The importance of the microstructure of snow in nature and engineering

M. Schneebeli

WSL Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland.

Abstract

Snow is a sintered material of ice crystals. In a terrestrial environment snow exists at a very high homologous temperature and undergoes rapid recrystallization. Due to the extremely variable shape of the snow crystals, this sintered material exhibits a very wide range of porosities, between 0.9 to 0.2. The physical and mechanical properties are determined by the shape of the crystals and the connections (bonds) in between. Using 3D-micro-computertomography (μCT), we are able to measure the texture at a microstructural level, giving new insight to the thermal and mechanical behaviour of this material. In addition, the elastic properties can now be simulated as a framework of ice. These results are applied to diverse areas as snow avalanche forecasting and snow engineering.

Introduction

Snow is a natural resource and material used heavily by the society in northern or alpine landscapes. It is essential for winter tourism, to store water for hydro-power production and irrigation, but also to improve trafficability, especially in the arctic. However, in steep terrain, the formation of snow avalanches is an important natural hazard. The study of snow is concerned to these main aspects, which have to consider nature and engineering concurrently. What makes snow special to any natural or artificial material we live with? There are two prominent features: the high homologous temperature and the high and very variable porosity. The homologous temperature is a dimensionless parameter that is defined as the absolute temperature divided by the absolute melting temperature...
of the material: \( \text{Th} = \frac{T}{T_m} \), with \( T \) for temperature and \( T_m \) for the melting temperature of the material, both in K. Snow exists in a terrestrial environment at a very high homologous temperature, never lower than 0.85. Similarly high homologous temperatures are found in deep-lying rocks. This condition creates a very strain-rate dependent mechanical behaviour, and snow is extremely brittle at high strain rates, above about \( 10^{-3} \text{ s}^{-1} \), but ductile at lower rates \([1]\). The porosity ranges from about 0.95 to 0.3. Such a wide range of porosity causes a wide variation of its physical and mechanical properties. The high \( T_m \) and the high porosity favor rapid recrystallization processes, which are called metamorphism. This process modifies by water vapor transport the shape and connections between the ice crystals, and by this also the physical properties \([2]\). Here, the methods and examples to investigate the microstructure of snow will be presented and an example between the link of the microstructure to the thermal properties.

**Methods**

The microstructure of snow is measured using microtome-tomography or x-ray tomography. Microtome-tomography requires to replace the air by a liquid with a slightly lower melting point than ice, we use dimethylphtalate, which has a melting point at \(-3^\circ\text{C}\), but can be substantially supercooled. Snow samples with a density above 400 kg m\(^{-3}\) are cast under vacuum. After that the snow is sliced with an automated microtome and the surface is digitally photographed. Further digital processing is performed to segment the image into ice and air, and then the original structure is reconstructed. The advantage of this method is that also very fragile snow samples can be cast in the field. X-ray microtomography is used in the cold lab. We use a CT-scanner which has a pixel size between 20 – 80 \( \mu \text{m} \), depending on the size of the imaged cross section (\( \mu \)-CT 80, Scanco, Switzerland). This CT is run in a cold-room at a temperature of \(-15^\circ\text{C}\). The advantage of this method is that we can measure non-destructively and directly observe metamorphism. This has several advantages compared to the method uses by \([3]\), because no preliminary preparation of the sample is necessary.

To measure the change of thermal properties during metamorphism an instrumented and insulated sample of sieved snow was prepared, with a homogenous porosity of 0.71 (Fig. 1). The weight of the sample was measured at every time-step, the change in weight during the entire experiment was less than 0.3%. The temperature in the center of the sample was \(-8.5^\circ\text{C}\), the temperature gradient 100 K/m. The sample was instrumented with a thermocouple and a heat flux sensor at the bottom, and 2 thermocouples and a heat flux sensor at the top. Horizontal temperatures differences were checked before the experiment with thermocouples distributed in the middle of the experimental device using glass beads, maximum deviation was 0.1 K between center and edge. At the top and the bottom of the sample a 2 mm thick surface of pure ice was applied between the snow and the heat flux sensors. By that we created well defined boundary
conditions in respect of the vapour pressure. Temperatures are measured by thermocouples. Heating of the bottom was controlled to within 0.1 K.

Figure 1: Insulated and instrumented snow sample inside the micro-CT. At the bottom and the top of the sample heat flux and temperature are continuously measured.

The snow used consisted of small rounded grains (Fig. 2). This snow was sieved into the sample, and the density distribution was checked by imaging the cross-section every 0.2 mm with CT. The variation in density was less than 5%.

Figure 2: Snow crystals at the start and the end of the experiment, both pictures at the same scale.

**Results**

The microstructure of snow is central to the formation of slab avalanches. Slab avalanches have their main fracture zone usually in a very thin layer, often only a few mm thick. Figure 3 shows such a weak zone, consisting of small rounded crystals above a thin crust of crystals which have undergone a melt-freeze cycle.
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Just below this crust faceted snow crystals formed due to the high temperature gradient. These faceted crystals create an extremely brittle material, tending to propagate a fracture. Especially the sharp change between the stiff and strong crust and the few bonds of the faceted crystals create a weak interface. The scale of this transition makes it impossible to measure it with classical mechanical methods, and it is also impossible to see it in the snow profile.

Figure 3: Microstructure of the shear-layer of a snow avalanche. Left image: rounded grains, melt-freeze crust and first faceted crystals. Right image: Faceted crystals below the melt-freeze crust.

The characterisation of surface of snow roads and ski slopes is important to understand the interactions between the wheel of vehicles and the gliding and carving properties of skies. Vertical sections, as shown in Figure 4, make it possible to visualize the structural properties, deformation zones and to analyze micro- and macrostructural properties.

Figure 4: Vertical section and density distribution at the surface of snow roads together with the density distribution averaged over a thickness of 0.2 mm. The left image shows a very heterogenous surface created by tilling an initially frozen hard crust, the right image shows a two-layered profile.
Laboratory experiments combined with the CT make it possible to investigate undisturbed snow samples at different metamorphic stages. With this method the large uncertainties caused by inhomogeneities, which arise also in sieved samples, can be excluded. A first example of the power of this method is shown in Figures 5 and 6. Figure 5 shows the rapid changes in the size of the snow grains caused by vapor flux. These changes cause during the first 30 hours a slight decrease in thermal conductivity, because the old and small bonds are dissolved, such that the conductivity through the ice matrix is reduced, also crystal diameter is already rapidly growing. This is followed by a rapid increase of thermal conductivity, caused by the formation of new bonds. The thermal conductivity is changing from 0.98 W m\(^{-1}\) K\(^{-1}\) to 0.12 W m\(^{-1}\) K\(^{-1}\) (Fig. 6).

Figure 5: 3D-visualization of the snow at the begin of the experiment, after 24.2 h, 80.8 h and 137.9 h. The temperature gradient and the associated vapour flux created a rapidly changing microstructure. Side length is 5.4 mm.
Figure 6: Change in thermal conductivity

Conclusions

Using tomographic methods the microstructure of snow can be visualized and measured. Combining simultaneous measurements of physical and mechanical properties with non-destructive imaging has a strong potential to improve the understanding of the effects of metamorphism and the associated changes in microstructure. Until now, microstructure could only poorly described by the shape of the grain. Sturm [2] did not find a clear correlation between thermal conductivity, density and snow type. The experiment shown here clearly demonstrates that there must be a correlation. It is also clear, that an improved mechanical understanding must include the microstructure at a very detailed level, because the spatial changes are very rapid.

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References

