The University Centre in Svalbard

AT-211 Ice Mechanics, Loads on Structures and Instrumentation

Laboratory Report
Group 2

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Abstract

The report covers a series of experiments performed in cold laboratories at University Center in Svalbard (UNIS) in the spring semester 2015, and the results obtained after the data processing. All the experimental work was carried out in AT-211 course - Ice Mechanics, Loads on Structures and Instrumentation from 4th March to 7th March. The activities included a water-cooling test, an ice expansion test, thin-sections test and uniaxial compression tests. These tests aimed to investigate the behavior of water and different types of ice.

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1. Introduction

The mechanical properties of sea ice are important for design of arctic offshore structures. It is of the essence to know the bearing capacity and physical properties of ice, in order to calculate safety hazards.

We performed different tests with sea ice in the laboratory at UNIS, to get more knowledge about ice formation. This was also an introduction to certain methods and instruments, regarding our field work later in the semester.

Weather and climate conditions in field work varies, and have impact on these tests, therefore our results is only valid for one type of conditions. However, the laboratory tests will give us some idea of how water and ice behaves, as well as knowledge about certain scientific methods.

2. Water Cooling Test

2.1 The setup

The experiment on water-cooling was performed at UNIS Cold Laboratory. Illustration and photo of the setup are shown on figure 1. A cylindrical bucket with seawater from Adventfjorden (34 ppt) was placed into an insulation box with sizes 60x60x48 cm made of Styrofoam. The setup allows cooling only from the top of the bucket. Temperature of water on different depths was measured with Fiber Braggs Gratings thermistor string [1]. FBG thermistor string consists of 12 Braggs gratings cells with distance of 1 cm between sensors inside a fiber. The top sensor of the string was measuring temperature at 1 cm above the water surface; the second one was placed just above the surface, other sensors were measuring temperature in the water. Temperature of the air was also logged with thermocouple thermometer. The other groups did the same tests, only with fresh water, slush and more saline water.

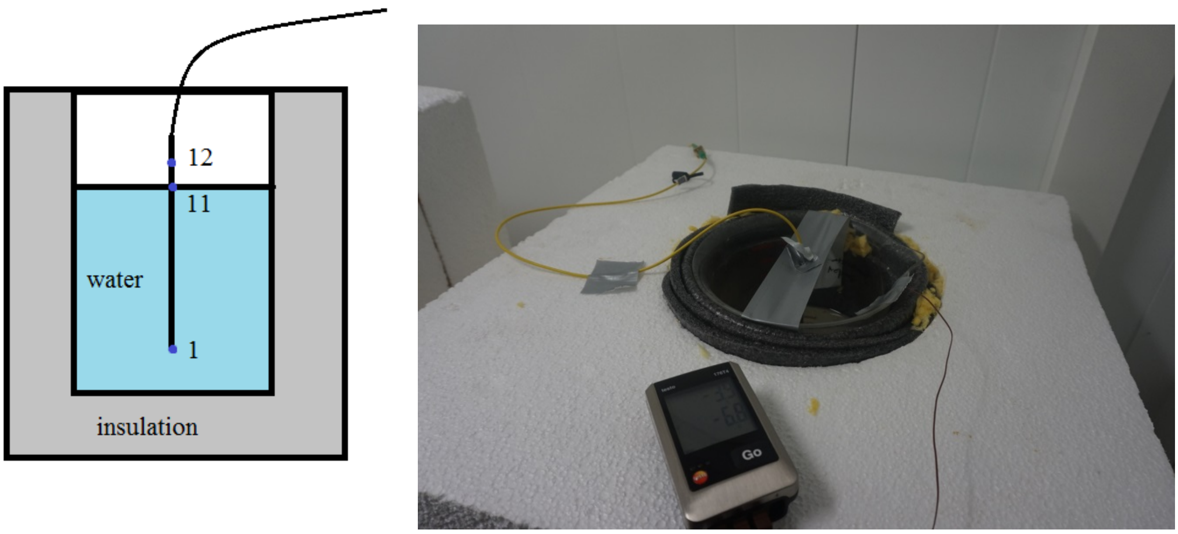


Figure 2.2.1 - Scheme and picture of the experiment

2.2 Theory

Density of water depends on temperature and salinity [2]. Seawater has maximal density at the temperature of approximately -3.5 C (shown in figure 2.2.2), which is less than freezing point (-1.9 C). During cooling from the top, the temperature of the top layers decreases, therefore the density increases and more dense water sinks down. As a result, mixing occurs, and the water temperatures on all levels in the bucket becomes approximately the same.

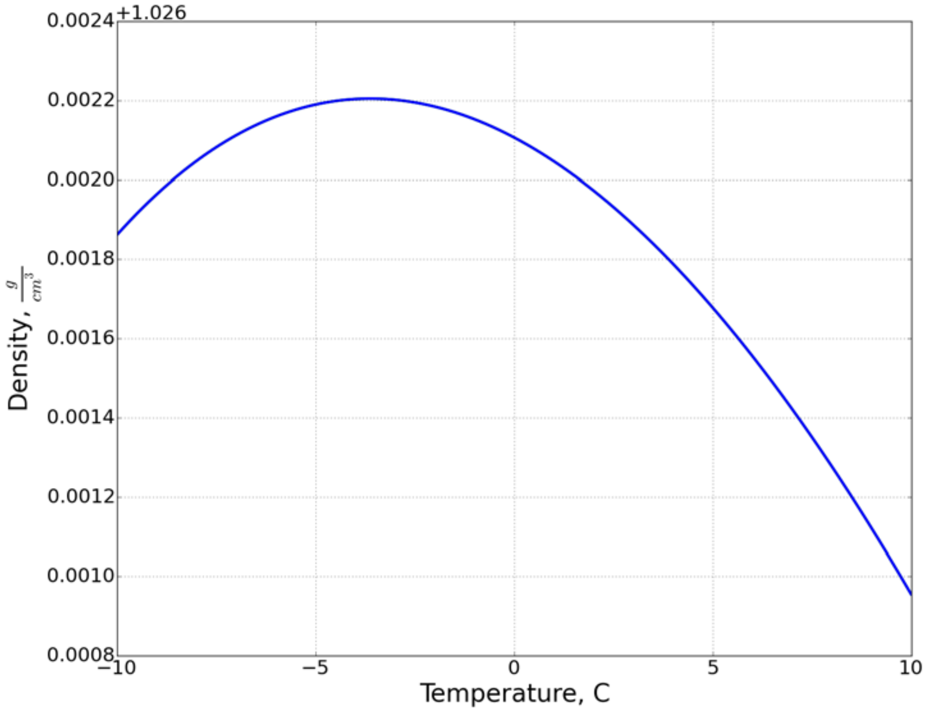


Figure 2.2.2 - Dependence of density from temperature for seawater

Fresh water has a maximal density at the temperature of 4 C, which is above the freezing point (0 C). Therefore, it should have same behavior as seawater only at temperatures above point of maximal density. Under cooling as the point was reached, water at the top layers becomes less dense with time, so mixing stops.

The critical point for saline water – that is when temperature of maximal density equals to freezing point – is -1.2 C for water salinity of 24.7 ppt [3].

2.3 Results

The water temperature at different levels is shown on the figure 2.3.3.

The oscillations in the temperature measurements are caused by the changing temperature inside the cold laboratory. Period of these oscillations is about 11 minutes and corresponds to turning fans on and off. Therefore, it is difficult to rely on these temperature measurements.

During our experiment, there was convection all the way to the freezing point at -2 C. After 5 hours, ice starts to form at the level of 1 cm below the surface. A closer look on this point is shown on the figure 2.3.4. The remaining water stayed at the freezing point, which was slightly decreasing due to increasing salinity of unfrozen water. This happens due to the fact that salinity of ice is usually 2-4 times less than salinity of the water it was frozen from. As ice freezes, salt is rejected from it causing the salinity increase. The temperature of the air just above the surface was different from the temperature of the air on the level of 1 cm above; hence the water influenced the air temperature.

On the figure 2.3.5, similar plots are shown for fresh water. The water was mixing down to 4 C, after which convection stopped. After the mixing stopped, temperatures on different levels fluctuated, due to water freezing at 0 C.

Figure 2.3.6 and figure 2.3.7 show the temperature profiles during experiments with sea and fresh water. The profiles are plotted each 1000 seconds of the experiments, in which the color changes from dark to blue with time. The temperature profiles are vertical for the time when the convection was established and inclined for water-cooling without mixing (for fresh water).

