Comet strength properties

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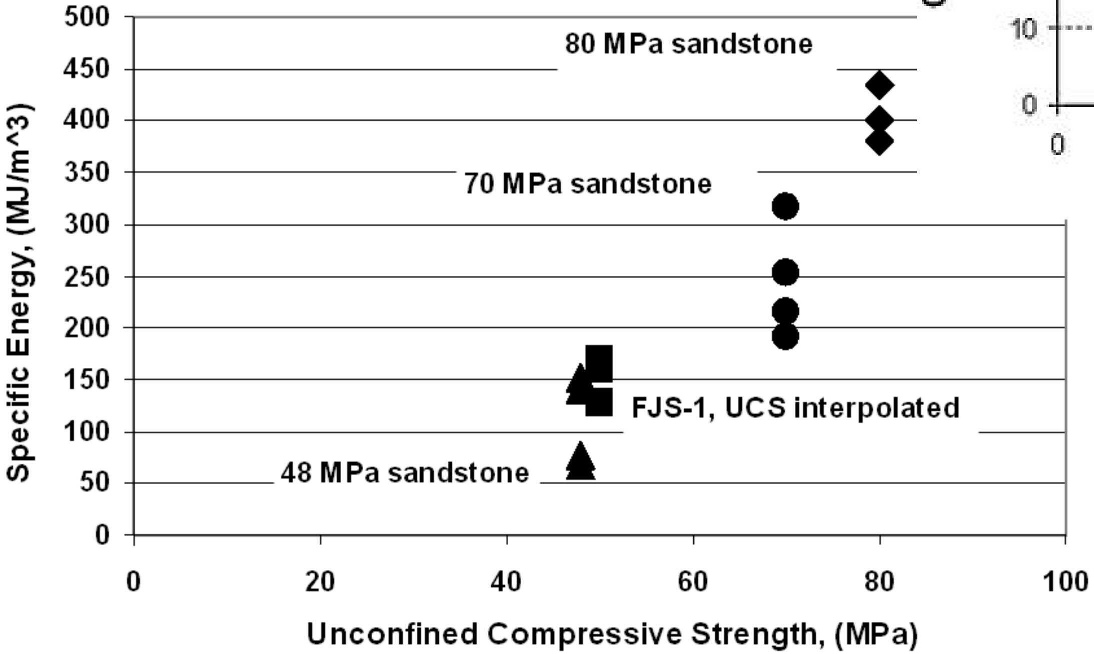
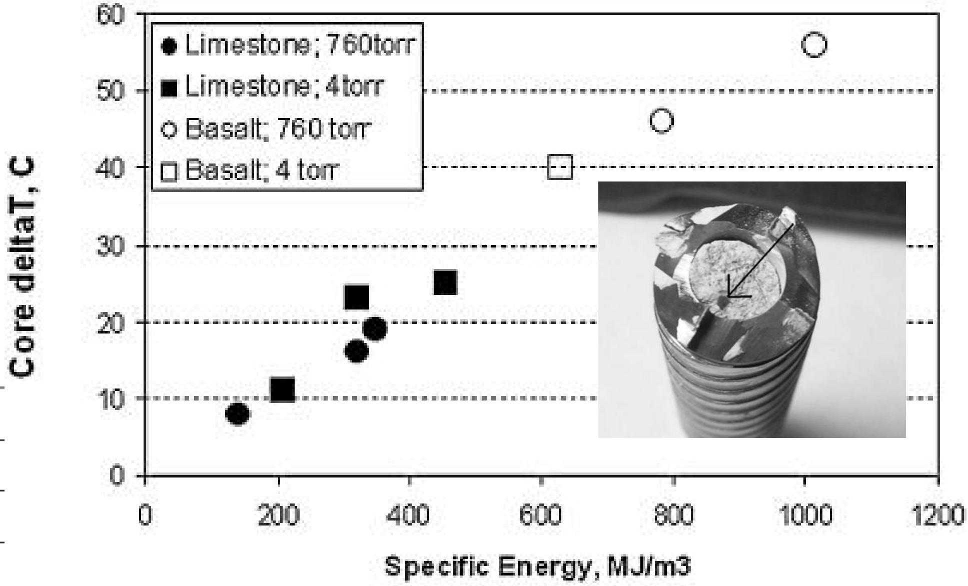
Why do we care about material strength?

- Sample acquisition approach, energy, forces are a function of material strength
- Sample temperature during sample acquisition is a function of "all of the above"
- Sample energy can also tell us degree of cementation, material properties etc. that could be useful for science

Zacny et al., 2006





Zacny et al., 2007

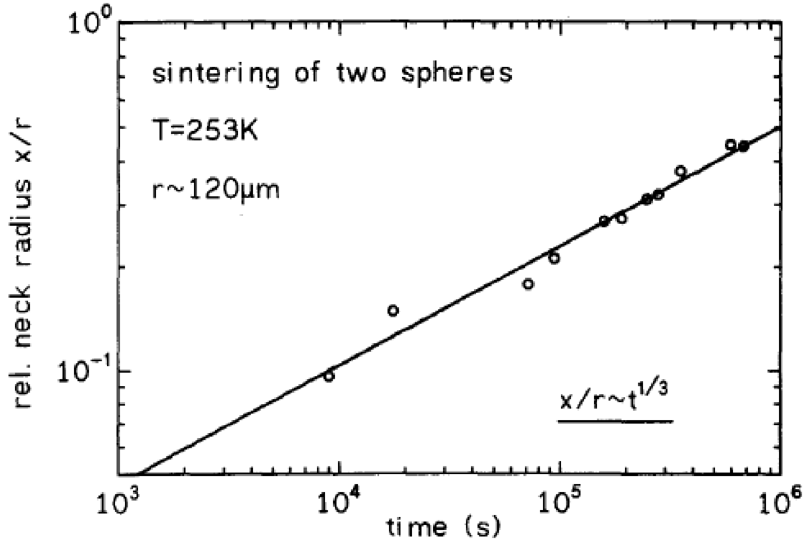
Strength comes from sintering

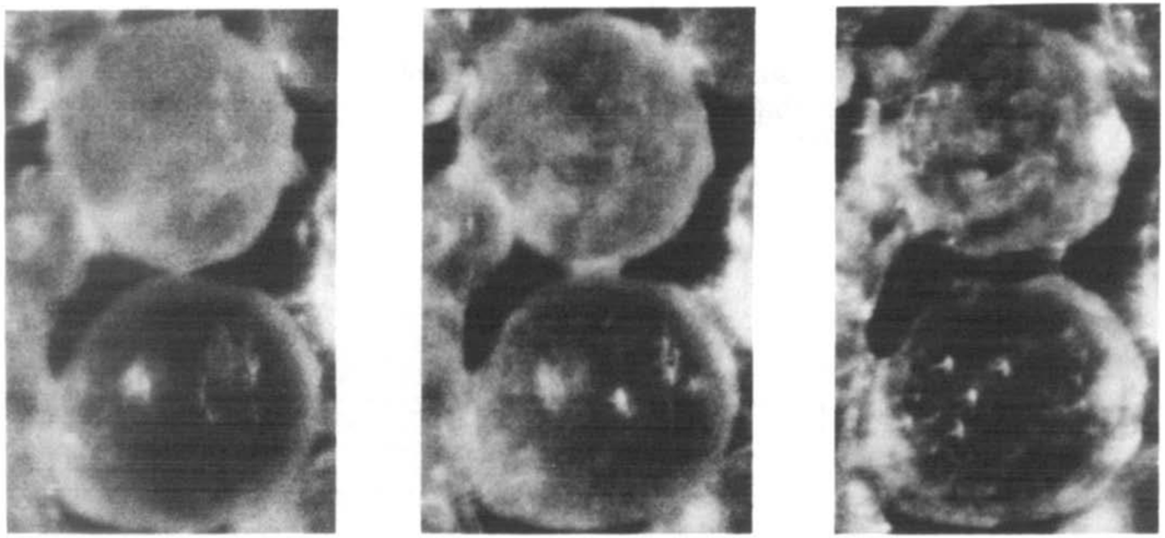
(Thomas et al., 1994)

