**EXPERIMENTAL STUDY ON THE RHEOLOGY OF ICE-SILICA BEADS MIXTURES: EFFECTS OF SILICA CONTENT AND TEMPERATURE ON THE FLOW LAW.** Minami Yasui and Masahiko Arakawa, Graduate School of Environmental Studies, Nagoya University (Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan. e-mail:yasui@eps.nagoya-u.ac.jp)

**Introduction:** Planetary explorations revealed various flow features on Mars and icy satellites related to water ice mixed with silicate materials. For example, polar layered deposits on Mars include exposed sequence alternating dark dust and bright ice, so each layer is expected to contain various ratios of water ice and dust [1-4]. Also, the surface on Ganymede consists of two colored areas, bright area and dark area, and it is expected that these areas have different ratios of ice and rock. Many topographic features related to ice-solid particle mixtures are found on these surfaces. Therefore, rheology of ice-solid particle mixtures is important to study the formation condition of these topographic features. Furthermore, the surface temperatures of these bodies are very low: it is -60°C on Mars, and -160°C on Galilean satellites (except for Io) in the average. So, we must examine the temperature dependence of the rheology of ice-solid paricle mixtures.

Thus, we focused our attention on the flow law, and carried out deformation experiments of the ice-solid particles mixtures. At the temperature on the surface of icy satellites, the deformation type of ice could not be ductile and change to brittle. In the case of pure water ice, the brittle-ductile boundary is on the line expressed by the following equation, $d\varepsilon/dt[\mathrm{s}^{-1}] = 1.6\times10^{6}\exp(-42.6[\mathrm{kJ/mol}]/RT)$, where $d\varepsilon/dt$ is strain rate [5]. This boundary could be affected by the silica inclusion. So, we examined the brittle-ductile boundary of the mixtures.

**Experimental methods:** The sample was prepared by mixing ice particles (0.3-1mm in the diameter) with silica beads having the diameter of 1μm. The silica contents are from 1 to 80wt.%, and at the temperature below -15°C, they are 30, 50, and 80wt.%. We made the samples by following method. The sample was made of ice grains, beads and liquid water. The ice particles were mixed with beads homogeneously. This mixed grains were put into a cylindrical mold and pore space was filled with cold water (0°C). We call the sample prepared by this method frozen sample (f.s.). We used other method to prepare f.s. with the silica content higher than 50wt.%: the suspention of silica beads was frozen at -10°C. We also prepared pure ice sample for the comparison with the mixtures. The samples removed from the cylindrical mold were kept in a cold room at the temperature of –10°C for one day. The sample has a cylindrical shape with the diameter of 30mm and the length of 60mm.

We made the uniaxial compression tests under constant strain rates from $2.9\times10^{-3}$ to $8.6\times10^{-7}$ $\mathrm{s}^{-1}$ in a cold room at -10, -15, -20, and -25°C.

**Results:** We used the flow law expressed by the relationship between the applied strain rate $d\varepsilon/dt$ and the maximum stress $\sigma_{max}$ on the stress-strain curve, $d\varepsilon/dt = A_0\exp(-Q/RT)\sigma_{max}^{\ n}$, where $Q$ is activation energy, $R$ is gas constant (8.314 $\mathrm{JK^{-1}mol^{-1}}$), $T$ is absolute temperature, and $A_0$ and $n$ are constants dependent on silica content. This equation is equivalent to a flow law derived from creep tests [6].

*Effect of silica content.* The relationship between strain rate and maximum stress for various silica contents at the constant temperature of -10°C is shown in Fig.1. At the silica contents up to 10wt.%, the maximum stresses become almost a constant with increasing the strain. However, at the silica contents from 10 to 80wt.%, the maximum stress becomes larger as the silica content increases. At the temperature of -10°C, the deformation type is ductile deformation. So, we examined the flow parameters, $A$ and $n$, for various silica contents. Here, we defined the parameter $A \equiv A_0\exp(-Q/RT)$. Firstly, the $A$ exponentially decreases with increasing the silica content and can be fitted by the exponential equation, $A=9.7\times10^{-6}\exp(-8.4\times10^{-2}C)$, where $C$ is the silica content in wt.%. Secondly, the $n$ is almost constant of $n$=3-4 at the silica contents up to 10wt.%. However, it becomes 6-7 at the silica contents from 30 to 80wt.%.