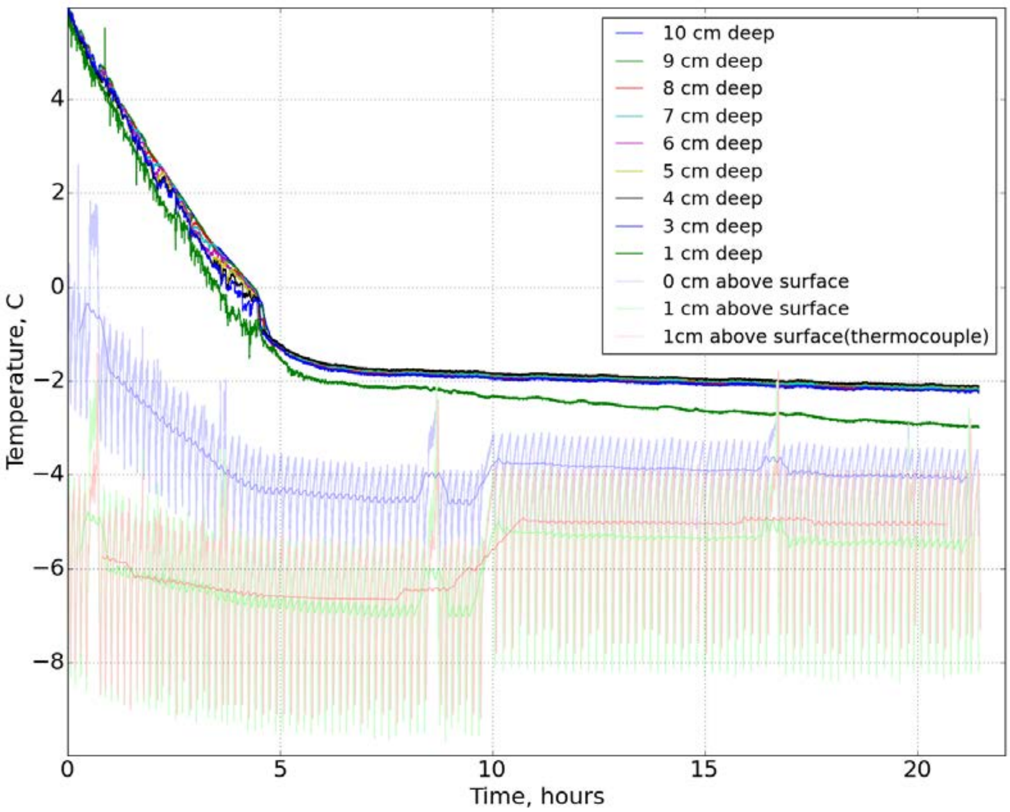


Figure 2.3.3 - Temperature during experiment

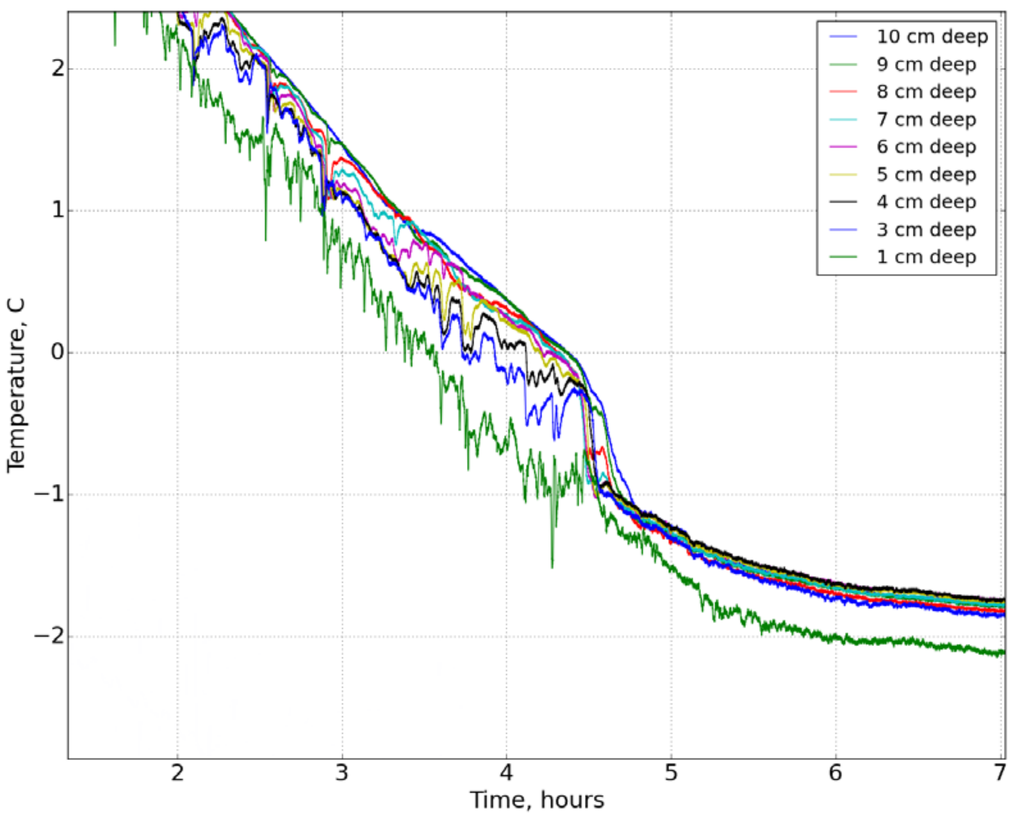


Figure 2.3.4 - Temperature during experiment close to freezing point

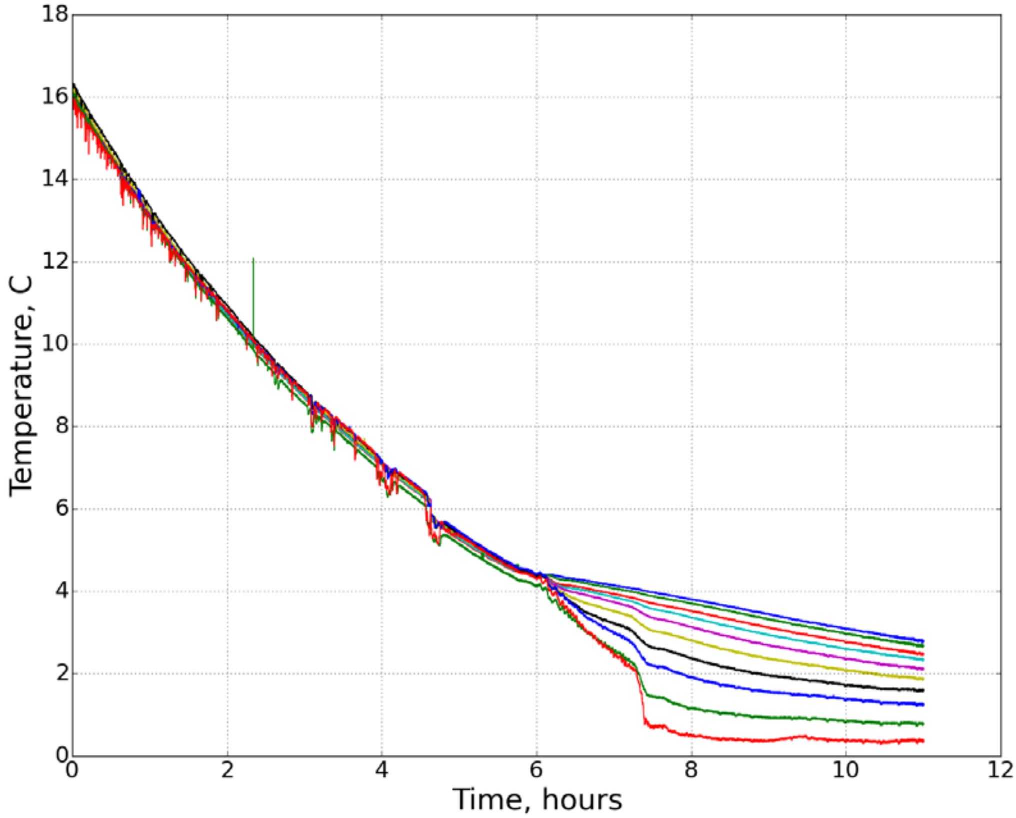


Figure 2.3.5 - Temperature change for fresh water

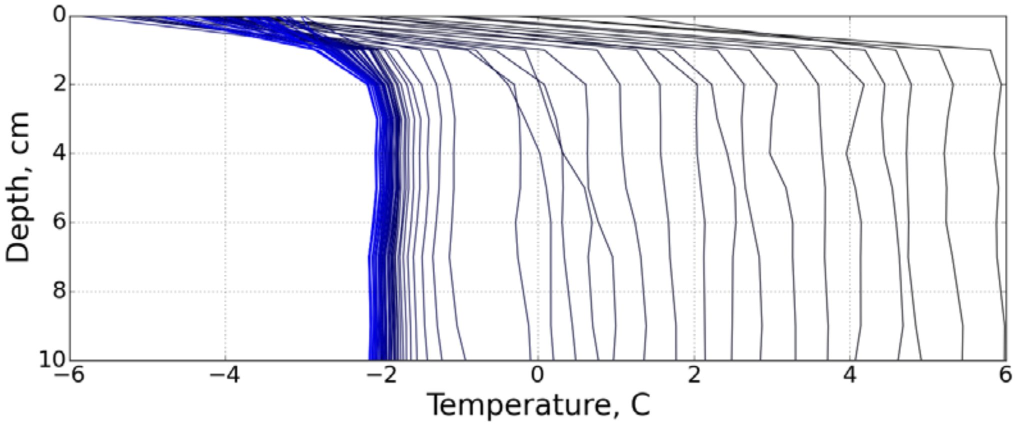


Figure 2.3.6 - Temperature profile for seawater

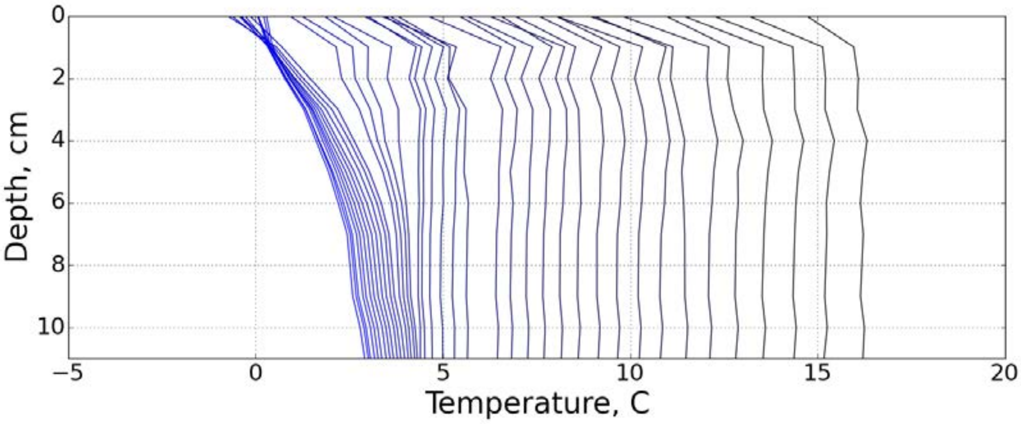


Figure 2.3.7 - Temperature profile for freshwater

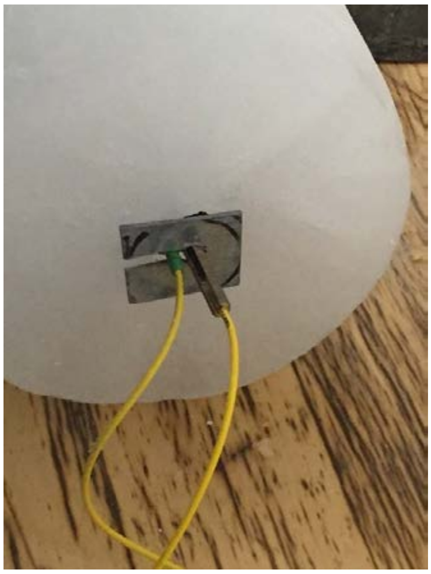
3. Ice Expansion Test (Thermo-elastic waves in saline ice)

