Study of a temperature gradient metamorphism of snow from 3D images: time evolution of microstructures, physical properties and their associated anisotropy

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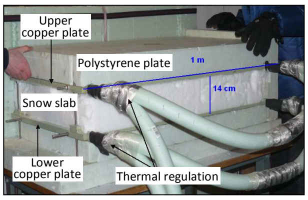
CONTEXT/GOAL

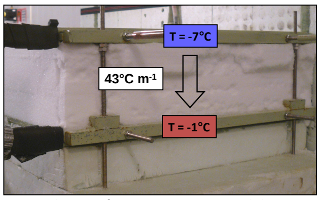
The temperature gradient metamorphism is a frequent process which affects the snowpack structure leading often to weak layers (faceted crystals and depth hoar). One of its main features is the development of vertical structures of ice but its impact on physical properties has been investigated by few studies. In this poster, we study the time evolution of several properties of a snow slab subjected to a controlled temperature gradient. For this purpose we use 3D images of snow samples obtained by X-ray micro-tomography. Some properties are computed in the x-, y- and z-directions of the samples so that we can determine their anisotropy coefficient. Finally, we present two analytical models based on ellipsoidal inclusions as ways to estimate the effective thermal conductivity and permeability of snow.

EXPERIMENT

1. Cold room experiment: snow slab subjected to a temperature gradient



The cold room apparatus designed to control the temperatures at the top and bottom of a snow slab.



Conditions of temperature imposed during three weeks in a cold room at –4°C.

2. Cold room manipulations: obtention of impregnated snow cores

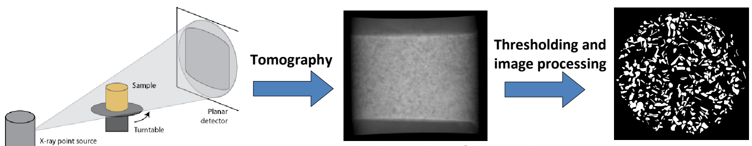
Sampling into the snow slab.

Impregnation: pores are filled by a solvent.

Freezing: metamorphism stopped and consolidation.

Machining: extraction of a snow core.

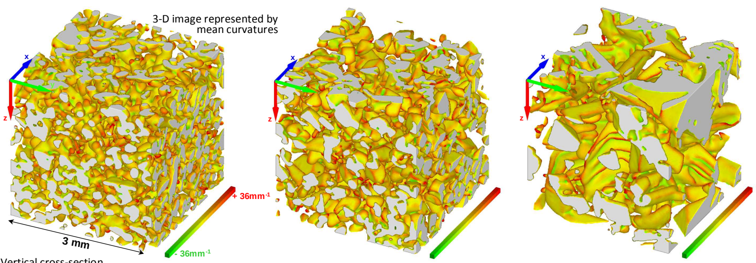
3. X-ray tomography and image processing: obtention of 3D images of snow

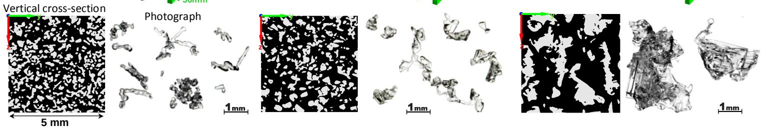


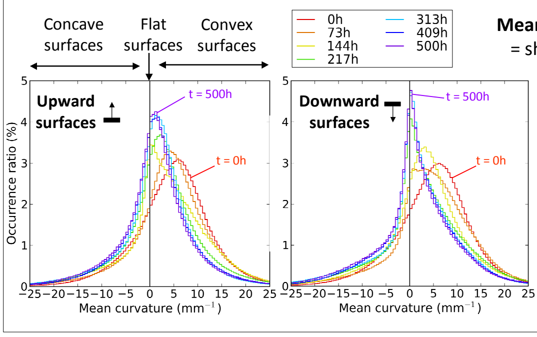
Principle of X-ray tomography. Several radiographies of the sample at different angular positions. 3D binary image of the sample (ice in white).