Sintering: formation of ice bridges between the ice and/or dust particles

Transport mechanisms:

- Sublimation - re condensation
- Grain boundary diffusion
- Lattice diffusion
- Surface diffusion (at low T)





Sintering of two ice particles at-20°C. Sintering times: 3min, 1 day, 1 week

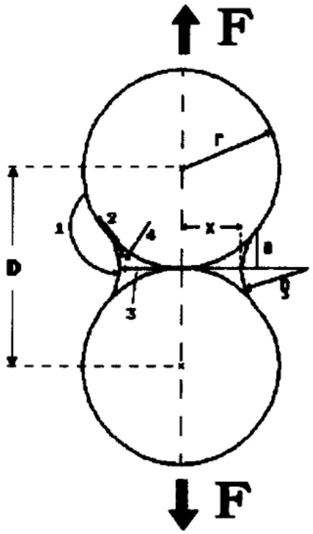


Fig. 1. The two-spheres model with different transport mechanisms (1. sublimation and recondensation, 2. surface diffusion, 3. grainboundary diffusion and 4. lattice diffusion).

Strength of porous ice-mineral bodies

(Thomas et al., 1994)

$$\sigma = \frac{\sigma_0 + k/\sqrt{d}}{N(x,r)} + \left(\frac{60\,E}{\pi a}\right)^{1/2} \left(\frac{V}{1-V}\right)^{1/4} (x(t)/r)^2 (1-\Phi)^{3/2}$$

- σ_0 and k are material constants measured for ice down to -40 °C.
- V is the volume content of mineral within the ice particles
- E is Youngs modulus of water ice
- a is the diameter of the indentor
- Φ porosity

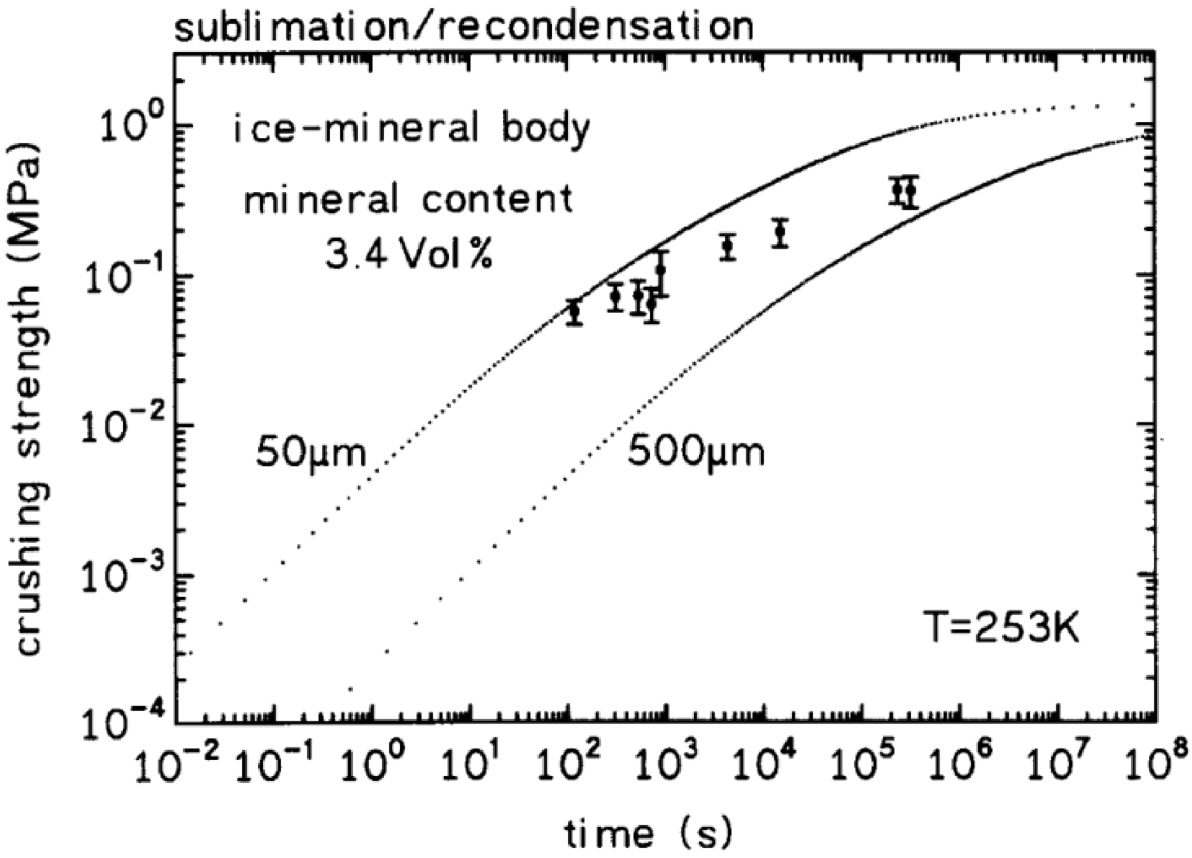


Fig. 7. Comparision of experimental and calculated crushing strengths of an icy body with a mineral content of 3.4Vol%.