3.1 The setup

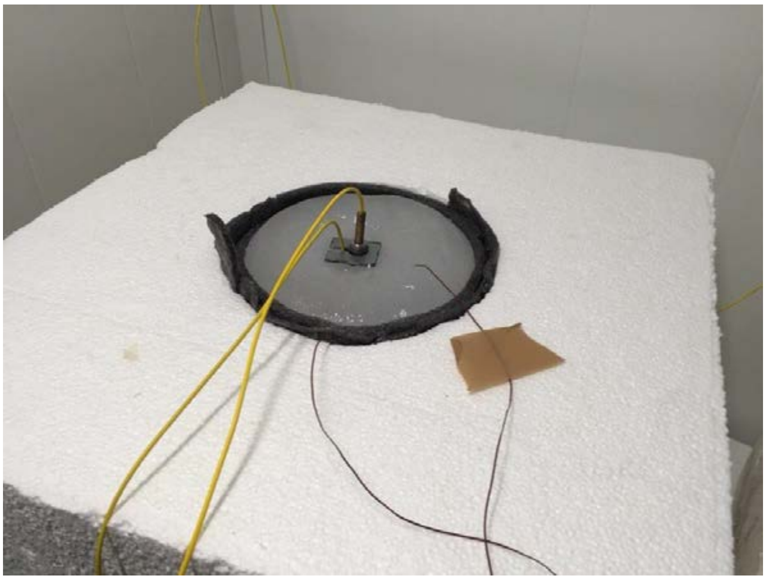
The experiment on thermo-elastic waves was performed in UNIS Cold Laboratory. The Ice sample with shape of a cylinder (sizes approximately 20x20 cm) as shown in figure 3.1.1a) was prepared in advance. The salinity of the ice was 2 ppt. A hole though the sample was made for FBG strain and temperature sensors figure 3.1.1b). The sensors were packed in isolating material to prevent air convection inside the cylinder and protected from water (Figure 3.1.1c). The sensors were installed into the sample and the ends of the strain sensors were fixed as shown in Figure 3.1.1d). The ice cylinder was placed into insulation box Figure 3.1.1e) and thermocouples were attached to the top and bottom of the sample Figure 3.1.1f).

(a)

(b)

(c) (d)

(e) (f)

Figure 3.1.1 - The setup

3.2 Theory

In the absence of external stress strain is defined as:

$$\varepsilon = \alpha \Delta T \tag{3.2.1}$$

Where ΔT – temperature change; α – thermal expansion coefficient.

Strain is determined as change of length divided on total length that is

$$\varepsilon = \frac{\Delta L}{L} \tag{3.2.2}$$

Strain can be measured with a Fiber Braggs Gratings (FBG) sensor. Fiber Braggs Grating reflects a certain wavelength, which depends on distance between gratings. This distance, in turn, is affected by the temperature change and deformation of the fiber. The Relative change of reflected wavelength is given by

$$\frac{\Delta\lambda}{\lambda ref} = GF\frac{\Delta L}{L} + TK\ \Delta T \tag{3.2.3}$$

$$\Delta\lambda = \lambda - \lambda ref$$

Where GF = 0.719 and TK = 5.5* 10 $^{-6}$ for the FBG sensors are used in the experiment.

The FBG temperature sensor is covered with metal shell which prevents fiber from deformations; hence temperature change near strain sensor can be measured which, in turn, is used for calculation of strain from strain sensor. As the result strain if determined as

$$\varepsilon = \frac{\Delta L}{L} = \frac{1}{GF}\left(\frac{\lambda_d - \lambda_{dref}}{\lambda_{dref}} - \frac{\lambda_T - \lambda_{Tref}}{\lambda_{Tref}}\right) \tag{3.2.4}$$

Where λ_d – current wavelength for strain sensor;

λ_{dref} – reference wavelength for strain sensor;

λ_T – wavelength for temperature sensor;

λ_{Tref} – reference wavelength for temperature sensor.

3.3 Results

Figure 3.3.1 shows strain and temperature change near strain sensor within ice with time. During all experiment ice was contracting.

Against the background contraction, oscillations can be seen. These oscillations are due to periodical temperature change in the Lab, which is connected to the work done by the Lab`s cooling system. The period of oscillations is about 11 minutes.

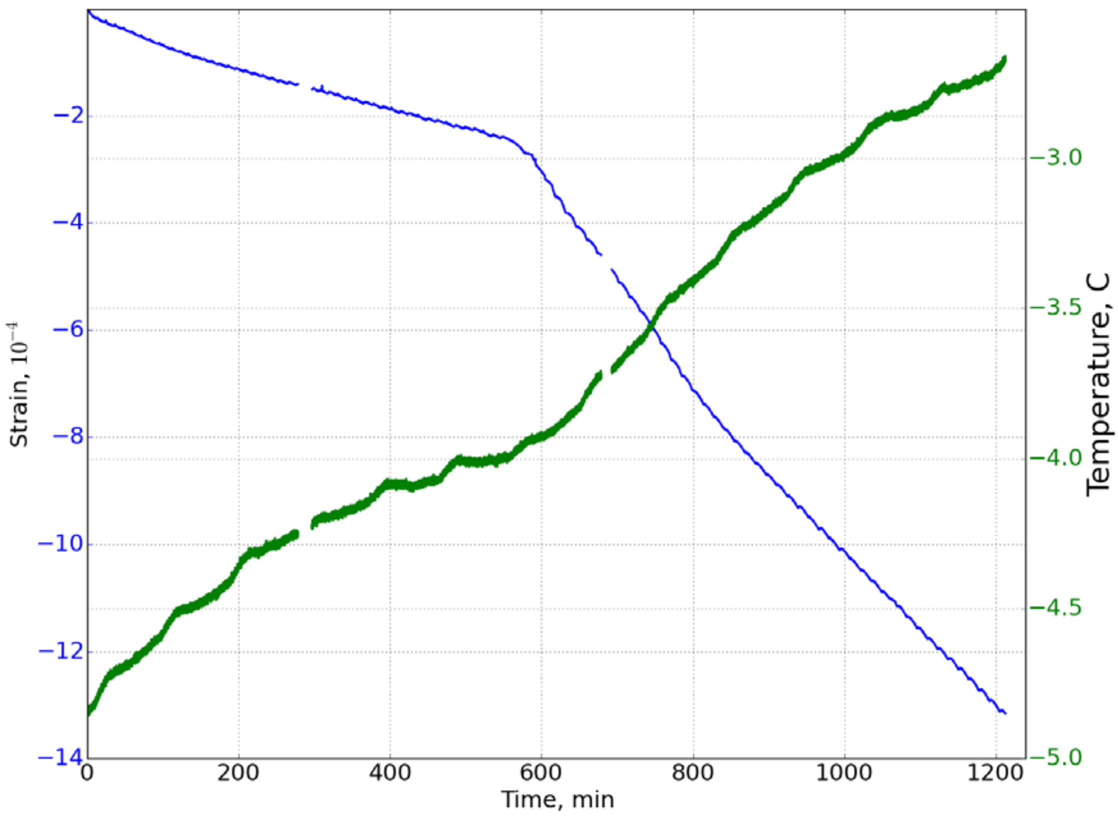


Figure 3.3.1 - FBG strain and FBG temperature during experiment

Figure 3.3.2 shows strain and temperature from sensors installed at the top and bottom of the ice sample. After approximately 9 hours temperature in the Cold Lab was switched from -4 C to -2 C. The surface temperature changed faster than bottom temperature of the sample. It is reasonable to choose time periods from 350 to 500 min and from 1000 to 1100 min for closer investigation since temperature was changing slightly within these time windows.

Figure 3.3.3 shows strain oscillations at the time when temperature in the Cold Laboratory was about -4 C. The green line is linear approximation of strain. Then this linear approximation was subtracted from strain data to receive oscillations due to thermo-elastic waves. It is shown on figure 3.3.4. The period of strain oscillations corresponds to the period of temperature oscillations in the room (approximately 11 minutes). The amplitude of waves for the ice with salinity of 2 ppt at the temperature of -4 C is about $4*10^{-6}$.

