EXPERIMENTAL STUDY ON RESTITUTION COEFFICIENTS OF POROUS ICE BALL SIMULATING SATURN'S RING PARTICLES. Yukari Toyoda[1], Masahiko Arakawa[1], and Minami Yasui[1] [1]Kobe university (Graduate School of Science, Kobe University, 1-1, Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan. First author's e-mail address: 181s418s@stu.kobe-u.ac.jp)

Introduction: Saturn's rings have a width of tens of thousands of kilometers and a thickness of hundreds of meters, and they are composed of water ice particles with a diameter of a few mm to meters. The average relative impact velocity among ring particles is estimated to be less than several cm/s [1]. As a result of their mutual impacts, ring particles are expected to have rebounded and disrupted. Therefore, mechanical evolution of Saturn's ring and the structure are affected by the impact process of ring particles.

Numerical simulations indicate that the restitution coefficient of ring particles should be less than 0.6 to maintain thin annular rings: ring particles should impact each other inelastically [2]. On the other hand, laboratory experiments showed that the restitution coefficient of ice ball was >0.8 at the impact velocity lower than 40.6 cm/s, comparable with those of Saturn's ring particles[3]. Recently, Cassini's observations showed that Saturn's ring particles might be aggregates of ice particles with high porosity [4]. However, there are few laboratory experiments to measure the restitution coefficient of porous ice and they did not examine the effect of porosity on the restitution coefficient systematically. Therefore, it is necessary to examine the impact processes of highly porous ice ball simulating ring particles in order to clarify the internal structure of Saturn's ring particles necessary for keeping Saturn's disks thin.

In this study, we conducted low-velocity impact experiments for porous ice balls in order to study the effect of porosity on the relationship between the impact velocity and the restitution coefficient.

Experimental methods: We did free-fall impact experiments for a porous ice ball on a target in a cold room (-15 ºC). Porous ice ball (the radius of 1.5 cm and the porosity Φ_p of 47, 53, and 60%) was made by compacting ice particles (the average size of 20 µm) into sphere by using a spherical mold. The targets were made of an ice and a porous ice. The ice target was a plate with a smooth surface, and the porous ice target was a disk shape with the radius of 1.5 cm, the height of 2 cm, and the porosity of 43–62% which was made in the same way as the spheres. The porous ice ball and the disk were sintered for 1 week in the freezer (-20 ºC) to control the mechanical strength.

The restitution coefficient was calculated by the measured time interval between the collisions as $\varepsilon_j = \Delta t_{j+1}/\Delta t_j$ ($\Delta t_j = t_j - t_{j-1}$, where j is the number of impact). The interval was measured by using an AE sensor, a laser displacement meter, and a small high-speed camera. The initial impact velocity $v_{i,1}$ was controlled by changing the height of a falling point and the $v_{i,1}$ ranged from 0.78 to 265.8 cm/s.

Results: We observed two types of depression on the impact point of porous ice balls; they are compression type and sticking type as shown in Fig. 1. The compression type showed a flat surface while the sticking type showed a crater-like depression with the mass transfer to a plate. The compression type was observed for the ice plate, and the sticking type was observed for the porous ice disk.

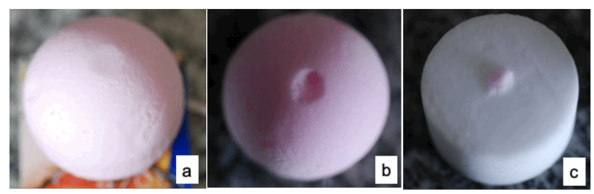

Fig. 1. Types of depression made on porous ice balls. a) compression type, b) sticking type (a small crater), and c) sticking type (mass transfer from a ball).

Fig. 2 show the relationship between the restitution coefficient of the porous ice ball, ε, and the impact velocity for ice plate and porous ice disk, respectively. The ε continued to decrease with the increase of the impact velocity for both ice plate and porous ice disk. In the case of ice plate, the ε decreased as the porosity increased at the high impact velocity region. While it was closer to 0.7, irrespective of the porosity at the small impact velocity range. In the case of porous ice disk, the ε for the lower porosity was always larger than that for the higher porosity in the whole range of the impact velocity.

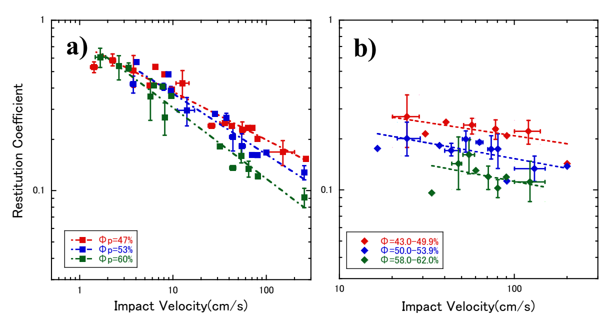

Fig. 2. Relationship between the impact velocity and the ε for (a) ice plate and (b) porous ice plate, respectively.

