planetary formation (Farinella et al., 1983). Furthermore, icy bodies larger than 200 km in radius, unlike the smaller objects, tend to have preserved small topographic anomalies (Croft, 1992). Farinella et al. (1983) and Croft (1992) proposed a criterion to explain this abrupt change in surface irregularities in small bodies. Farinella et al. (1983) studied the surface irregularities of small icy satellites and suggested that they were determined by the ratio of the crust material strength to the gravitational stress exerted in the crust. When the crust strength exceeds the gravitational stress, the material strength can support the surface topography. When the gravitational stress exceeds the material strength, the surface topography relaxes toward a gravitational equilibrium figure, i.e., a sphere. However, small icy satellites very close to planets, such as Pan and Prometheus, have an ellipsoidal figure due to tidal stress. Croft (1992) proposed that the dominant mechanism driving topographic relaxation was viscous flow: the transition radius between relaxed and non-hydrostatic shapes could be determined from the ratio of gravitational stress to planetary material viscoelasticity. He suggested that internal temperature strongly affects viscous creep, which drives the relaxation to a spherical shape. In this process, Johnson and McGetchin (1973) and Croft (1992) found that the longest topographic wavelength, corresponding to the global shape of the body, relaxed first, with smaller features progressively following. Therefore, the critical size at which the transition of the surface irregularity occurs in an icy satellite might depend on the scale of the topography (Turcotte et al., 1981). Since viscous relaxation depends strongly on temperature and gravitational stress, Croft (1992) adopted the Maxwell relaxation model to calculate the physical conditions for topographic relaxation. He found that the temperature required to cause topographic relaxation of

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saturnian satellites was about 120–130 K. However, this temperature was too high compared to the accretional temperature in the saturnian satellite system, which was believed to be about 60–100 K (Pollack et al., 1991). However, the thermal history of small icy satellites should also be considered to explain the observed topographic features. When we apply Croft's model to small icy satellites, it is necessary to properly model the viscoelastic properties of icy bodies, which are a function of their material composition and microstructure.

The viscosity of an icy body material can be determined by measuring how the material flows under stress. From this we infer a flow law, which represents the relationship between the stress and the strain rate at the steady-state deformation at each temperature. The flow law is determined by many parameters, such as composition, structure, and temperature. Spacecraft observations enable us to estimate the mean densities of icy satellites, and the spectral features of reflected light on their surfaces provide constraints on our understanding of their composition. However, the density of small icy satellites has evolved as a result of compaction during the accretion process. Thus, icy satellites might retain various degrees of residual porosity in their interiors, even at present (Leliwa-Kopystynski and Kossacki, 2000). However, it is very difficult to estimate the rock content and the residual porosity of icy satellites simultaneously based only on the observed mean density. The radiation equilibrium temperature of the icy bodies at distances from the Sun farther than the orbit of Saturn is very low, <100 K, while the internal temperatures of icy satellites are estimated to be greater than the surface temperatures as a result of radioisotope decay and accretion heating (e.g., Matson et al., 2009). The flow laws of icy materials with various rock contents and temperatures have been studied (Durham et al., 1992, 2009; Mangold et al., 2002; Yasui and Arakawa, 2008). However, the effect of porosity on the flow law of ice–rock mixtures has not yet been studied systematically.