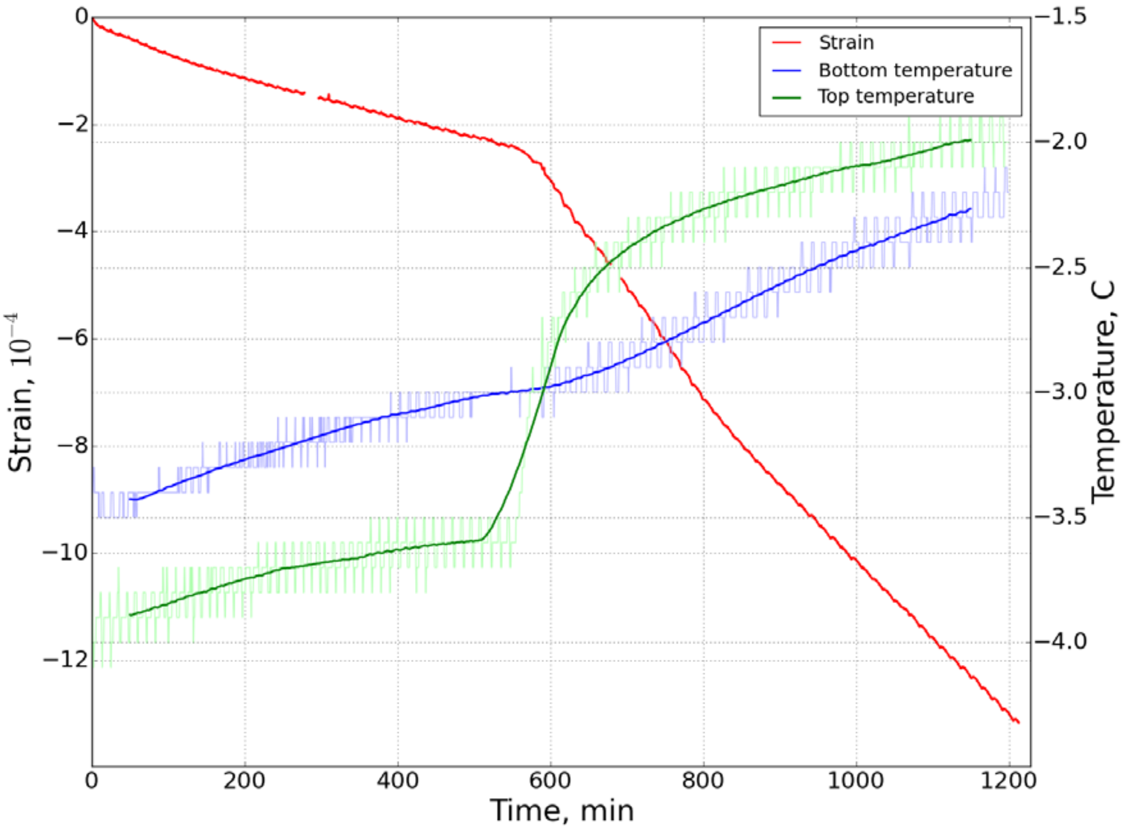


Figure 3.3.2 - FBG strain and thermocouple temperature during experiment

Figure 3.3.5 and figure 3.3.6 are given for the time, when temperature in the room and at the top layer of the sample was approximately -2 C. At this point amplitude of thermos-elastic waves is $4.6 * 10^{-6}$.