Sintering at cryogenic temp

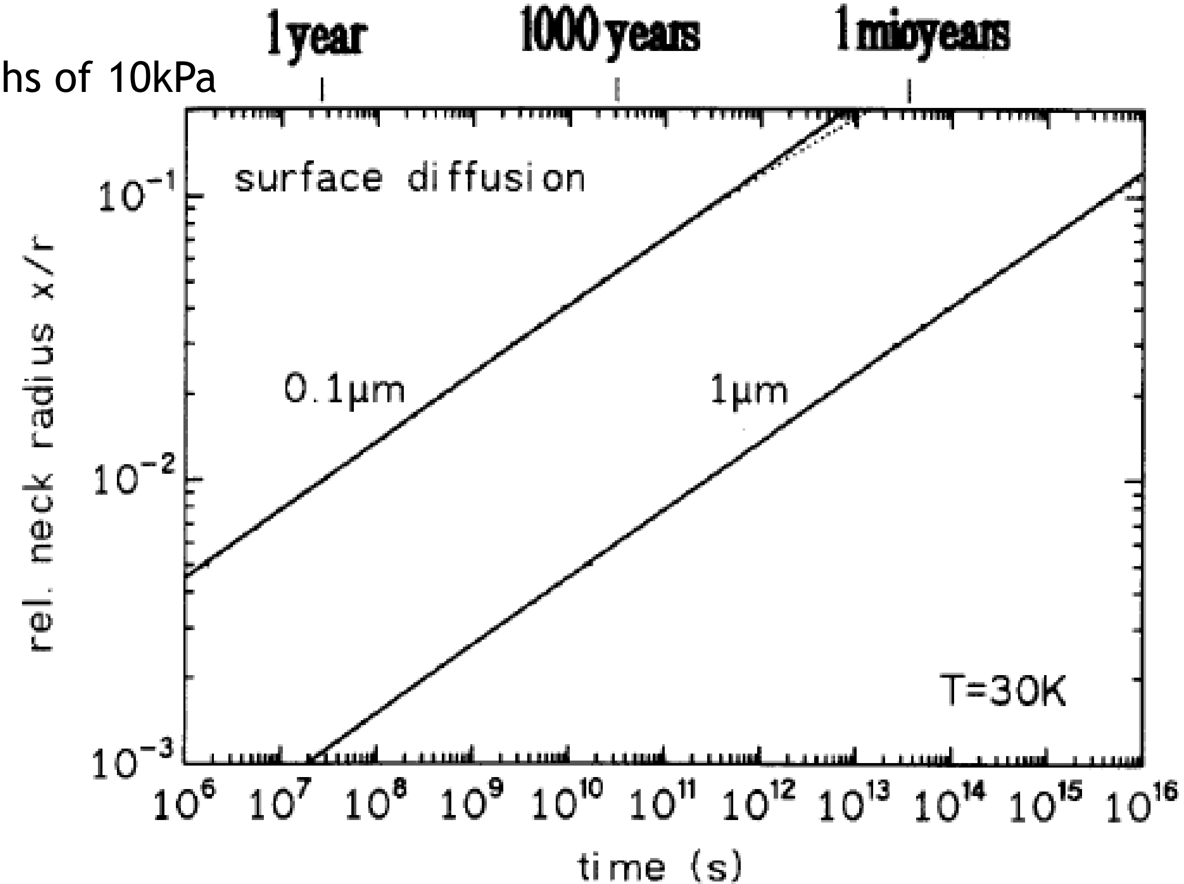
(Thomas et al., 1994)

At Low T, exclude the following sintering mechanisms:

- Sintering of particles where the mass transport is via the sublimation-condensation route can be excluded, since the vapor pressure of ice at temperature below I00 K is negligibly small.
- Transport via lattice diffusion within the ice grains or grain boundary diffusion are strongly temperature dependent via their respective diffusion coefficients.

At Low T, possible sintering mechanism:

- Surface diffusion of water molecules along the particle surfaces towards necks between particles.
- At 50K, comet can reach strengths of 10kPa

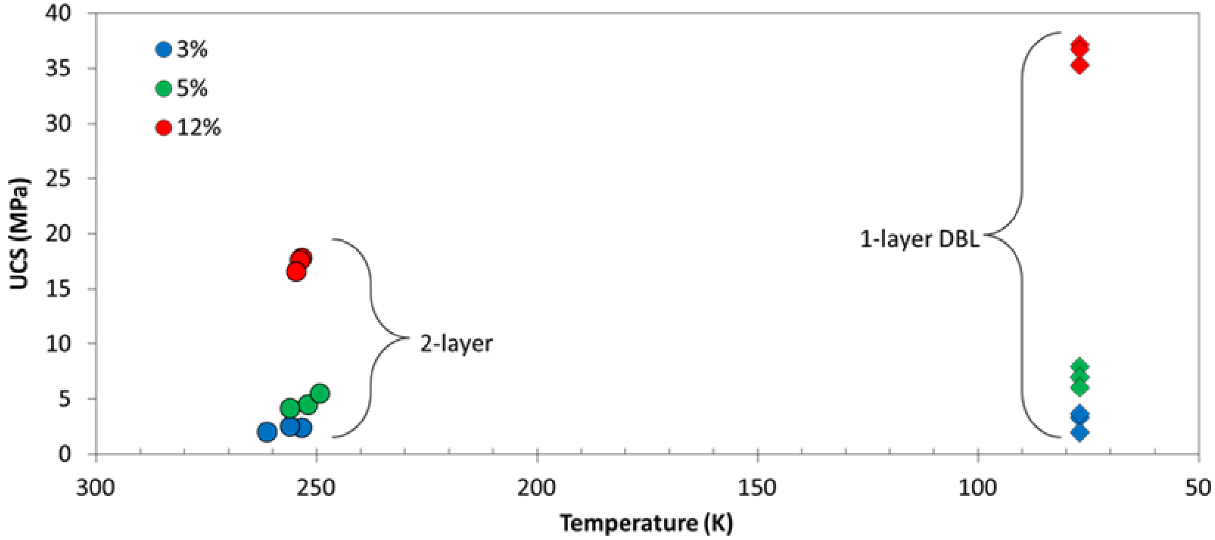


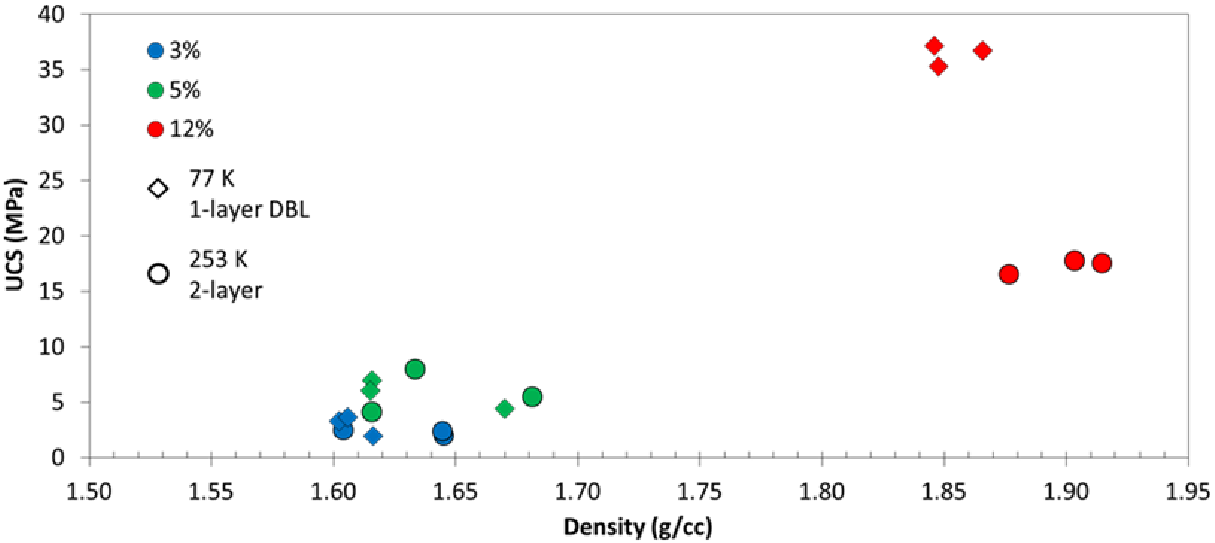
Neck growth of ice particles with radii of 0.1 and 1 micron calculated by surface diffusion for a temperature of 30K.