3D IMAGES OF SNOW – MEAN CURVATURE

t = 0 hour | t = 73 hours | t = 500 hours

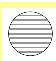




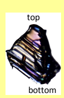


Mean curvature distribution
= shape of the ice surface

→ t = 0h
homogeneous



→ t = 500h
top: rounded
bottom: faceted



SNOW PROPERTIES COMPUTED FROM 3D IMAGES

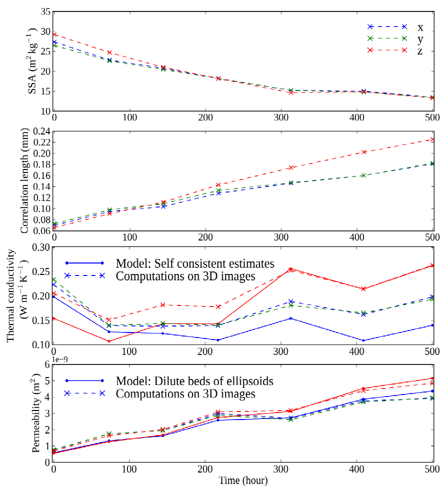
Density: no change ≈ 300 kg m^{-3}

Specific Surface Area SSA
= ratio of surface / mass
(intercept method, Flin et al. 2011)

Correlation length l_c
= characteristic length of an heterogeneity (grain+pore)
(Löwe et al. 2010)

Effective thermal conductivity k
= ability to conduct heat
(Calonne et al. 2011)

Air permeability K
= ability to let the air flow
(Calonne et al. 2012)



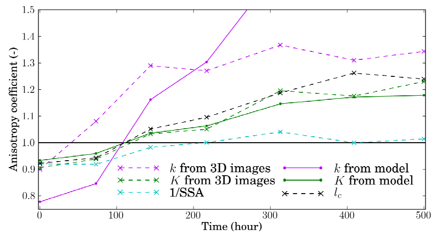
→ Physical properties evolve because of the ice reorganisation without change in density (Schneebeli et al. 2004, Satyawali et al 2008).

SNOW ANISOTROPY

Anisotropy coefficient = **z - value** / **xy - value**

→ Development of anisotropic properties: values higher along the z-direction.

→ Link between microstructure and physical properties.

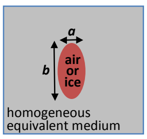


ANALYTICAL MODELS OF SNOW

Models are based on ellipsoidal inclusions and require basic information such as:

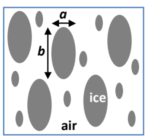
- density (ice/air proportion)
- correlation lengths (ellipsoids shape) such as $a = (l_{cx}+l_{cy}) / 2$ et $b = l_{cz}$

Self consistent estimates
Thermal conductivity (Torquato 2002)



- ellipsoidal inclusions of air or ice in a homogeneous equivalent medium, i.e. an infinite matrix whose effective thermal conductivity is the unknown to be calculated.
- connectivity of the air/ice phase

Dilute beds of ellipsoids
Permeability (Torquato 2002)



- ellipsoidal inclusions of ice in an air matrix
- no connectivity of the ice phase
→ K estimate is multiplied by the self consistent estimate of air tortuosity to reflect the spatial arrangement of the ellipsoids.

→ estimates are of the same order of magnitude as snow properties.
→ estimates reproduce roughly the anisotropy of properties.

CONCLUSIONS

3D images of snow samples at the micron scale obtained by X-ray tomography offer a great potential of exploitation. In this poster, we studied the time evolution of a snow slab which undergoes a temperature gradient metamorphism based on computations performed on 3D images. Our results highlight the following points:

- initial ice grains evolve gradually toward depth hoar showing rounded and faceted surfaces at the top and base of the grains, respectively (mean curvature).
- the structure develops preferentially in the z-direction (l_c), which induces an anisotropic behavior of the heat conduction (k) and the air flow (K).
- parametrizations of physical properties based on density (e.g. Yen et al. 1981, Calonne et al. 2011) should include microstructural parameters reflecting the general shape of heterogeneities (size, anisotropy).
- analytical models of ellipsoidal inclusions based on basic information offer good estimates of properties and anisotropy coefficients of snow.

In overall, we provide a detailed dataset which may be used as a guideline and a validation tool for snow models at micro and macro scale.

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