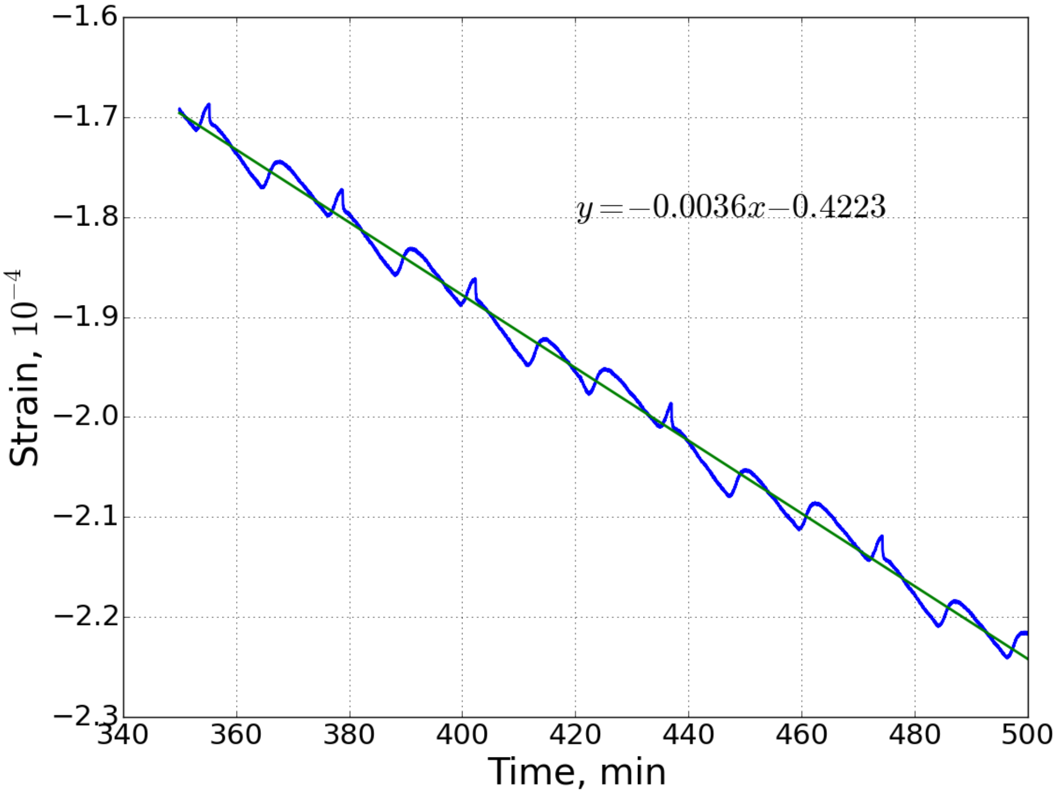


Figure 3.3.3 - Strain around temperature of -4 C

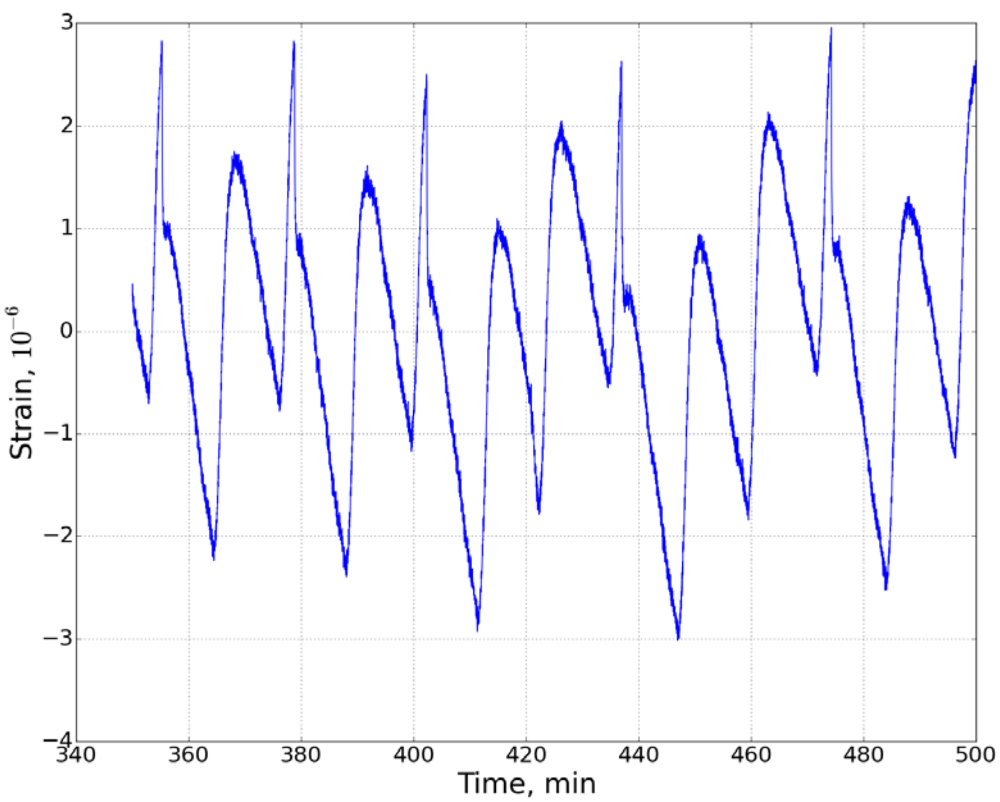


Figure 3.3.4 - Oscillations due to thermowaves around temperature of -4 C

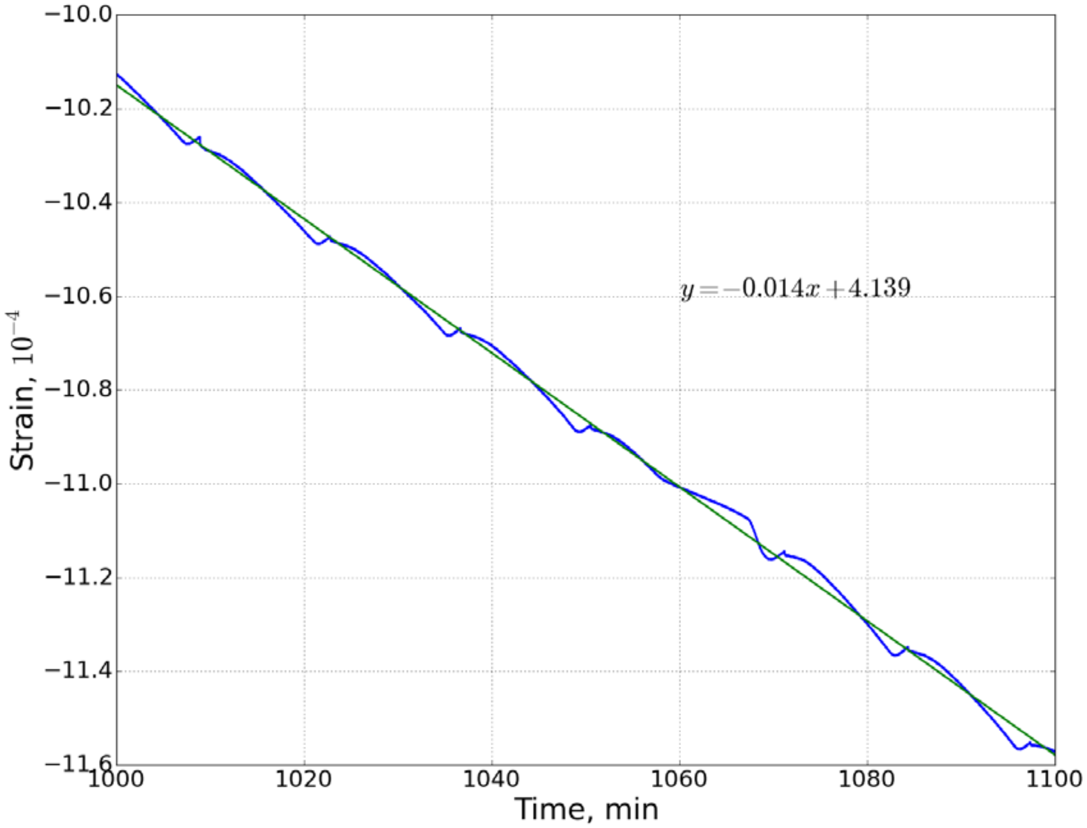


Figure 3.3.5 - Strain around temperature of -2 C

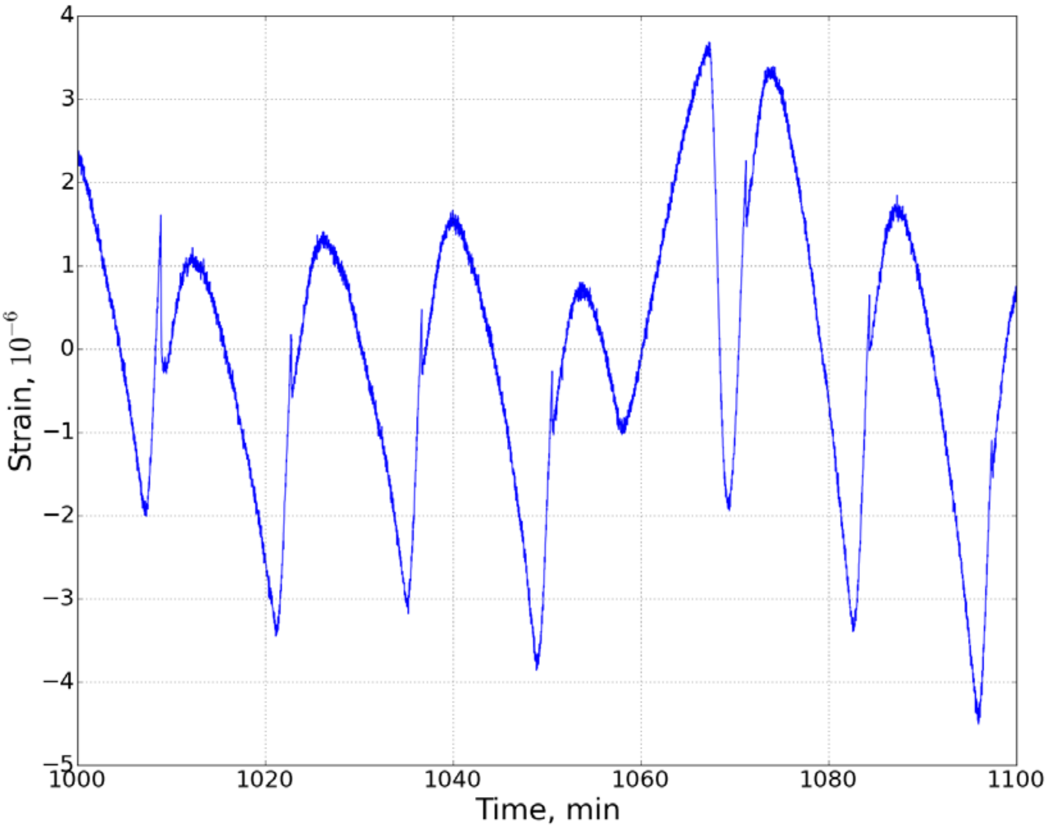


Figure 3.3.6 - Oscillations due to thermowaves around temperature of -2 C

4. Thin section test

4.1 Theory

The crystal structure of ice provides the information that is possible to be used for examination of physical properties of ice. The ice growth determines the processes of crystals formation and lattice developing, and the composition of the crystals determines the strength and strain of ice.

During the ice formation process, the atoms at some point are well bonded in layers, but these layers are less firmly attached to each other. The deformation usually happens parallel to the layer structure, this direction is defined as “basal plane”. The perpendicular to basal plane direction is called “c – axis“.

The orientation of the “c – axis” defines the wavelength of light which can interfere, and is determined by the optical length. The thermal conductivity and elastic stiffness are perpendicular to this direction; hence the grains grow along the basal plane, which is the direction of heat flux. As the ice crystals alter the polarization, the light that is normally not transmitted with two perpendicular filters, takes on a color depending on the crystal orientation. From this, the size and orientation of the crystals can be estimated. There are three different types of ice structures depending on the “c – axis“ orientation:

1. Columnar ice with vertical directed “c – axis“ is defined as *S1 ice*;
2. Columnar ice with horizontal and randomly directed “c – axis“ is *S2 ice*;
3. Columnar ice with horizontal and aligned “c – axis“ is *S3 ice*.

When the temperature becomes low enough, the water freezing process starts. At first the frazil ice or slush is formed with the c-axis crystals oriented randomly. Being influenced by randomly oriented heat flux, as well as by winds and waves, the granular ice forms on the surface. After the first (upper) layer is formed, the heat flux orients vertically, so the crystals start to grow in this direction parallel to each other. This ice is called columnar ice (Figure 4.1.1).

The salinity of ice influences its strength by increasing its porosity. The salt is usually mostly rejected during the ice formation, but once it is trapped, it can form brine pockets in the ice.

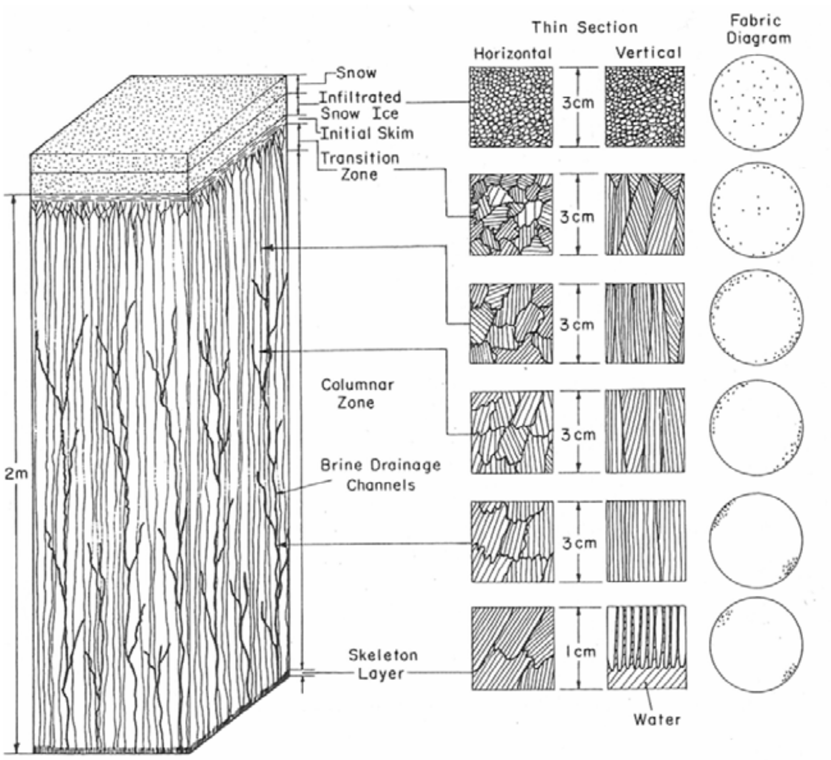
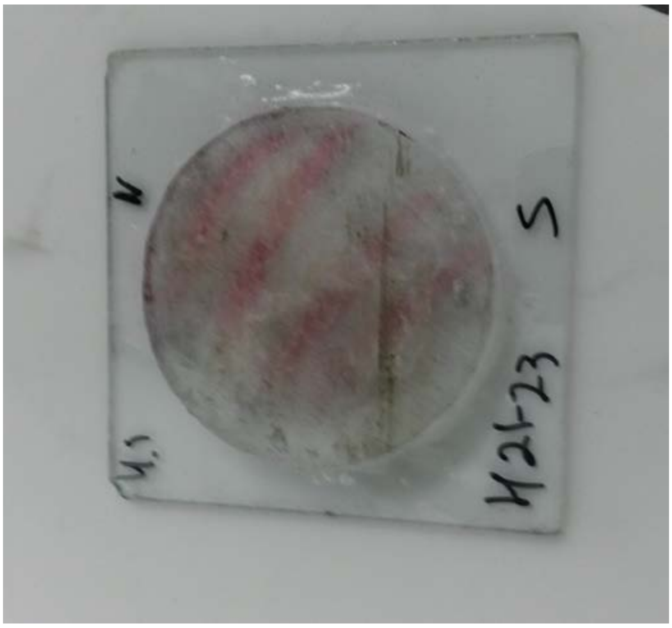


Figure 4.1.1 - Structure of ice

4.2 Procedure

To investigate the crystal structure of ice, we use a thin-sections test. This test is based on the ability of ice crystals to be polarized by the light from the two polarizers and to appear in different colors depending on the c-axis direction. This allows to measure the size and orientation of ice crystals and to determine the ice structure.

The vertical and horizontal cut ice slams were observed; the samples were cut out of the larger chunk of ice and fixed on the glass plates by adding distilled water (Figure 4.2.1a). They were made thin enough (less than 1 mm) by using the microtome, after which they were placed between the two cross-polarized glasses (Figure 4.2.1b).