Ice cemented lunar soil (worst case scenario)

Atkinson and Zacny, 2017

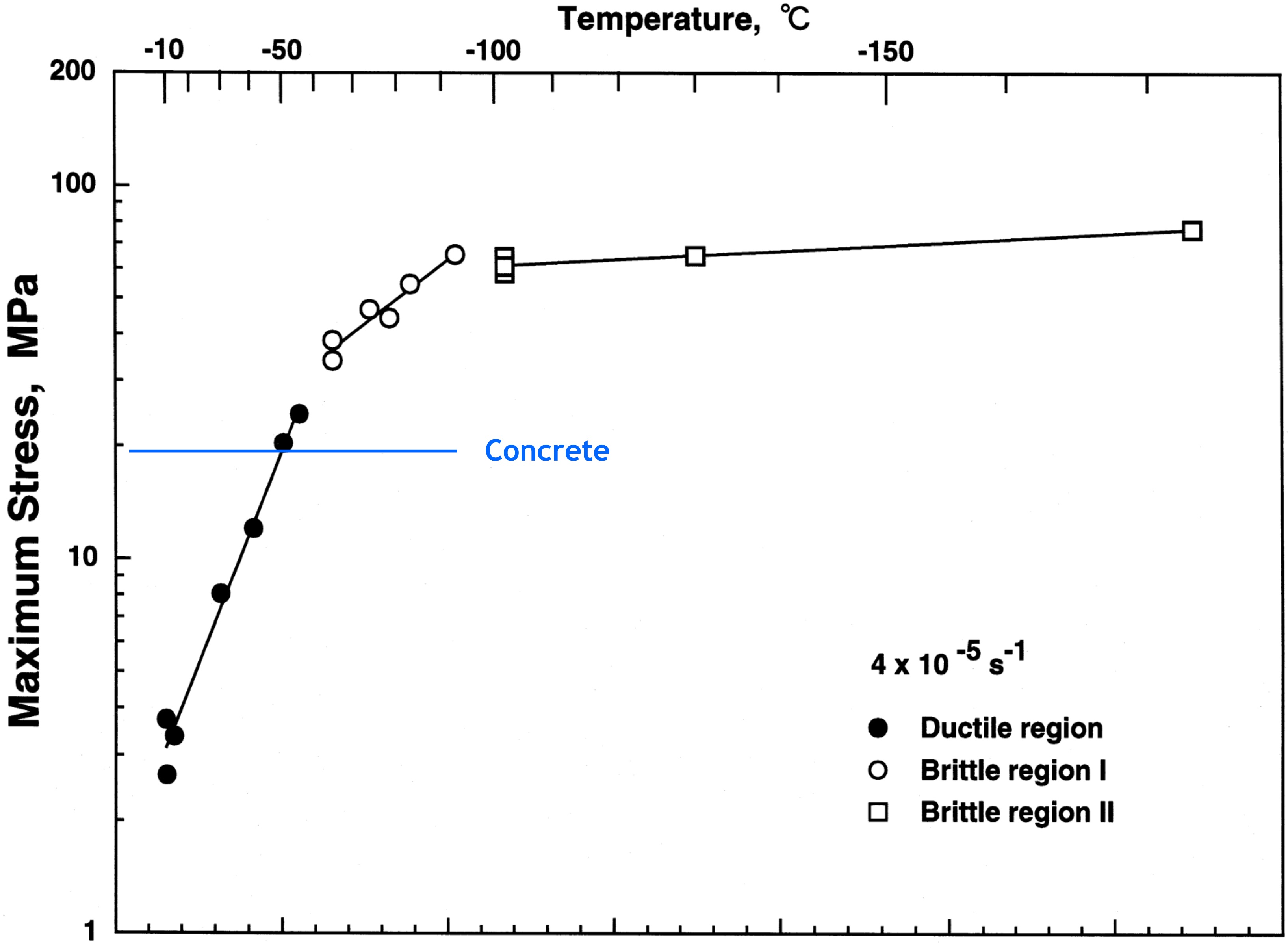
Dense icy-soil is very strong





Crystalline Ice
(worst case scenario)

Arakawa and Maenor, 1997



Gas-laden amorphous ice

Bar-Nun and Laufer, 2002

- Samples of gas-laden amorphous ice prepared at 80 K and 10^-5 Torr on a cold plate
- Scrapped into a tray until 5-10 cm deep. Final result: fluffy agglomerate of 200-μm ice grains.
- Heated from above by IR radiation
- 1.5 cm dia half-sphere cone penetrometer to measure strength at 1 atm (**<u>chamber opened</u>**).

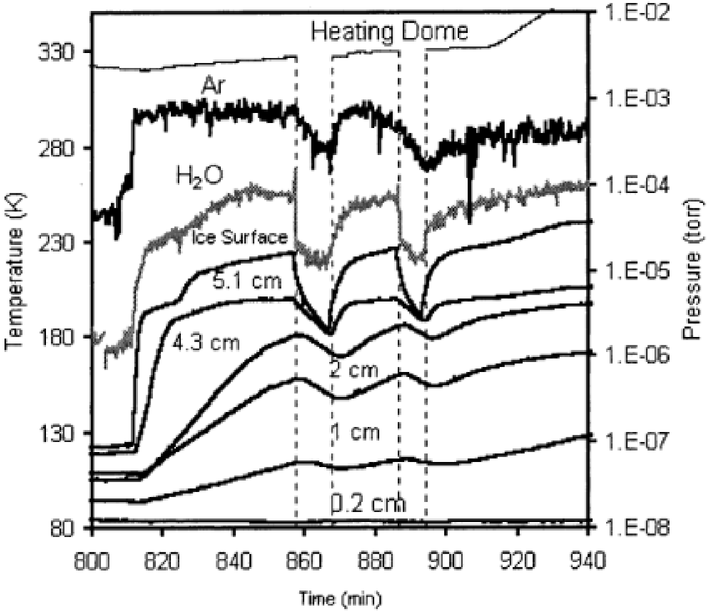
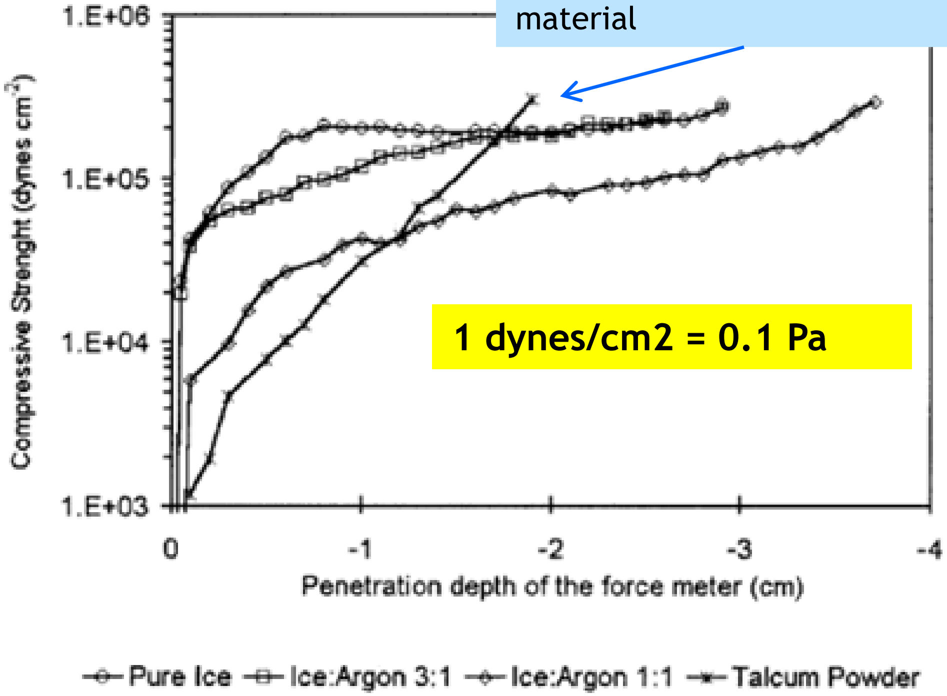


Fig. 4. Temperature profiles of the thermocouples as a function of their distance from the 80 K bottom plate. Note also the sharp decrease and increase of the water flux vs the sluggish-response of the argon emanation, when the ice sample is covered by the cold plate and upon its removal.



