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Dynamic compaction experiments of porous materials: Implications for impact compaction of pre-planetesimals

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Introduction: Two theories are proposed for the growth mechanism of bodies with the diameter from cm to several hundreds meters (pre-planetesimals). One is that planetesimals could form by a gravitational instability in the dust layer of a protoplanetary disk. The other is that planetesimals could form by a repeating impact coagulation of dust aggregates. In this study, we focus on the latter theory. There are some problems that planetesimals could not grow because of rebound and catastrophic disruption among pre-planetesimals caused by the increase of average density. Sakamoto (2013) did free-fall impact experiments of porous snow simulating icy pre-planetesimals by using the stainless cylinder to examine the compaction conditions, and clarified the relationship between the impact stress and the final density profile and the size of compaction area. However, the impact velocities in her study were 0.7 to 3.5 m/s, relatively lower compared to the average impact speed of pre-planetesimals. In this study, we conducted impact experiments of porous materials at >5 m/s to examine the compaction mechanism, impact stress, and density profile.

Experimental methods: The target was high porous snow with the initial porosities of 70 and 80% and perlite particles with the density of 85 kg/m^3 simulating the icy and rocky pre-planetesimals. We did impact experiments of snow in the cold room (-10 ℃) at ILTS, Hokkaido University, and perlite at Kobe University, by using the one-stage vertical and horizontal light gas guns. The vertical gun was used for only snow targets. The target was prepared by packing ice grains or perlite particles into the acrylic tube, up to 120 mm depth, and the blue ice grains or the red perlite particles were put into the target every 20 mm from the bottom due to measure the density changing with depth. The piston was set on the target surface in the acrylic tube, and accelerated by the projectile to compress the target. The projectiles were an elastic ball with the diameter of 25 mm for horizontal gun and same ball installed on the cylindrical sabot with the diameter of 30 mm for vertical gun. The pistons were a polycarbonate, an aluminum, and a polyacetal cylinders with the diameter of 30 mm and the height of 10-30 mm to examine the effects of piston type. The impact velocities were 2-118 m/s. The impact compaction of the target was observed by a high-speed digital camera. The shutter speed was set to be 20 to 100 μs, and the frame rate was set to be 6000 to 10000 fps.

Results: First, we measured the impact stress from the motion of piston, σ_p, and compared σ_p with the strength calculated by Kinoshita method, Y. As a result, the σ_p was almost same with the Y for both perlite and snow targets.

Next, we measured the final density of target, ρ_f, and obtained the relationship between the ρ_f and the kinetic energy or the momentum of projectile. As a result, we found that the ρ_f for perlite was determined by the kinetic energy while that for snow was determined by the momentum. Furthermore, we proposed the model of ρ_f for perlite and snow by assuming these compaction mechanisms: the perlite compressed due to the fracture of perlite particles while the snow compressed due to the decrease of area among ice grains. We compared these models with our experimental results and found that they were almost consistent with each other.

Finally, we examined the relationship between the σ_p and the final density of top layer in the target, ρ_{f1}. As a result, we obtained as ρ_{f1}=3.0${\sigma_p}^{0.8}$ for perlite and ρ_{f1}=127${\sigma_p}^{0.3}$ for snow in kPa. The data for snow at σ_p >100 kPa was scattered because the compaction mechanism was changed at σ_p >100 kPa.

Keywords: pre-planetesimal, dynamic compaction, impact experiment, final density, Kinoshita strength, compression viscosity