(a)

(b)

Figure 4.2.1 - (a) The sample (b) Microtome

Light is not transmitted with the perpendicular filters, but as the ice crystals alter the light polarization, they transmit light in a color according to c-axis orientation (optical axis).

4.3 Results and Discussion

The Figure 4.3.1 shows the vertical cross-sections of sea ice sample. They elongate in the vertical direction, parallel to the heat flux, which is the main direction of ice growth. Thus, the resulted structure is defined as columnar ice. Brine channels are visible because they are located vertically so salt goes down; air bubbles are possible to see as well, and are usually more rounded. The crystals are relatively large and have the regular columnar shape, which means that this cross-section is more likely be taken from the middle part of the core. The width of grains observed is about 1 cm.

Figure 4.3.2 is a horizontal section. It is possible to observe the largest crystal here, by the area that has the same color features. The grain size varies, but is approximately several square cm.

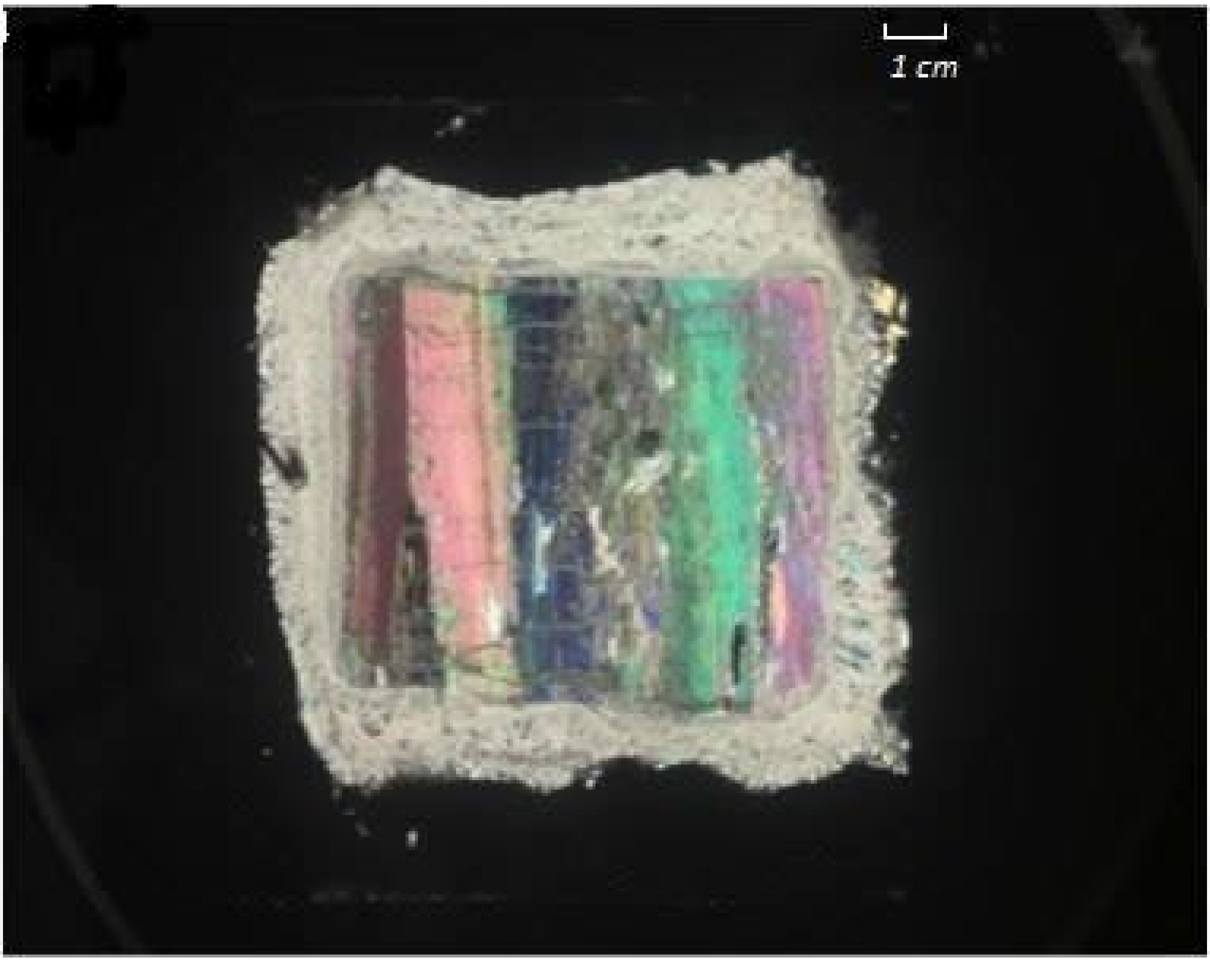


Figure 4.3.1 - Vertical, 38-40 cm, core 4.2

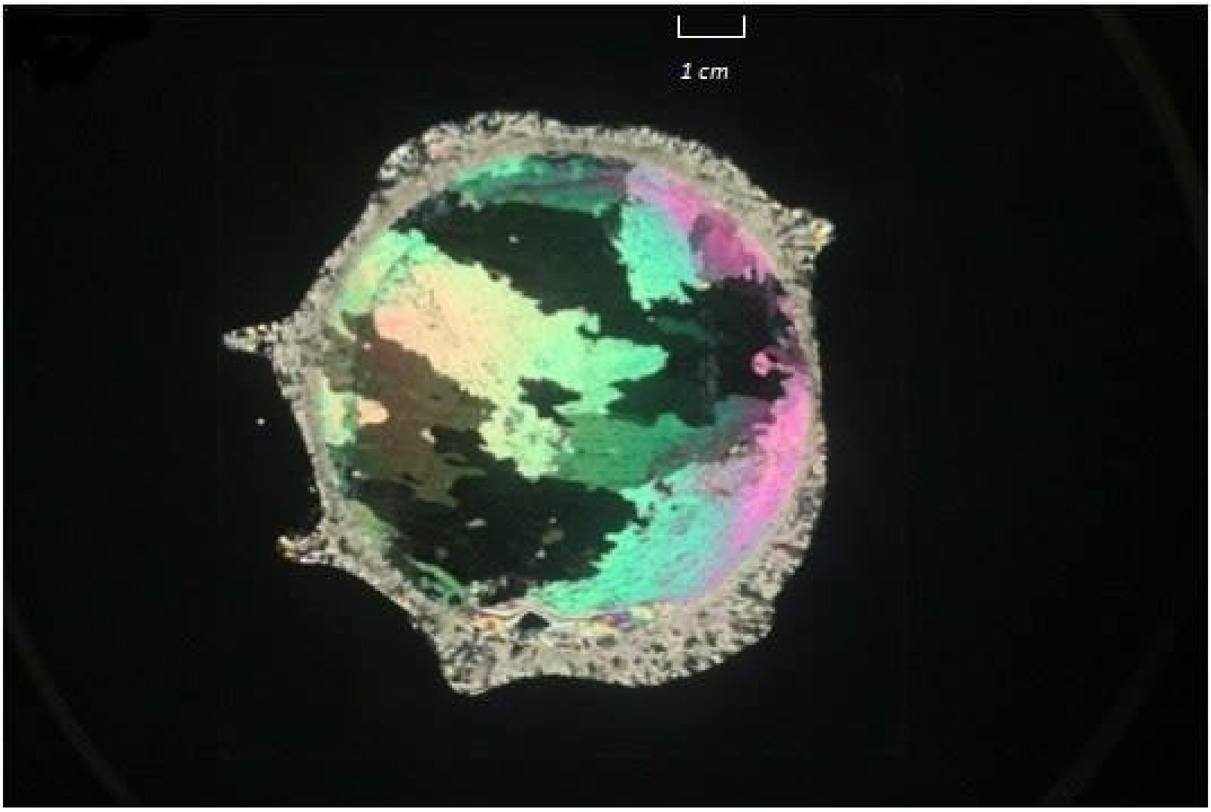


Figure 4.3.2 - Horizontal, 21-23 cm, core 4.1

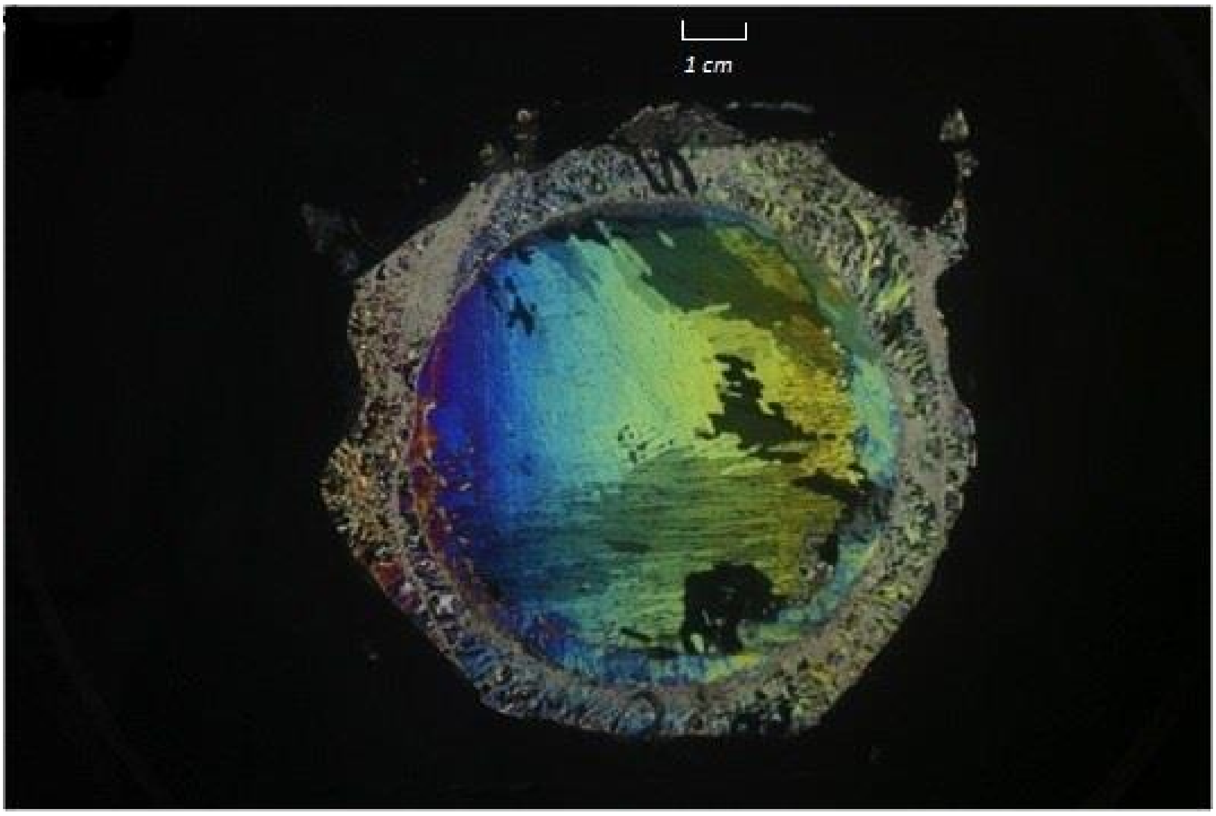


Figure 4.3.3 - Horizontal, 38-40 cm, core 4.2

The third sample (Figure 4.3.3) is a horizontal cross section. This specimen was taken from the lower part of the ice core. The shape of grains differs from the previous sample and the size of them is larger. It can be observed that ice is becoming more columnar with depth; the crystals with horizontal c-axis orientation tend to become larger as they are closer to the bottom of the sample. The typical grain size is approximately 1 cm (for horizontal section).

We also looked at the samples using a microscope. The brine pockets and air bubbles are clearly seen in Figure 4.3.4 and Figure 4.3.5.

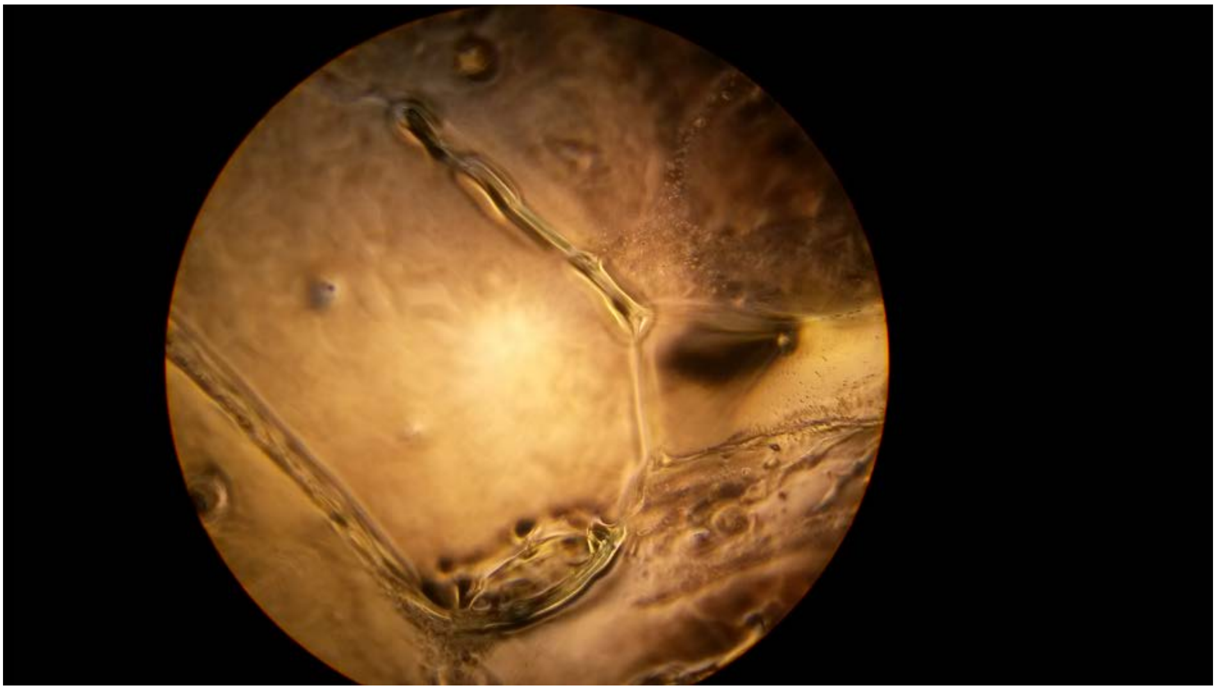


