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Dynamic compaction experiments of snow: Implications for low-velocity impact compaction of icy pre-planetesimals

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Introduction: In the standard solar model, planetesimals could form by gravitational instability in the dust layer of a protoplanetary disk. However, there is a significant problem that planetesimal could not grow because of dust settling disturbance by turbulent flow in the disk. We focused on a pre-planetesimal, which is a body with the diameter of cm to several hundreds meters. Recently, some researchers suggest that planetesimals could form by impact coagulation of pre-planetesimals. However, there are also some problems, such as catastrophic disruption. Some researchers studied the formation processes of pre-planetesimals by numerical simulations. Geretshauser et al. (2011) proposed the impact model of porous silicate-dust aggregates, and found seven impact regimes (compaction, disruption, and adhesion) depending impact velocity and size ratio of impactor and target, and the compaction degree was different with regime. However, this model did not include compaction curves measured in laboratory experiments. In this study, we conducted low-velocity impact experiments for high porous snow simulating icy pre-planetesimals, and studied the impact compaction conditions. We measured the density profile changing with depth, compaction area size, and stress, and obtained the empirical equations related to density distribution and compaction area.

Experimental methods: We did impact experiments in the cold room at -10 degree C in ILTS, Hokkaido University. The projectile was a stainless cylinder with the diameter of 25 mm, the height of 40 mm, and the mass of 149 g. On the lower, a PVC disk with the diameter of 26 mm was set due to suppress the ejecta. The projectile was accelerated by free fall, and the drop distance changed from 50 to 900 mm. The impact velocities were 0.7 to 3.5 m/s. The target was prepared by packing ice grains into the acrylic tube with the diameter of 26 mm. The porosities were 70, 80, and 90 %. Ice grains were made by spraying water into LN2, and then the ice grains were sieved to sort grains from 50 to 500 micron-m. The target has the length of 100 mm, and the blue ice grains were put into the target every 20 mm from the bottom due to measure the density changing with depth. The blue ice grains were produced by spraying blue water into LN2. The impact compaction of the target was observed by a high-speed digital camera. The shutter speed was set to be 20 and 50 micron-s, and the frame rate was set to be 3000 and 5000 fps. The acceleration sensor was set on the upper surface of projectile to measure the stress. The voltage measured by acceleration sensor was recorded by oscilloscope and data logger. The sampling number of data logger was set from 2.5 x 10^5 to 10^6 and the sampling interval was set to be 20 micron-s.

Results: We analyzed the stress by using the data of acceleration sensor and high-speed camera images. The maximum stress, s_{max}, which is defined to be a maximum stress on the stress profile, was 20-100 Pa for 70 % snow, and 15-50 Pa for 80 % snow, and that of 70 % snow was 1.3-2 times larger than that of 80 % snow. Additionally, the s_{max} increased with the impact velocity in both targets. The stress obtained from the data of acceleration sensor corresponded to that for high-speed camera images. Furthermore, the yield strength, Y, calculated by Kinoshita method and these obtained stresses were almost same. Next, we compared the final density of uppermost layer of target, r_1, and the s_{max} to study the density profile. As a result, the r_1 increased with the s_{max}, the relationships between r_1 and s_{max} were expressed as r_1 = 1.7 x $10^2 {s_{max}}^{0.2}$ for 70 % snow and r_1 = 1.2 x $10^2 {s_{max}}^{0.3}$ for 80 % snow, respectively. Finally, we calculated the bulk modulus, K, by using the relationship between the yield strength, Y, and the average density of target, r_{ave}, and the K was 1.8 MPa for 70 % snow and 0.2 MPa for 80 % snow, respectively.

Keywords: icy pre-planetesimal, impact compaction, low-velocity impact experiment, density profile, compaction area, bulk modulus