Expected curve for granular material

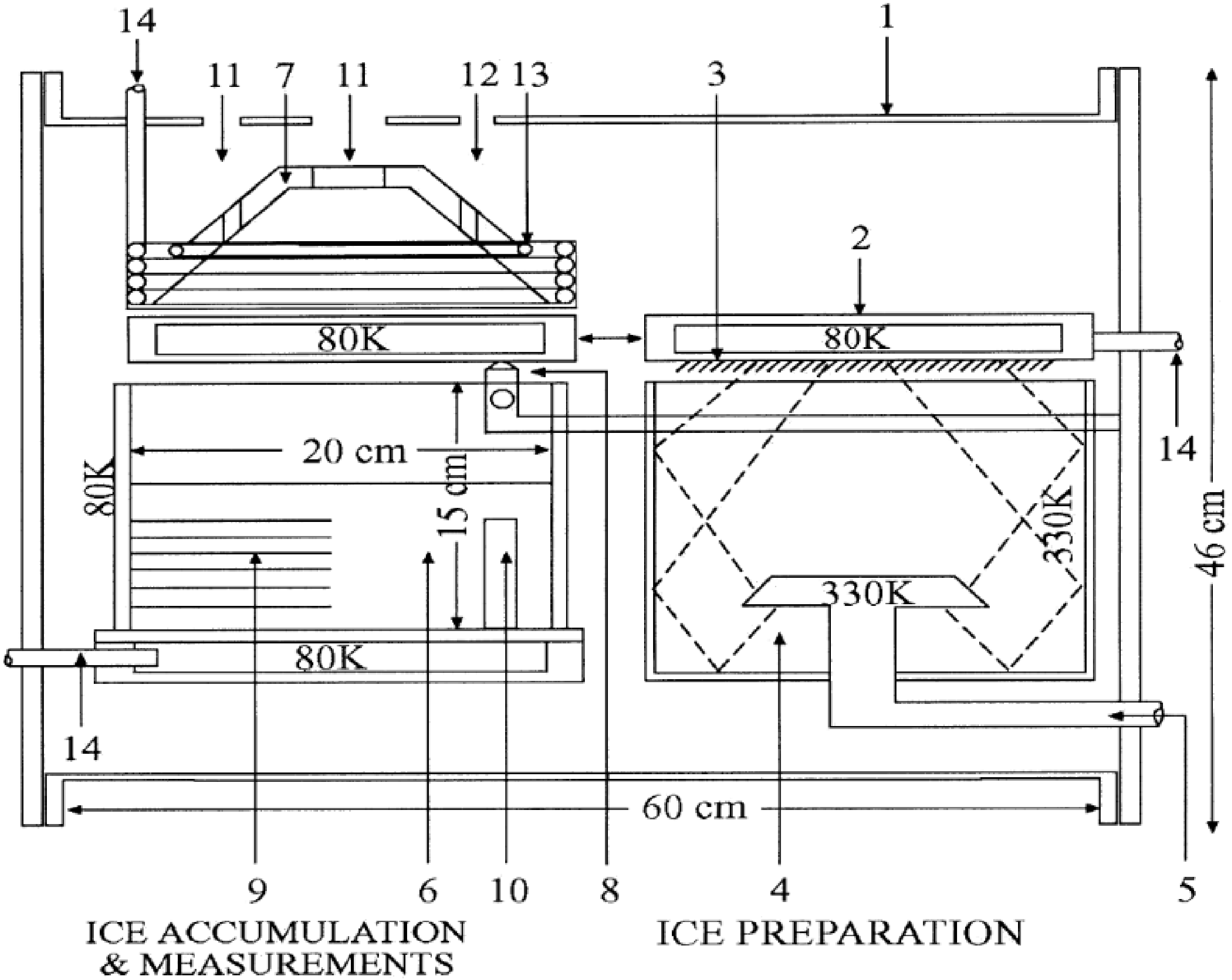
1 dynes/cm2 = 0.1 Pa

Fig. 6. Compressive strength of the studied ice samples as function of the penetration depth in the ice.

Gas-laden amorphous ice 2/2

Bar-Nun and Laufer, 2002

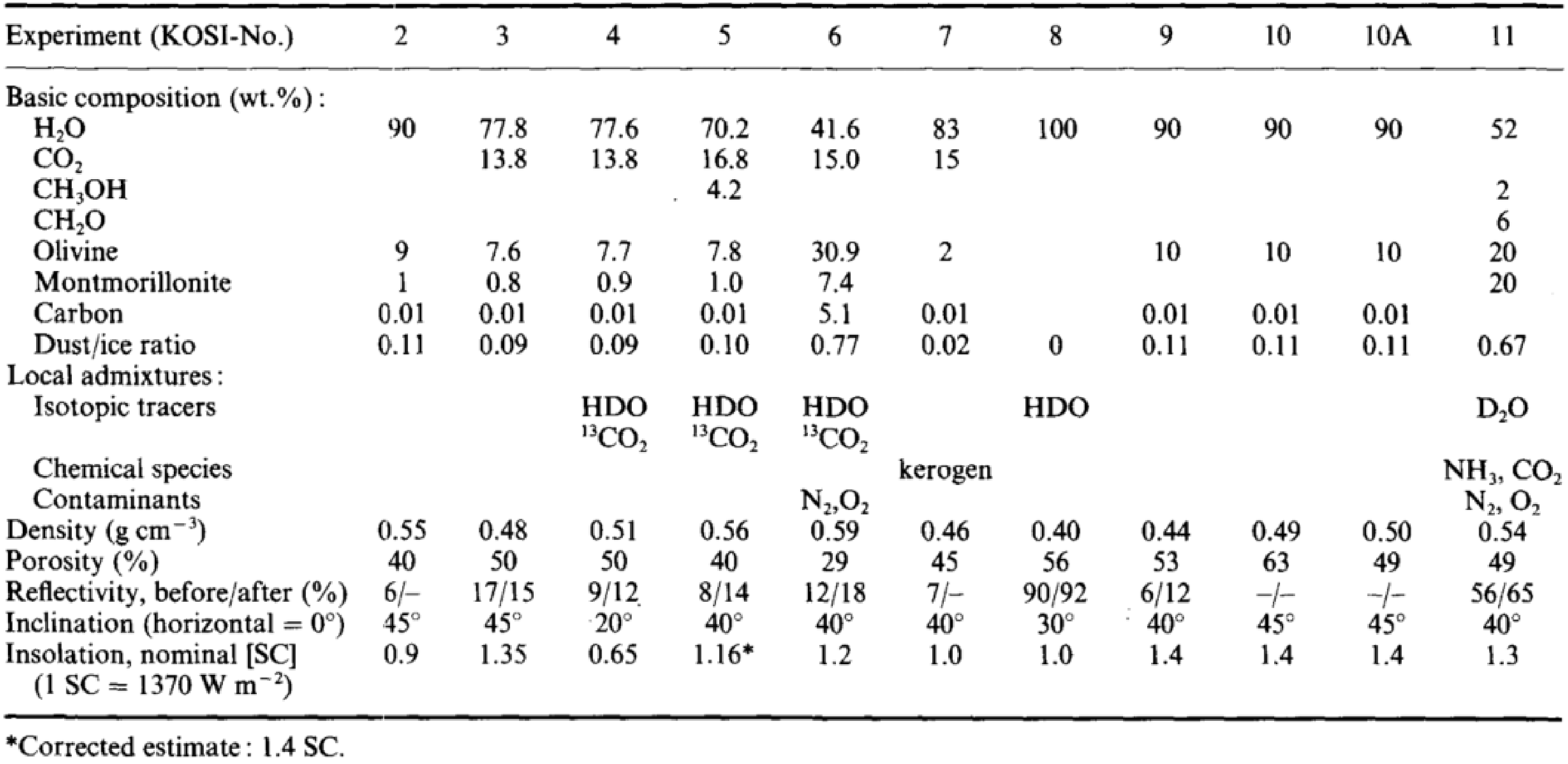
(1) Vacuum chamber
(2) cold plate at 80 K;
(3) 200-m amorphous gas-laden ice
(4) homogeneous flow of water vapor and gas
(5) water vapor and gas pipes;
(6) 200 cm2 and 5–10-cm thick ice sample
(7) heating dome
(8) 80 K cold knife;
(9) thermocouples;
(10) density measurements
(11) mass spectrometer
(12) ionization gauge;
(13) heating tape
(14) LN2 cooling pipes.