These relationships could be expressed by the empirical equation, $\varepsilon = \varepsilon_0 v_i^{-b}$, and the b was obtained to be 0.28-0.42 for the ice plate and 0.16-0.20 for the porous ice disk. Furthermore, the b increased with the increase of the Φ_p for both targets.

Discussions: We calculated the energy dissipation during the impact (E_{dis}) by using the obtained ε and the compression volume (ΔV) by using the width of the depression on the ball. The relationship could be expressed by the empirical equation, $\Delta V = V_0 E_{dis}^n$ and the n was obtained to be 0.75–1.5 in this study. This means that the compression volume was almost proportional to the energy dissipation. So, we assumed the energy conservation during the impact and the dissipated energy was written as $E_{dis} = Y_{d,i}\Delta V$. Then, the compressive strength, $Y_{d,i}$, was calculated to be 1.1-16.9 MPa for Φ_p=47%, 0.6-18.7 MPa for 53%, and 0.06-1.7 MPa for 60%. We also conducted the compression tests for porous ice balls by using a mechanical testing machine and obtained the compression volume by using the width of depression of ball caused by the ductile deformation, and more the measured load and the displacement was used to calculate the compression energy. Then, the compressive strength ($Y_{d,t}$) was calculated from the equation, $E_{comp} = Y_{d,t}\Delta V$. The compressive strength, $Y_{d,t}$, was calculated to be 0.3-5.7 MPa for Φ_p=47%, 0.2-2.8 MPa for 53%, and 0.2-1.0 MPa for 60% from the compression tests. Fig. 3 shows the relationship between the $Y_{d,i}$, the $Y_{d,t}$ and the filling factor of porous ice ball, compared to the previous results obtained by [5]. From these results, we found that the $Y_{d,i}$ was almost consistent with the $Y_{d,t}$ within

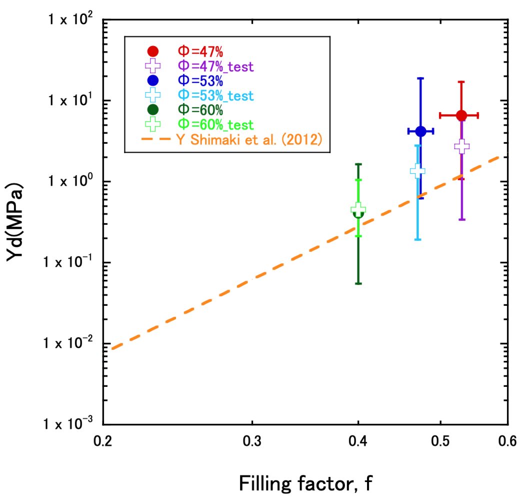

Fig. 3. Relationship between the compressive strength of porous ice and the filling factor. The circle and cross points show the $Y_{d,i}$ and the $Y_{d,t}$, respectively. The dynamic yield strength of snow is shown for comparison [5].

the errors although the $Y_{d,i}$ was slightly larger than the $Y_{d,t}$ due to the difference of the deformation rate. Therefore, the decrease in the restitution coefficient of our porous ice ball might be explained by the ductile deformation of porous ice.

Finally, we estimated the restitution coefficient, ε, of Saturn's ring particles by extrapolating our experimental results to the range of their impact velocity as shown in Fig. 4. We found that the ε for a collision between porous ices was <0.6 at the impact velocity larger than 0.1 cm/s. This velocity range was almost consistent with those of ring particles estimated from the numerical simulation (0.3–2 cm/s) [1].

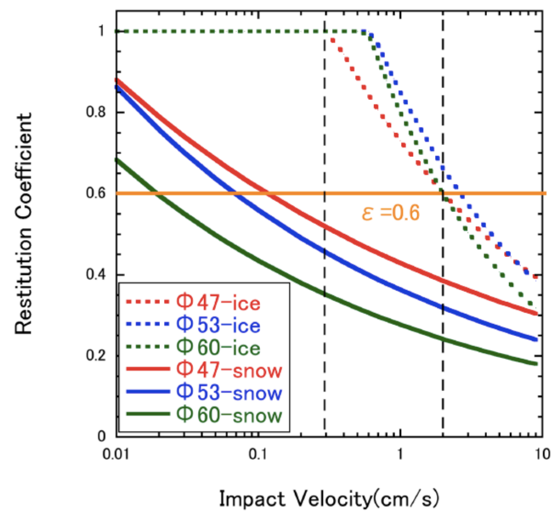

Fig. 4. Extrapolation of our obtained empirical equations showing the relationship between the ε and the impact velocity to low impact velocity. The solid and dashed lines show the extrapolated results for the porous ice disk and the ice plate, respectively.

References: [1] Ohtsuki, K. et al. (2020) *Icarus, 344,* 113346. [2] Ohtsuki, K., and Toyama, D. (2005) *Astronom. J., 130,* 1302–1310. [3] Higa, M. et al. (1998) *Icarus, 133,* 310-320. [4] Zhang et al. (2019) *Icarus, 317,* 518-548. [5] Shimaki, Y., and Arakawa, M. (2012), *Icarus, 221,* 310–319.