Experimental study on the rheology of ice-silica beads mixtures: Effects of silica content and temperatures on the flow law

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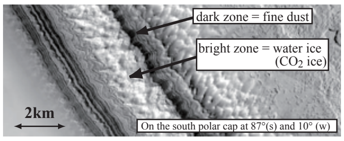
I. Introduction

a. Ice-silica mixtures in the solar system

Various flow features related to water ice mixed with silicate materials are found on Mars and icy satellites.

[Polar layered deposits on Mars]



(by NASA/Malin Space Science Systems)

[Ganymede (Jovian icy satellite)]

Mean density: 1.94 g/cm^3 → ice-rock mixture

(bright zone = ice-rich, dark zone = rock-rich)

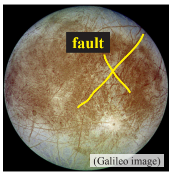
→ **Rheology of ice-silicates mixture** is important to study the formation condition of these features, particularly, **dependence of silicates content should be studied**.

b. Importance of temperature

Surface temperatures of Mars and icy satellites have a wide range.

	Temp.
Mars	20~-140°C
Europa	-120~-220°C
Ganymede	~-160°C
Titan	~-180°C

→ We must examine the **dependence of temperature**.



When temperature is low, brittle failure may occur.

→ **Brittle-ductile transition may be affected** by silicate inclusions.

PURPOSES

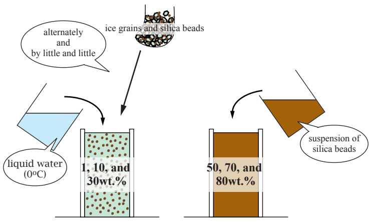
We focused our attention on the **rate dependent strength**, and carried out deformation experiments of the ice-silicate mixtures. We studied

1) Dependence of **silicates content** and 2) **temperature** on the strength, and
3) **Brittle-ductile transition**, at which the deformation type changes from ductile to brittle, of the mixtures.

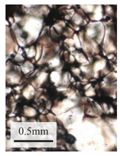
II. Experimental Methods

a. Samples

Materials: ice grains (0.3-1mm in the diameter)
silica beads (1μm in the diameter)
Silica contents: 0, 1, 10, 30, 50, 70, and 80wt.%
Preparation methods:



The samples were kept in a cold room at -10°C for more than one day.

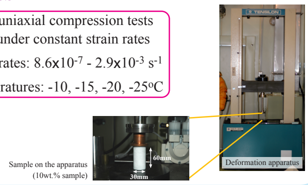


[Photograph of thin section]
The content is 10wt.%.
(white area: ice grain
black area: beads and frozen liquid water (ice matrix))

Ice matrix is distributed among ice grain boundaries evenly.

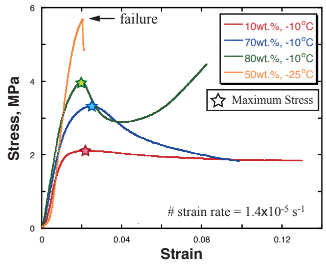
b. Tests

Tests: uniaxial compression tests under constant strain rates
Strain rates: 8.6x10^{-7} - 2.9x10^{-3} s^{-1}
Temperatures: -10, -15, -20, -25°C



III. Results

a. Stress-strain curves



[Difference of stress behaviors]

i) ductile deformation:
Stress reaches the maximum, and after that it is,
(red: 0-10wt.%) decreasing -> being constant
(blue: 30-70wt.%) remaining to decrease
(green: 80wt.%) decreasing -> increasing

ii) brittle failure:
(orange) Stress abruptly drops at a certain strain.

b. Rate dependent strength (Flow law)

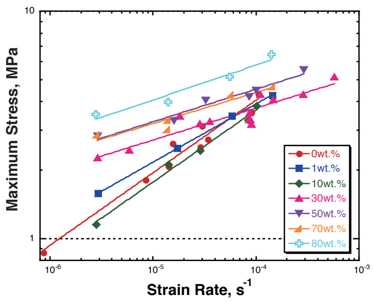
$$\dot{\varepsilon} = A \cdot \sigma^n = A_0 \exp\left(-\frac{Q}{RT}\right) \cdot \sigma_{max}^{\ n}$$

(Mellor and Cole, 1982)

$\dot{\varepsilon}$: strain rate (s^{-1})
σ_{max} : maximum stress (MPa)
Q : activation energy (J/mol)
R : gas constant (8.314 J K^{-1}mol^{-1})
T : absolute temperature (K)
A_0 & n : constants
→ depend on **silica content** and **temperature**.

We examined two effects;
a) silica content → A and n
b) temperature → n and Q

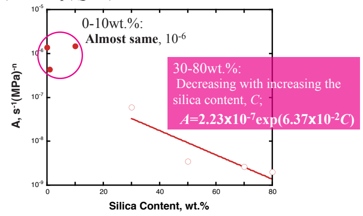
c. Effect of silica content at -10°C



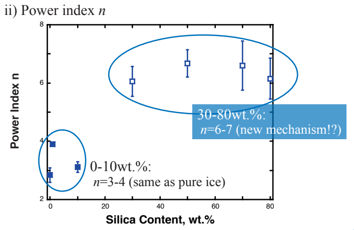
0-10wt.%: σ_{max} does not depend on the silica content.
30-80wt.%: σ_{max} becomes **larger** as the silica content increases.