KOSI Experiments

Kochan et al., 1998

- 11 KOSI experiments performed at various conditions.
- All experiments used water ice with some mixing of CO2, methanol, formaldehyde, ammonia, etc.
- Refractory constituents were minerals olivine and montmorillonite (4-15 µm median grain distribution)
- Mixture of carbon (soot or charcoal) used to reduce albedo
- Porous mixtures created by spraying a water suspension of materials into liquid nitrogen
- Heated from above by horizontal IR radiation

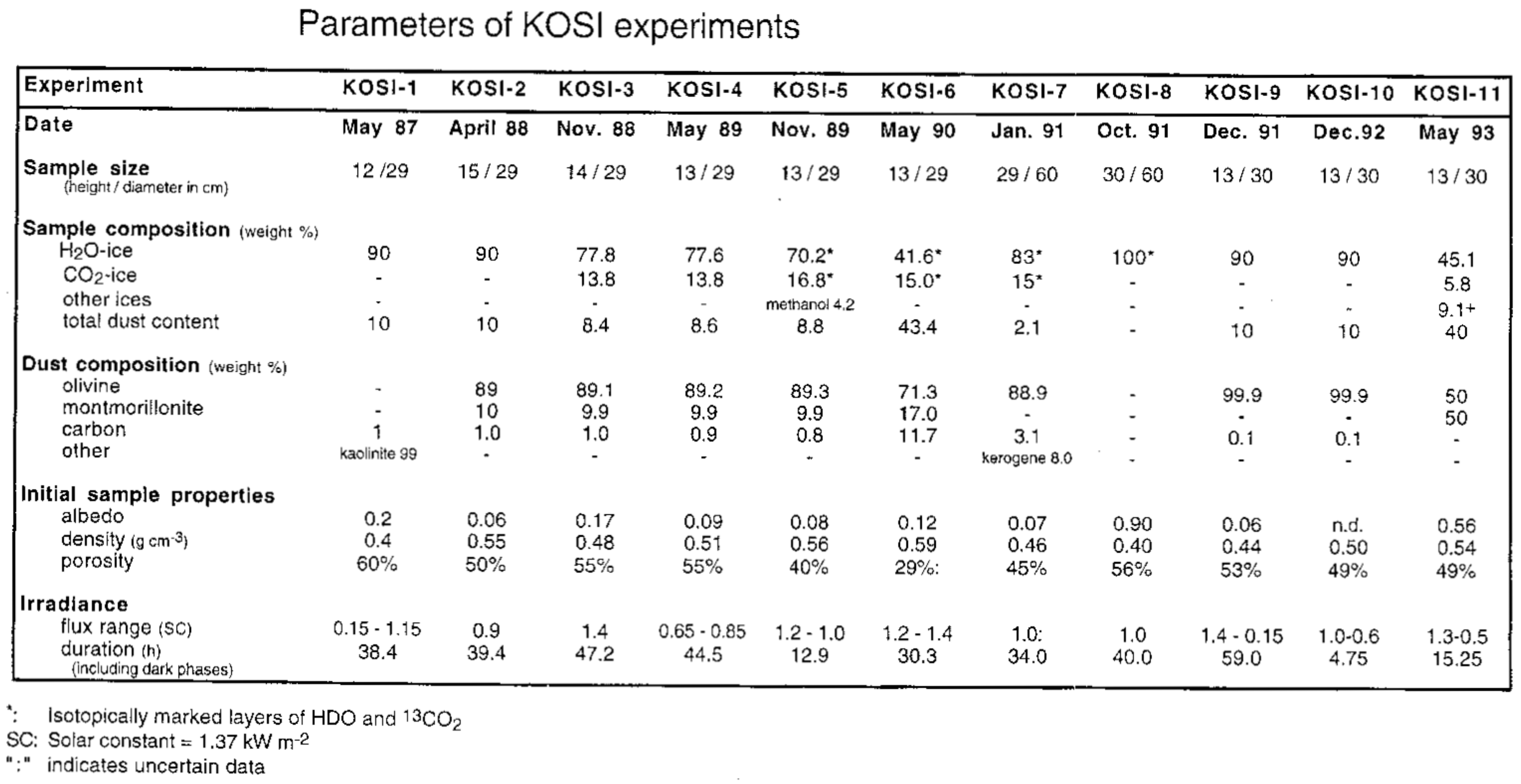


Experiment (KOSI-No.)	2	3	4	5	6	7	8	9	10	10A	11
Basic composition (wt.%):											
H_2O	90	77.8	77.6	70.2	41.6	83	100	90	90	90	52
CO_2		13.8	13.8	16.8	15.0	15					
CH_3OH				4.2							2
CH_2O											6
Olivine	9	7.6	7.7	7.8	30.9	2		10	10	10	20
Montmorillonite	1	0.8	0.9	1.0	7.4						20
Carbon	0.01	0.01	0.01	0.01	5.1	0.01		0.01	0.01	0.01	
Dust/ice ratio	0.11	0.09	0.09	0.10	0.77	0.02	0	0.11	0.11	0.11	0.67
Local admixtures:											
Isotopic tracers			HDO $^{13}CO_2$	HDO $^{13}CO_2$	HDO $^{13}CO_2$		HDO				D_2O
Chemical species						kerogen					NH_3, CO_2
Contaminants					N_2,O_2						N_2, O_2
Density ($g\ cm^{-3}$)	0.55	0.48	0.51	0.56	0.59	0.46	0.40	0.44	0.49	0.50	0.54
Porosity (%)	40	50	50	40	29	45	56	53	63	49	49
Reflectivity, before/after (%)	6/–	17/15	9/12	8/14	12/18	7/–	90/92	6/12	–/–	–/–	56/65
Inclination (horizontal = 0°)	45°	45°	20°	40°	40°	40°	30°	40°	45°	45°	40°
Insolation, nominal [SC] (1 SC = 1370 $W\ m^{-2}$)	0.9	1.35	0.65	1.16*	1.2	1.0	1.0	1.4	1.4	1.4	1.3

*Corrected estimate: 1.4 SC.