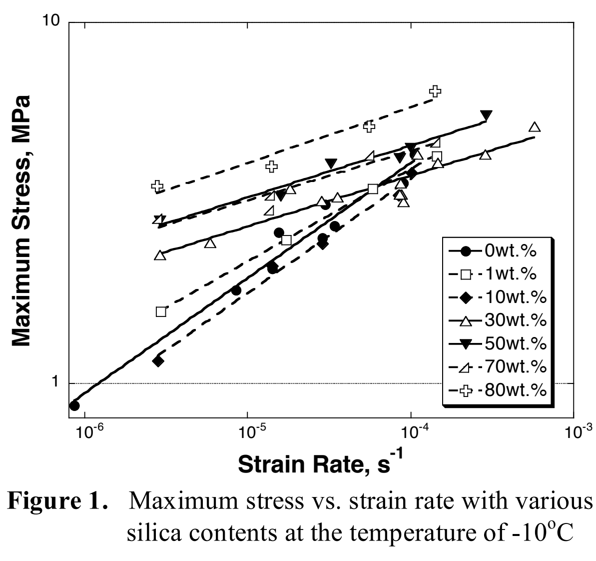


**Figure 1.** Maximum stress vs. strain rate with various silica contents at the temperature of -10°C

*Effect of temperature.* The relationships between strain rate and maximum stress for 30 and 50wt.% samples at various temperatures are shown in Fig.2a and 2b, respectively. In the case of 30wt.%, the maximum stress becomes larger, but the slopes of fitting lines do not change when the temperature becomes lower. On the other hand, in the case of 50wt.%, the deformation type changes from ductile deformation to brittle failure below -20°C. Furthermore, the maximum stress is almost constant when the deformation type shows brittle failure. The similar behavior is found in the case of 80wt.%. So, we examine brittle-ductile boundary of 50 and 80wt.% samples. Figure 3 shows a deformation map, which is written by $T$ and $d\varepsilon/dt$, obtained by the experiments for 50 and 80wt.% samples. As a result, the temperature of brittle-ductile boundary of the mixtures is 40-60°C higher than that of pure ice at the same strain rate [5]. Thus, we found that the mixtures of 50 and 80wt.% samples could break easily in comparison with pure ice. Next, we examine the flow parameters in the region of ductile samples (at higher than -15°C for 50 and 80wt.%). As a result, the $n$ is found not to change for the samples with the same silica contents at any temperatures. We suppose that the deformation mechanism does not change with the decrease of the temperature. It is well known that the parameter $A$ depends on the temperature. So, we examine the activation energy, $Q$, of 30wt.% sample because all of the 30wt.% samples show ductile deformation. As a result, the $Q$ is about 130 kJ/mol and is close to that of pure ice at the temperature higher than -8°C [7]. From this previous work, we know that the deformation mechanism of pure ice at higher than -8°C is grain boundary sliding (gbs) of ice crystals. So, the deformation mechanism of 30wt.% sample might be also gbs at the temperature lower than -10°C. The silica beads distributed among ice grains could be responsible for this deformation mechanism.

**References:** [1] Cutts J. A. et al. (1979) *JGR, 84,* 2975–2994. [2] Squyres S. W. (1979) *Icarus, 40,* 244-261. [3] Toon O. B. et al. (1980) *Icarus, 44,* 552–607. [4] Milkovich S. M. and Head J. W. (2005) *JGR, 110,* E01005. [5] Arakawa M. and Maeno. N. (1997) *Cold regions science and technology, 26,* 215-229. [6] Mellor M. and Cole D. M. (1982) *Cold regions science and technology, 5,* 201-219. [7] Barnes P. et al. (1971) *Proc. Roy. Soc. London, A324,* 127-155.

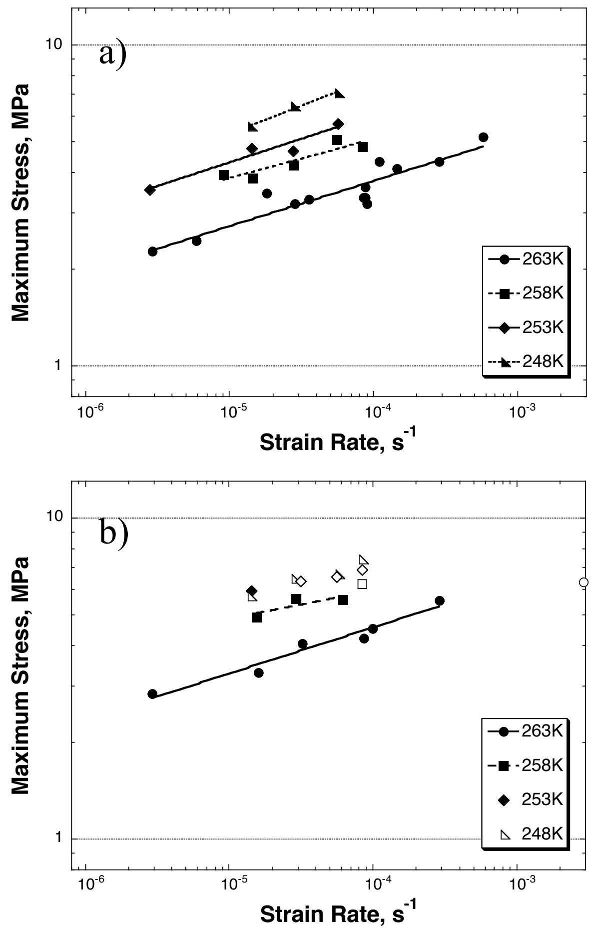


**Figure 2.** Maximum stress vs. strain rate at various temperatures. The open symbol means that the deformation type is brittle failure.
a) 30wt.% b) 50wt.%.

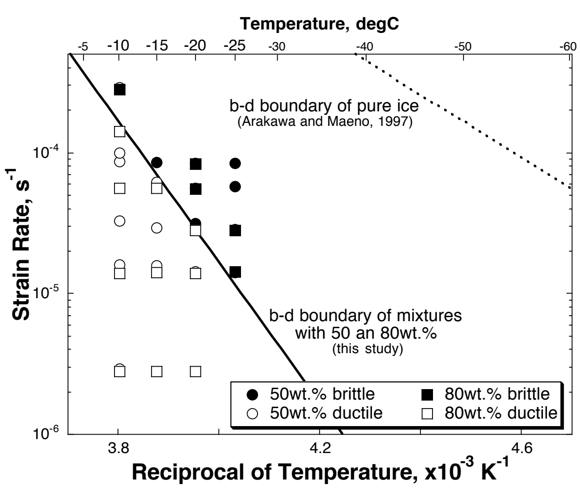


**Figure 3.** Deformation types of mixtures for 50 and 80wt.% samples. The brittle-ductile bound -ary of pure ice is referred to the retults of Arakawa and Maeno [5].