Deformation type: **ductile deformation**
→ Flow law is applicable !

i) $A=A_0\exp(-Q/RT)$

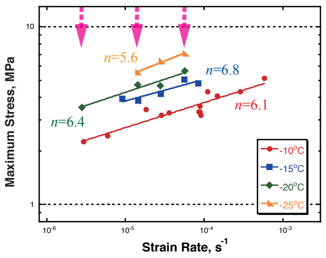


ii) Power index n



d. Effect of temperature

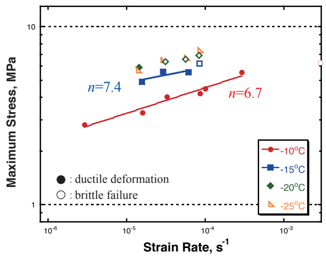
i) 30wt.%



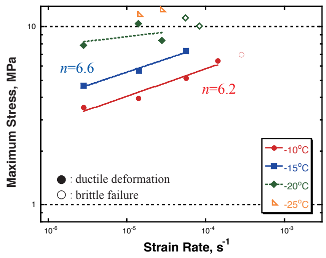
As the temperature becomes lower,
- Deforamtion type is still **ductile deformation**.
- σ_{max} becomes larger.
- Slopes of the fitting lines do not change.

→ ***n* is almost same**, about 6.2.

ii) 50wt.%

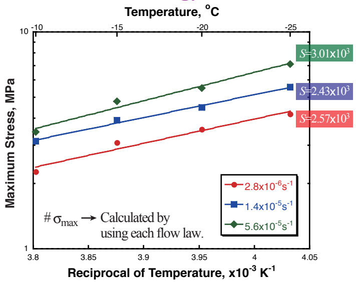


iii) 80wt.%



As the temperature becomes lower,
- **Deformation type changes from ductile deformation to brittle failure below -20°C.**
- σ_{max} is almost constant when the type is brittle failure.
- ***n* is almost same when the type is ductile deformation**, for 50wt.% n is about 7.0, and for 80wt.% n is about 6.4.

e. Activation energy (30wt.%)



These fitting lines can be expressed by the following equation;

$$\sigma_{max} = \left(\frac{\dot{\varepsilon}}{A_0}\right)^n \exp\left(\frac{Q}{nR} \cdot \frac{1}{T}\right)$$

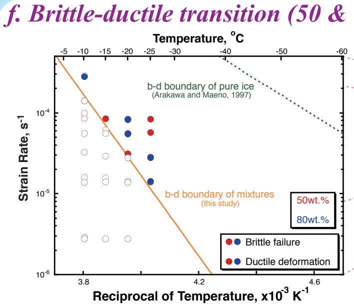
Slope of the line, S

To calculate Q, we use the average values of S and n, 2.67x10^3 and 6.22, respectively.

	Q	deformation mechanism
30wt.% (this study)	138	grain boundary sliding?
pure ice (>-8°C)	120	grain boundary sliding
pure ice(<-8°C)	80	dislocation creep

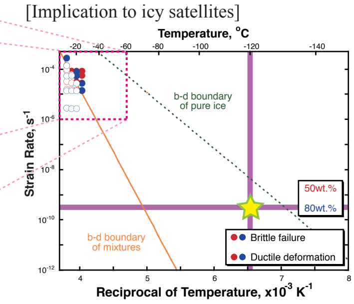
(Data of pure ice by Barnes et al.[1971])

f. Brittle-ductile transition (50 & 80wt.%)



The b-d boundary is **30-50°C higher** than that of pure ice in the temperature.

[Implication to icy satellites]



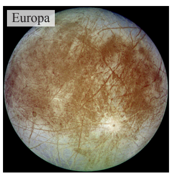
The b-d boundary is described as,

$$\dot{\varepsilon}_{bd} = A_{bd} \exp\left(-\frac{E_{bd}}{RT}\right)$$

(by Arakawa and Maeno [1997])

	A_{bd} (s^{-1})	E_{bd} (kJ/mol)
mixtures (this study)	1.62x10^{15}	95.6
pure ice	1.59x10^6	42.6

x10^{13} x2



[Case of Europa]
MAX Temp. → -120°C
Strain rate by tidal deformation → 10^{-9}~10^{-10} s^{-1}

pure ice: Ductile deformation region
mixture: Brittle failure region

SUMMARY

We found several effects of silica beads inclusion and temperature on the rheology of mixtures.

i) Silica content (-10°C)
[0-10wt.%]
A: Almost same n: 3-4
[30-80wt.%]
A: Decreasing with increasing the silica content, C; **A=2.23x10^{-7}exp(6.37x10^{-2}C)**
n: **6-7**

ii) Temperature
[30wt.%]
Deformation type: Ductile deformation
n: **Not change**
Activation energy: 138 kJ/mol
[50-80wt.%]
Deformation type: **Changing from ductile deformation to brittle failure below -20°C**
n: Not change (only ductile deformation)

iii) Brittle-ductile transition (50 & 80wt.%)
The b-d boundary of mixtures is **30-50°C higher** than that of pure ice in the temp.