Figure 4.3.4 - Vertical section in microscope

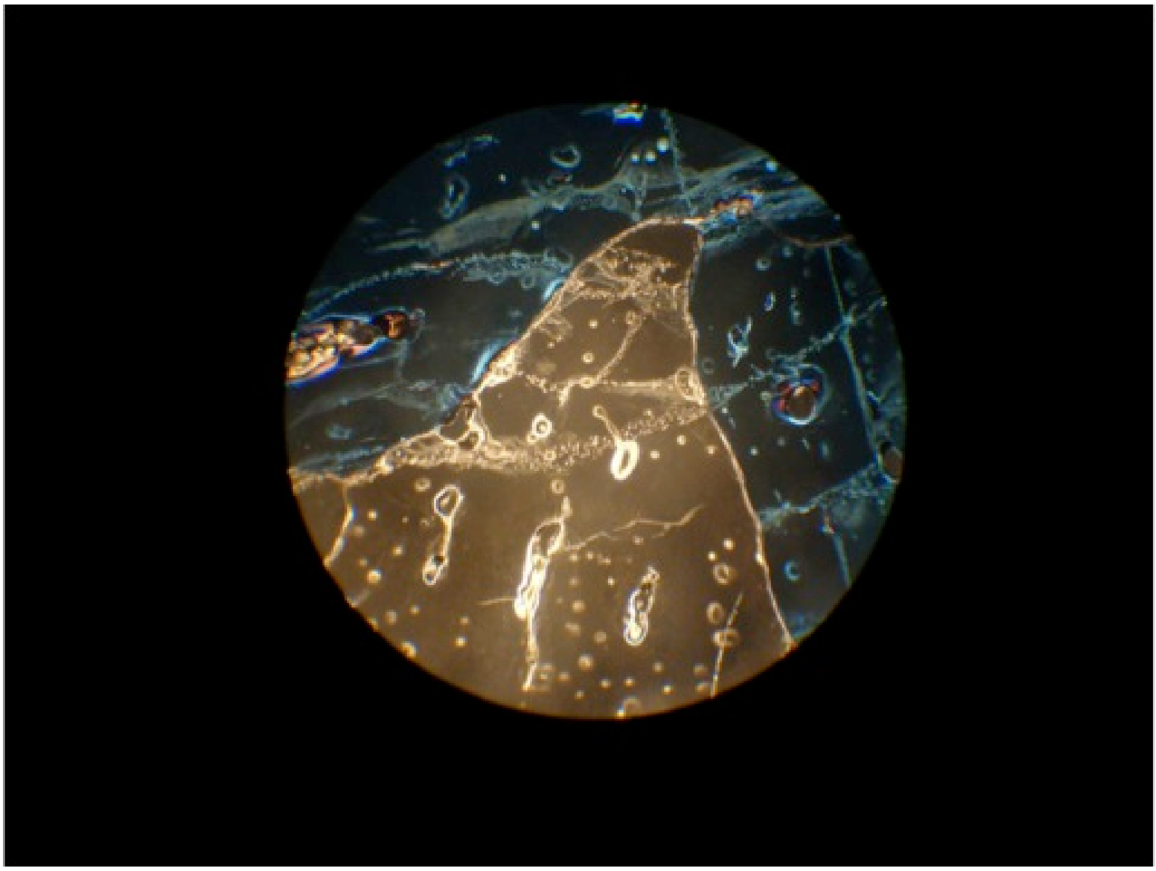


Figure 4.3.5 – Horizontal section in microscope

5. Uniaxial compression test

5.1 Theory

An uniaxial compression test measures the unconfined compressive strength of a material. It demonstrates the behavior of ice when it is loaded, and the maximum load applied before failure occurs. Strength of the ice sample depend on porosity, salinity, temperature, strain rate, applied load and grain sizes.

Stress (σ) is the internal forces acting between particles in the sample. We can calculate the stress, by using equation (5.1.1), where F is force and A is the cross-sectional area of the sample.

$$\sigma = \frac{F}{A} = \frac{kN}{mm^2} = MPa \qquad (5.1.1)$$

When we calculate the stress using Eq. (5.1.1), we asume that force is equally distributed over the entire cross-section.

Strain (ε) is the deformation which occurs in a material if it is exposed to stress. Strain is the relation between the change in length deformation (Δl) and the initial length (l_0) of the sample. Strain is given by equation (5.1.2)

$$\varepsilon = \frac{\Delta l}{l_0} \qquad (5.1.2)$$

During the compression test, we have a constant strain rate. Strain rate ($\dot{\varepsilon}$) is defined as the change in strain with time. Depending on the strain rate, the deformation can be either ductile or brittle. Before the failure, the ice sample is said to be an elastic material. The young modulus (E) describes the inflexibility of an elastic material. It is the relationship between the change in stress and the strain, calculated from equation (5.1.3).

$$E = \frac{\text{Change in Stress}}{\text{Strain}} = \frac{\Delta\sigma}{\Delta\varepsilon} \qquad (5.1.3)$$

The strength of the ice sample depends on the strain rate. With increasing strain rate, the maximum stress (failure point) can go from ductile deformation to brittle deformation as shown in Figure 5.1.1.