KOSI Experiments

Kochan et al., 1998



Parameters of KOSI experiments

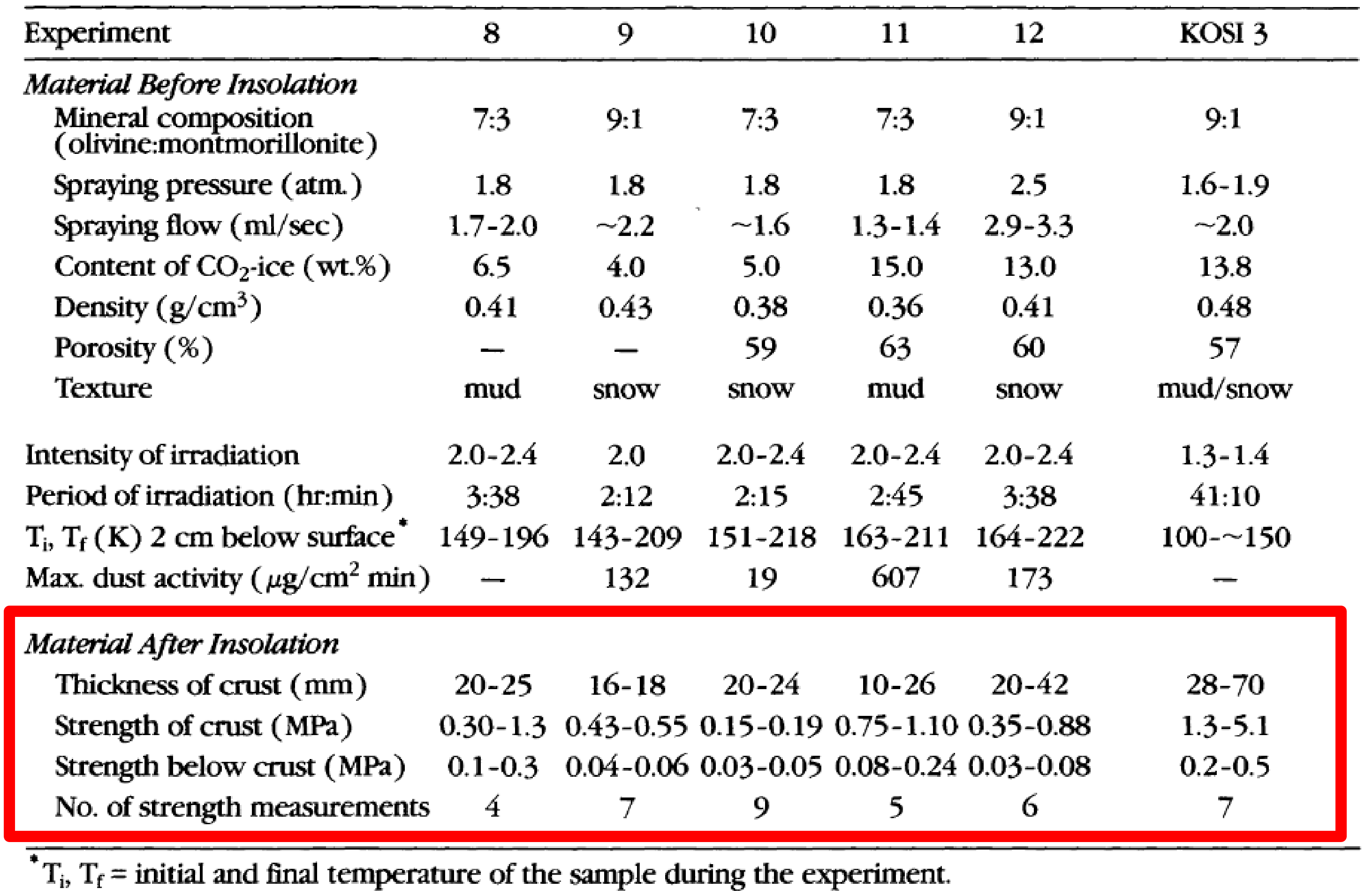
Experiment	KOSI-1	KOSI-2	KOSI-3	KOSI-4	KOSI-5	KOSI-6	KOSI-7	KOSI-8	KOSI-9	KOSI-10	KOSI-11
Date	May 87	April 88	Nov. 88	May 89	Nov. 89	May 90	Jan. 91	Oct. 91	Dec. 91	Dec.92	May 93
Sample size (height / diameter in cm)	12 /29	15 / 29	14 / 29	13 / 29	13 / 29	13 / 29	29 / 60	30 / 60	13 / 30	13 / 30	13 / 30
Sample composition (weight %)											
H_2O-ice	90	90	77.8	77.6	70.2*	41.6*	83*	100*	90	90	45.1
CO_2-ice	-	-	13.8	13.8	16.8*	15.0*	15*	-	-	-	5.8
other ices	-	-	-	-	methanol 4.2	-	-	-	-	-	9.1+
total dust content	10	10	8.4	8.6	8.8	43.4	2.1	-	10	10	40
Dust composition (weight %)											
olivine	-	89	89.1	89.2	89.3	71.3	88.9	-	99.9	99.9	50
montmorillonite	-	10	9.9	9.9	9.9	17.0	-	-	-	-	50
carbon	1	1.0	1.0	0.9	0.8	11.7	3.1	-	0.1	0.1	-
other	kaolinite 99	-	-	-	-	-	kerogene 8.0	-	-	-	-
Initial sample properties											
albedo	0.2	0.06	0.17	0.09	0.08	0.12	0.07	0.90	0.06	n.d.	0.56
density (g cm^{-3})	0.4	0.55	0.48	0.51	0.56	0.59	0.46	0.40	0.44	0.50	0.54
porosity	60%	50%	55%	55%	40%	29%:	45%	56%	53%	49%	49%
Irradiance											
flux range (SC)	0.15 - 1.15	0.9	1.4	0.65 - 0.85	1.2 - 1.0	1.2 - 1.4	1.0:	1.0	1.4 - 0.15	1.0-0.6	1.3-0.5
duration (h) (including dark phases)	38.4	39.4	47.2	44.5	12.9	30.3	34.0	40.0	59.0	4.75	15.25

*: Isotopically marked layers of HDO and $^{13}CO_2$
SC: Solar constant = 1.37 kW m^{-2}
":" indicates uncertain data

