Low-velocity impact experiments of porous ice ball simulating Saturn's ring particle: Porosity dependence of restitution coefficients and the mechanism of inelastic collision 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 ring system extends up to 282,000 kilometers from the Saturn but the vertical height is typically about 10 meters in the main rings. They are composed of water ice particles with a radius of a few cm to tens meters [1]. Cassini's observations suggested that main rings were flattened and dynamically steady state. The dynamics of main rings could be well controlled by inelastic collisions and shear motions of ring particles in the gravitational field of Saturn. Therefore, it is crucial to study the normal restitution coefficient of ring particles in order to understand the collisional process of ring particles and the dynamics of the Saturn's rings. There are several experimental studies regarding to low velocity collisions of Saturn's ring particles, and they mainly obtained restitution coefficients of water ice without porosity at various physical conditions [2,3]. However, recent observations by the ground telescope and Cassini mission showed that the ring particles could be porous water ice balls with high porosity of > 50% [4, 5]. The restitution coefficients of porous water ice balls have not been studied yet. Therefore, we conducted the low velocity impact experiments using porous ice balls simulating Saturn's ring particles and the restitution coefficients were measured to study the effects of porosity and impact velocity. We then discussed the physical mechanism of inelastic collisions reducing the restitution coefficient for porous ice ball and modeled the inelastic collisions by considering the plastic and viscoelastic deformation of the porous ice ball.

Experimental methods: We performed free-fall impact experiments for a porous ice ball on a target plate in a cold room (-14 ºC). Porous ice ball (the radius of 1.5 cm and the porosity ϕ_p of 49.6, 53.8 and 60.8%) was made by compacting ice particles (the average size of 11 μm) into sphere by using a spherical mold. The porous ice balls with different porosities are called LS, MS, HS respectively. Three types of plates were used as target plates (a granite plate, an ice plate, porous ice plates). The granite and ice plate were commercial products, the porous ice plates (the radius of 1.5 cm, the height of 2 cm and the porosity ϕ_t of 40.6 - 60.8%) were prepared using a cylindrical mold in the same manner as preparing the porous ice balls. The porous ice ball and the porous ice plate were sintered for 6-9 days in a freezer (-20 ºC) to control the mechanical strength. To derive the restitution coefficient of the porous ice ball, the time variation of the ball height was measured by using a laser displacement meter. And the restitution coefficient ε was calculated by the time interval between the collisions estimated from the derived time variation of the ball height as $\varepsilon_j = \Delta t_{j+1}/\Delta t_j$ ($\Delta t_j = t_j - t_{j-1}$, where j is the number of collisions). The initial impact velocity $v_{i,1}$ was calculated by differentiating the time variation of the ball height and $v_{i,1}$ ranged from 11.0 to 96.9 cm/s.

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

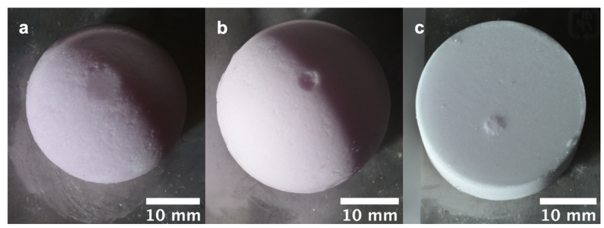

Fig. 1. Depressions on porous ice balls and mass transfer on a porous ice plate. a) compression type, b) spallation type (porous ice ball) and c) spallation type (porous ice plate).

Figs. 2 shows the relationship between the impact velocity v_i and the restitution coefficient ε for the granite plate and the porous ice plate. The relationship can be divided into a quasi-elastic region and an inelastic region by the critical velocity v_c. In the quasi-elastic region, the ε was constant value ε_qe regardless of the v_i. In the inelastic region, the ε decreased with increasing the v_i and this dependence can be explained using the theoretical model called Andrews' model [6]. Also, ε depended on the ϕ_p and the plate type. The ε decreased with increasing the ϕ_p and the ε_qe for the porous ice plate was clearly smaller than that for the other plates. These relationships could be expressed by the improved Andrews' model introducing the ε_qe to the conventional model as following Eq. 1,

$$\varepsilon = \begin{cases} \varepsilon_\mathrm{qe}\left[-\frac{2}{3}\left(\frac{v_\mathrm{c}}{v_\mathrm{i}}\right)^2 + \left\{\frac{10}{3}\left(\frac{v_\mathrm{c}}{v_\mathrm{i}}\right)^2 - \frac{5}{9}\left(\frac{v_\mathrm{c}}{v_\mathrm{i}}\right)^4\right\}^{1/2}\right]^{1/2}, & v_\mathrm{i} \geq v_\mathrm{c}. \\ \varepsilon_\mathrm{qe}, & v_\mathrm{i} \leq v_\mathrm{c} \end{cases}$$

The v_c and ε_qe were determined from the experimental results and listed in Table 1.