The mechanical properties of H_2O ice with various porosities have been studied previously. Maeno et al. (1978) measured the Young's modulus of an ice core obtained from an Antarctic ice sheet and found that it decreased from 5.0 to 1.0 GPa as porosity increased from 0.1 to 0.45. Furthermore, many researchers have studied the compressive viscosity of Antarctic ice in relation to the densification process from snow to ice under overburden pressure (e.g., Maeno and Narita, 1979), and it has been shown that the compressive viscosity increases as porosity decreases. The mechanical strength of sea ice has been studied in relation to ice engineering and to the collision of sea ice with structures. Sea ice is composed of H_2O ice, brine, and/or porosity, and the brine and/or porosity vary as a function of the environment in which they were formed. Many studies based on field observations, laboratory experiments, and numerical simulations show that mechanical strength exponentially decreases as porosity increases (e.g., Shafrova and Høyland, 2008). Although those researchers studied the effect of porosity on mechanical strength and viscosity, the effect of rock content on these parameters is still unclear. Actually, pores in sea ice are usually filled with brine, so the effect of porosity on sea ice strength has not been exactly quantified. Arakawa and Tomizuka (2004) conducted uniaxial compression experiments of porous pure ice and an ice–serpentine mixture at the constant strain rate of $5.6 \times 10^{-3}\ \mathrm{s}^{-1}$ and a temperature of $-10\ ^{\circ}\mathrm{C}$. They examined the compressive strength of porous pure ice and ice–serpentine mixtures with a serpentine powder content of 50 wt.% and various porosities. They found that the compressive strength decreased with the increase in porosity, and furthermore that the relationship between compression strength Y and porosity ϕ could be written as $Y = Y_0(1 - \phi)^n$, with the stress exponent n of the ice–serpentine mixture being about twice that of pure ice. That is, the effect of porosity on the compressive strength was very significant in the mixture. However, those authors examined the compressive strength at only one constant strain rate. It is expected that the strength of a porous ice–silicate mixture could depend on the strain rate, because our previous study clarified the rate-dependent mechanical strength of non-porous ice–silica mixtures (Yasui and Arakawa, 2008). Thus, we should conduct a compressive deformation test of porous ice–rock mixtures under various strain rates to obtain the rate-dependent strength or the flow law.

Therefore, we carried out deformation tests of ice–rock mixtures as a function of porosity, rock content, and temperature. Then we established the flow law inferred from the empirical equation obtained as a function of porosity and rock content. Finally, we applied these results to the modeling of topographic relaxation for small to middle-sized icy satellites.

2. Experimental methods

Deformation experiments were carried out to examine the strength of ice and solid particle mixtures and to study the effect of porosity on the strength of these mixtures. Ice–solid particle mixtures were prepared by mixing ice grains with solid particles in a cold room. The preparation method was the same as that introduced in Yasui and Arakawa (2009). Ice grains were produced by crushing commercial ice blocks. These grains were sieved to sort grains less than 710 μm across. Icy satellites are believed to have grown from the aggregation of submicron ice and silicate dust particles in the solar nebula; thus 1 μm-diameter silica spheres with a density of $2200\ \mathrm{kg\ m}^{-3}$ were used in our sample. The observation of cometary dust has shown that the silicate dust composing comet nuclei is micron-sized, and we note that comet nuclei are thought to be the remnants of icy planetesimals. Therefore, we used micron-sized silica particles in this study. However, it is difficult to speculate on the ice grain size of icy planetesimals because micron-sized ice dust could grow in size and/or could easily sinter, even at low temperatures. We then prepared ice grains several hundred microns in length to use as a sample in this study. However, the ice grain growth could be strongly suppressed by silicate dust dispersed among ice dust (Durand et al., 2006; Barr and McKinnon, 2007; Barr and Milkovich, 2008; Kubo et al., 2009), and the effects of other chemical impurities and amorphous ice on ice grain growth are not clear yet. The effect of ice grain size on the flow law is very important when grains are smaller than several tens of microns (Goldsby and Kohlstedt, 2001). The implications of ice grain size for ice–rock mixtures should therefore be studied. Furthermore, large amounts of well-sorted silicates with a size of 1 μm are widely available commercially for SiO_2, so-called silica. This silica powder was very convenient to use in preparing our sample because its physical properties are very simple, e.g., its morphology is spherical and its size distribution is monodispersed. Natural silicate dusts in the solar nebula show a more complex chemistry, and they might also be more complex in terms of morphology and size distribution. Thus, it is worthwhile in the future to consider more realistic silicate materials to study the effects of these properties on the flow law. The ice–silica mixtures had silica mass contents C of 0, 30, and 50 wt.%, and they were prepared by mixing ice grains with silica beads evenly in a plastic bag; the mixtures were then put into a stainless cylinder with a diameter of 20 mm. A piston was put into the cylinder, and this compaction device was set in a universal testing machine (TENSILON-2.5T) to apply a load onto the piston. The mixtures were compacted at a constant compression speed of $2.0\ \mathrm{mm\ min}^{-1}$ (the strain rate was $3.3 \times 10^{-4}\ \mathrm{s}^{-1}$) at temperatures of -10 to $-20\ ^{\circ}\mathrm{C}$. All experiments were performed with samples of the same geometry: the diameter was 20 mm, the height was 40 mm, and the mass of the mixture was changed to control the porosity. The porosity ranged from