KOSI Experiments

Roessler et al., 1990

- Strength measurement using 0.5 mm diameter rod with hemispherical tip at 0.2 mm/s
- All KOSI experiments showed hard layer beneath dust mantle resulted from the sublimed and after inward diffusion re-crystallized volatiles components.
- Strength, thickness, and depth of the crust varied. The crust formation follows crystallization temperature of the different volatile components (water, methanol, CO2)



Experiment	8	9	10	11	12	KOSI 3
Material Before Insolation						
Mineral composition (olivine:montmorillonite)	7:3	9:1	7:3	7:3	9:1	9:1
Spraying pressure (atm.)	1.8	1.8	1.8	1.8	2.5	1.6-1.9
Spraying flow (ml/sec)	1.7-2.0	~2.2	~1.6	1.3-1.4	2.9-3.3	~2.0
Content of CO_2-ice (wt.%)	6.5	4.0	5.0	15.0	13.0	13.8
Density (g/cm^3)	0.41	0.43	0.38	0.36	0.41	0.48
Porosity (%)	—	—	59	63	60	57
Texture	mud	snow	snow	mud	snow	mud/snow
Intensity of irradiation	2.0-2.4	2.0	2.0-2.4	2.0-2.4	2.0-2.4	1.3-1.4
Period of irradiation (hr:min)	3:38	2:12	2:15	2:45	3:38	41:10
T_i, T_f (K) 2 cm below surface*	149-196	143-209	151-218	163-211	164-222	100-~150
Max. dust activity ($\mu g/cm^2$ min)	—	132	19	607	173	—
Material After Insolation						
Thickness of crust (mm)	20-25	16-18	20-24	10-26	20-42	28-70
Strength of crust (MPa)	0.30-1.3	0.43-0.55	0.15-0.19	0.75-1.10	0.35-0.88	1.3-5.1
Strength below crust (MPa)	0.1-0.3	0.04-0.06	0.03-0.05	0.08-0.24	0.03-0.08	0.2-0.5
No. of strength measurements	4	7	9	5	6	7

*T_i, T_f = initial and final temperature of the sample during the experiment.

KOSI Experiments #5

Kochan et al. 1998

- 0.2 – 5 MPa: where recrystallization of water vapor was extensive
- 0.05 to 2 MPa where recrystallization of water vapor was less extensive

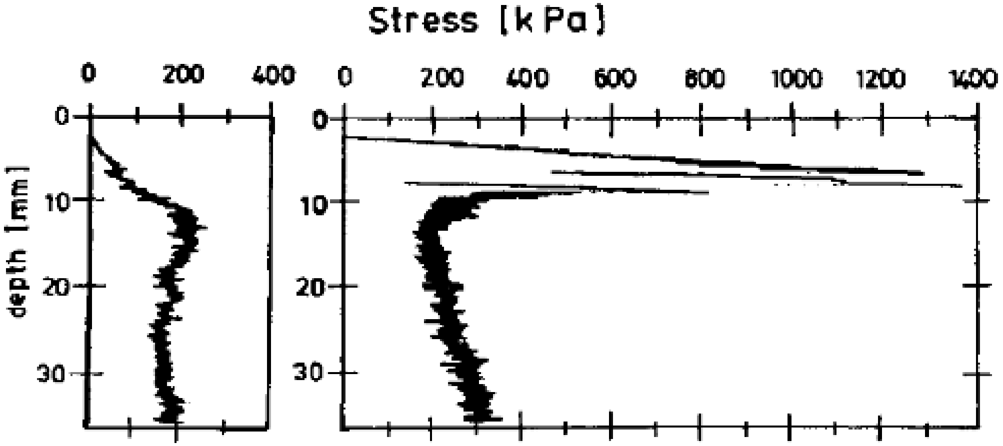
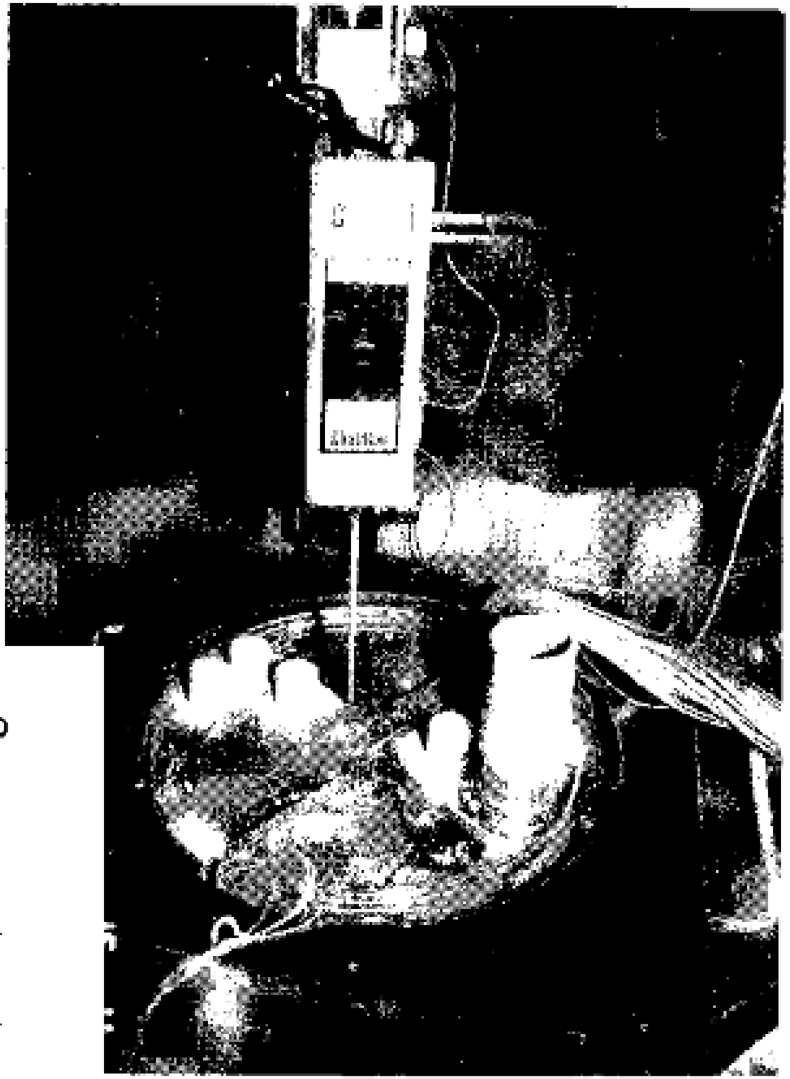


Fig. 21. Stress-depth profiles of a cometary analgous sample before (left) and after insolation (right). Small chamber experiment.



ardness test of the insolated sample using a
eter.

Conclusions

- Knowledge of material strength drives sampling approach, sample acquisition energies and forces and thermal impact on the sample captured
- Sintering seems to be the primary strengthening mechanism of a cometary material
- Sintering occurs at any temperature but sintering mechanisms and sintering rate changes with temperature (rate is lower at low temperature)
- At higher temperature sintering rate is greater (and we expect higher strength) but sublimation rate is higher (loss of volatile species which reduce material strength)
- The upper limit on strength is ice cemented ground or ice at cryogenic temperatures can reach 10s of MPa (much harder than commercial concrete)
- Strength of crystallized ice is higher than that of amorphous ice