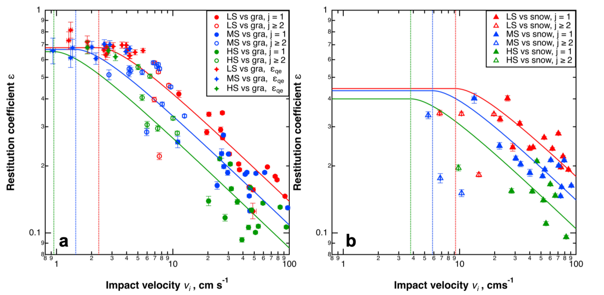

Fig. 2. Relationship between the impact velocity v_i and the restitution coefficient ε for a) granite plate and b) porous ice plate.

Porous ice ball	Target plate	ε qe	vc, cm/s	ξ
LS	granite	0.679	2.31	0.122
MS	granite	0.667	1.46	0.128
HS	granite	0.652	0.95	0.135
LS	Ice	0.677	2.31	0.123
MS	Ice	0.823	1.46	0.062
HS	Ice	0.755	0.95	0.089
LS	Porous ice	0.445	9.22	0.250
MS	Porous ice	0.435	5.84	0.256
HS	Porous ice	0.400	3.79	0.280

Table 1. The restitution coefficient in the quasi-elastic region $\varepsilon_{\mathrm{qe}}$, the critical velocity v_{c} and the constant ξ for granite, ice and porous plate.

Discussions: We could explain the relationship between v_{i} and ε in the elastic region using Andrews' model, in which the impact energy was simply dissipated by plastic deformation. And it is suggested that the energy dissipation mechanism in the quasi-elastic region should be different from that in the inelastic region. Then, we adopted the viscous dissipation model proposed by Dilley [7] to explain the energy dissipation mechanism in quasi-elastic region. In the Dilley's model, the impact energy was dissipated due to the viscoelastic deformation of the porous ice. The $\varepsilon_{\mathrm{qe}}$ can be described as $\varepsilon_{\mathrm{qe}} = e^{-\pi\xi/\sqrt{1-\xi^2}}$ and derived parameter ξ was listed in Table 1. The dependence of v_{c} on the filling factor $f = 1 - (\phi/100)$ for collisions between porous ice ball and the porous ice plate was determined by using a power law equation, $v_{\mathrm{c}} = v_{\mathrm{c,0}} f^{q_1}$, where $v_{\mathrm{c,0}}$ is v_{c} of the ice-ice collisions determined by Higa [3] and q_1 is a power law index. Also, we improved the Dilley's model by introducing the dependence of ξ on the filling factor f to the conventional model like $\xi = \xi_0 \left(\frac{R_1}{1.5\ \mathrm{cm}}\right)^{-0.5} \left(\frac{1}{\delta+1}\right)^{-0.2} \left(\frac{1}{\delta^3+1}\right)^{-0.1} f^{-q_2-0.1}$, where ξ_0 is ξ of the ice-ice collisions determined by Higa[3], R_1 is the radius of the ball, $\delta = R_1/R_2$ is the size ratio of the colliding balls, q_2 is a power law index. The derived constants are listed in Table 2. Finally, we extrapolated the ϕ_{p} dependence of ε by using the derived f dependence of v_{c} and ξ. For simplicity, it is assumed that collisions occur between a porous ice ball with the radius of 1.5 cm and a porous ice plate, they have same porosity ϕ. Unfortunately, Dilley's model is valid for the filling factor range of $0.25 < f \leq 1$ because the model breaks down for $\xi > 1$. Therefore, we calculated ε for the filling factor $0.25 < f \leq 1$ and the calculated results are shown in Fig. 3. From these results, it is found that the ε strongly depends on the ϕ.

Target plate	$v_{\mathrm{c,0}}$, cms^{-1}	q_1	ξ_0	q_2
Porous ice	41.4	2.38	0.0371	2.22

Table 2. The derived constants determining the filling factor f dependence of the critical velocity v_{c} and the constant ξ for the porous ice plate.

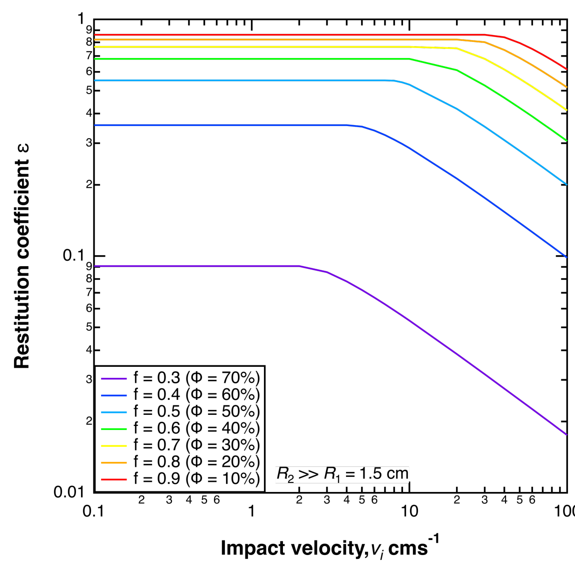

Fig. 3. Relationship between the impact velocity v_{i} and the restitution coefficient ε of collisions between the porous ice ball with radius of 1.5 cm and the porous ice plate, they have same porosity ϕ.

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