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Experimental study on the rheology of ice-rock mixtures: Implications for cosmoglaciology

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Icy bodies in the solar system have various shapes, bulk densities, and surface features. Icy satellites have a wide range of bulk density, 300 to 3000 kg/m^3, and those with small density have a residual porosity in their interiors while those with high density are composed of ice-rock mixtures. The shape of icy satellites is determined by the ratio of the stress by gravity and the material strength, that is, icy body has spherical shape when the internal stress is beyond the material strength. Furthermore, glacial features and large-scaled faults are observed on Mars polar regions and the surfaces of giant icy satellites such as Europa. Such the variations of shape and density and the tectonics of the surface features on Mars and icy satellites are controlled by the rheology and the failure stress of constituent.

Many researchers examined the rheology of H_2O ice. Particularly, they examined the effects of temperature and grain size on the flow law by laboratory experiments and field observations. However, icy bodies in the solar system are composed of ice-rock mixtures with various rock contents and small icy bodies are porous because of their small densities. Furthermore, the surface temperature can be estimated from the radiative equilibrium temperature while the internal temperature must be higher than the surface temperature. But it is very difficult to estimate the internal temperature distribution. Therefore, in order to clarify their evolutions and tectonics of Mars and icy satellites, we must examine the rheology of ice-rock mixtures in the wide range of rock content, porosity, and temperature. In this study, we did deformation experiments of ice-rock mixtures and examined these effects on the flow law systematically.

The samples were prepared by mixing ice particles with the diameter smaller than 710 μm and amorphous silica beads with the diameter of 1 μm. We prepared two kinds of samples. One is a frozen sample (f.s.) which is made by mixing ice particles, silica beads, and liquid water. The silica volume fraction of the f.s. was from 0 to 0.63 vol.%, and the porosity was 0%. The other is a pressure-sintering sample (p.s.s.) which is made by the compaction of ice particles and silica beads. The silica mass content of the p.s.s. was 0, 30, and 50 wt.%, and the porosity was changed from 0 to 25%. We did uniaxial compression tests under constant strain rate from 8.7×10^{-7} s^{-1} to 8.3×10^{-4} s^{-1} in the cold room at ILTS, Hokkaido University. The temperature was set from -10 to -25 ℃.

We examined the flow law expressed as $d\epsilon/dt=A_0\exp(-Q/RT)\sigma_{max}{}^n$, which σ_{max} is the maximum stress on the stress-strain curve and $d\epsilon/dt$ is the strain rate. The dependence of the silica content was different between f.s. and p.s.s.. The σ_{max} increased with the increase of the silica content in the case of f.s. while it decreased in the case of p.s.s.. On the other hand, the σ_{max} decreased with the increase of the porosity or the temperature for both samples. From these results, we obtained the parameters, A_0, Q, n, on the flow law. The power n and the activation energy Q depended on only silica content, and the n at the silica volume fraction larger than 0.15 became twice larger than that of pure ice (n=3). The Q increased with the increase of the silica content. The A_0 depended on the silica content and the porosity, and the empirical equation, $A_0=B\exp(\alpha\phi)$, which ϕ is the porosity, and B and α are constant depending on the silica content, could be obtained.

Next, we examined the deformation modes, ductile deformation or brittle failure. As a result, the f.s. at the silica volume fraction larger than 0.29 showed brittle failure at the temperature lower than -20 ℃. The temperature at the brittle-ductile boundary of the mixtures was 30-50 ℃ higher than that of pure ice at constant strain rate.

Keywords: Mars polar regions, icy satellites, ice-rock mixtures, porosity, flow law, brittle-ductile boundary