Experimental study on compaction process of highly porous ice: Implications for density change of icy regolith layer on icy bodies

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Ice sheets are found on the polar regions of Earth and Mars. Ice sheets were formed as snow was piled up and compacted into ice. Icy satellites are covered with ice regolith layer which is generated from impact craters by collisions of small bodies. It is supposed that this regolith layer is compacted by self-gravity, but the gravity of small icy satellites is very small and also the surface temperature is quite low, compared with that on the surfaces of Earth and Mars, so the compaction rate of ice regolith layer could be very low, then the deep icy regolith layer might be kept at high porosity on their surfaces. This icy regolith layer could be attributed to the evolution of the surface geology on icy satellites such as topographic relaxation and impact cratering. In this study, we focused on the compaction process of icy regolith layer on icy satellites and conducted compression experiments for highly porous ice under low stresses to examine the relationship between the compaction rate and the porosity.
Snow samples were prepared by filling ice particles with the diameter of ~20 μm into the cylinder mold and by compressing them by a piston into the cylinder with the diameter of 20 mm and the height of 40 mm. The initial porosity was 0.5-0.65. In order to examine the effect of sintering among ice particles on the compression rate, the sintering duration was changed from 0 to 200 hours. We conducted creep tests under constant stresses from 21 to 42 kPa. The displacement of the sample height was measured by a laser or a contact-typed displacement sensors while the diameter change was measured by using images take by a time lapse camera. The temperature was set to be -9and -11 ˚C.
First, we examined the relationship between the strain in a height direction, dh/h, and that in a horizontal direction (diameter change), dr/r, and found to be $(dr/r)=-0.11(dh/h)$. Thus, the compaction rate, $(1/\rho \cdot d\rho/dt)$, was found to be obtained to be -0.78 times the strain rate in a height direction (we call this rate as "compression rate" hereafter), $1/h \cdot dh/h$.
Next, we examined the effect of sintering duration on the compression rate. Under same stress condition, the compression rate was smaller as the sintering duration was longer. However, when the sintering duration passed the critical period, the compression rate was nearly constant even if the sintering duration passed longer. This critical period became shorter as the initial porosity was larger. In this study, to exclude the effect of sintering duration on the compression rate, we examined the effects of porosity, stress, and temperature on the compression rate that was expected for the sample sintering at the period loger than the critical period.
We examined the relationship between the compression rate and the porosity, ϕ, and found that the compression rate could be fitted by the following power equation under a constant stress, irrespective of the initial porosity, $1/h \cdot dh/dt = B\exp(C\phi)$, where B and C are constants. The constant increased exponentially with the increase of the stress, σ, that is, $B \propto \sigma^n$, where n is constant. The constants, C, and n, did not depend on the stress and obtained to be $C=24$, and $n=1.8$.
Finally, we evaluated the compaction processes due to self-gravity on the Antarctica and a saturnian icy satellite, Enceladus, by using our obtained empirical equation. We calculated the density and the elevation change of the snow layer on the Antarctica and the icy regolith layer on Enceladus. In this calculation, we assumed that the initial density was homogeneous, 180 kg/m^3, in the whole layer and the stress on the ground surface was 100 kPa. In the case of the Antarctica (a layer thickness of 10 m), the density just above the ground surface increased about three times and the thickness was changed to be a half after 100 years. In the case of Enceladus (a layer thickness of 5 km), the thickness was changed to be

a half after 100 years, as same as the case of the Antarctica, but the density just above the ground surface increased about only twice and the density in the layer on Enceladus was smaller than that on the Antarctica on the whole.

Keywords: highly porous ice, compaction, creep experiment, sintering duration, icy regolith layer