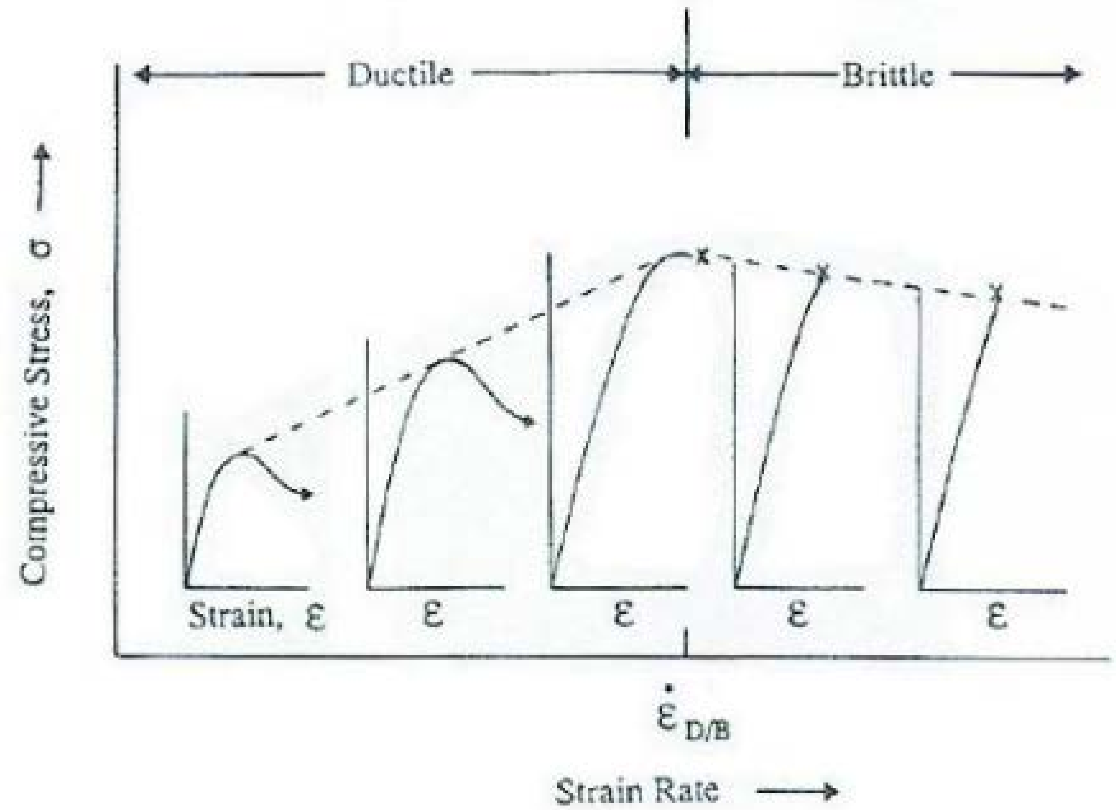


Figure 5.1.1 - Variation between stress and strain with increasing strain rate, which shows transition from ductile to brittle failure (Schulson, 1997)

5.2 Procedure/experimental set up

The uniaxial compression tests were performed in the cold laboratory at the University of Svalbard the 07th of March. We had an Ice core with depth 56 cm, collected in Svea, which we cut into two samples. We started by cutting the samples in the manual cutting machine (Figure 5.2.1) to 175 mm each. We measured weight, diameter and length of the samples, and then we placed the sample in the compression machine «knekkis» (Figure 5.2.2). We used a special lab view program for the test, with a constant strain rate. During the test, the labview program collected force, deformation and motorsteps versus the time. A picture of the core after the experiment is shown on the Figure 5.2.3. We measured the temperature in the middle of the core, about halfway into the sample. Then we put the sample into a box, melted it and measured the salinity with a salinity meter. Afterwards we got the data for the two samples, and calculated stress vs strain.

Figure 5.2.1 - Manual cutting machine, used to cut ice cores

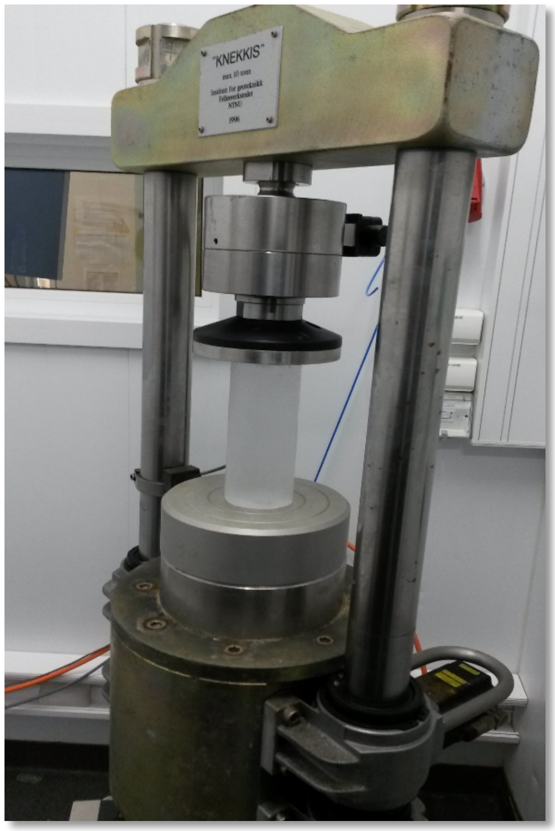


Figure 5.2.2 - Ice core in "Knekkis" before compression test

Figure 5.2.3 - Ice core after compression

5.3 Results

We measured the length, diameter and temperature in the lab, and the strain rate was put into the computer program before the test. Sample C7.1 was taken from 5 cm to 20 cm, on the top of the ice core. Sample C7.2 was taken from 20 cm to 56 cm, on the bottom of the ice core.

Table 5.3.1 – Parameters measured before and after the experiments, taken from the ice cores.

Parameters	**Units**	**Sample C7.1 (5-20 cm)**	**Sample C7.2 (20-56 cm)**
Weight	g	647,4	648,0
Length	mm	175	175
Diameter	mm	71,8	71,7
Temperature	℃	-7,2	-7,3
Strain rate	1/s	$5 * 10^{-4}$	$5 * 10^{-4}$

We calculated maximum stress for each sample with equation (5.1.1), using the maximum force value. We measured the salinity with a salinity meter. We calculated density, by dividing the mass of the sample on the volume of the sample.

Table 5.3.2 – Parameters calculated for both samples after the compression test

Parameters	**Units**	**Sample C7.1 (5-20 cm)**	**Sample C7.2 (20-56 cm)**
Max force	kN	18,74	51,48
Max stress	MPa	4,63	12,75
Max strain		0,02	0,02
Salinity	ppt	5,78	3,93
Density	$\mathrm{kg/m^3}$	913,7	917,1
Air porosity		0,0126	0,0064
Brine porosity		0,0413	0,0279
Brine porosity, other method		0,0417	0,0280
Porosity		0,0540	0,0368
Youngs modulus	GPa	"1,38"	5,18
Failure mode		Ductile	Brittle

We determined air, brine and total porosity using a script (porositykvh) in Matlab. This script was built on the equations described by Cox and Weeks [4]. Liquid brine content was also determined by another equation:

$$v_b = S\left(\frac{48{,}185}{|T|} + 0{,}532\right) \tag{5.1.4}$$

This was done, to see the difference in liquid brine content, using different methods. Both methods give approximately the same answer. The difference is so small, that it is negligible.

Using our data, we plotted stress vs strain for the two samples (Figures 5.3.1 and 5.3.2). We also plotted strength vs porosity for every sample taken from Svea, so that we could see if this coinsided

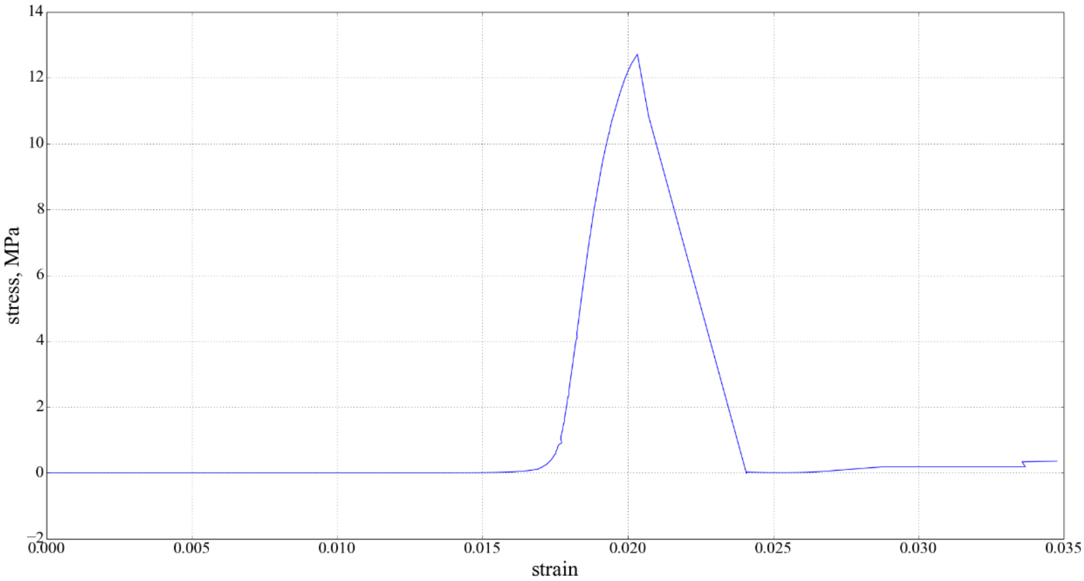


Figure 5.3.1 - Stress vs strain for core 7.2 (5 - 20 cm)

with Cox and weeks results (figure 5.3.3).

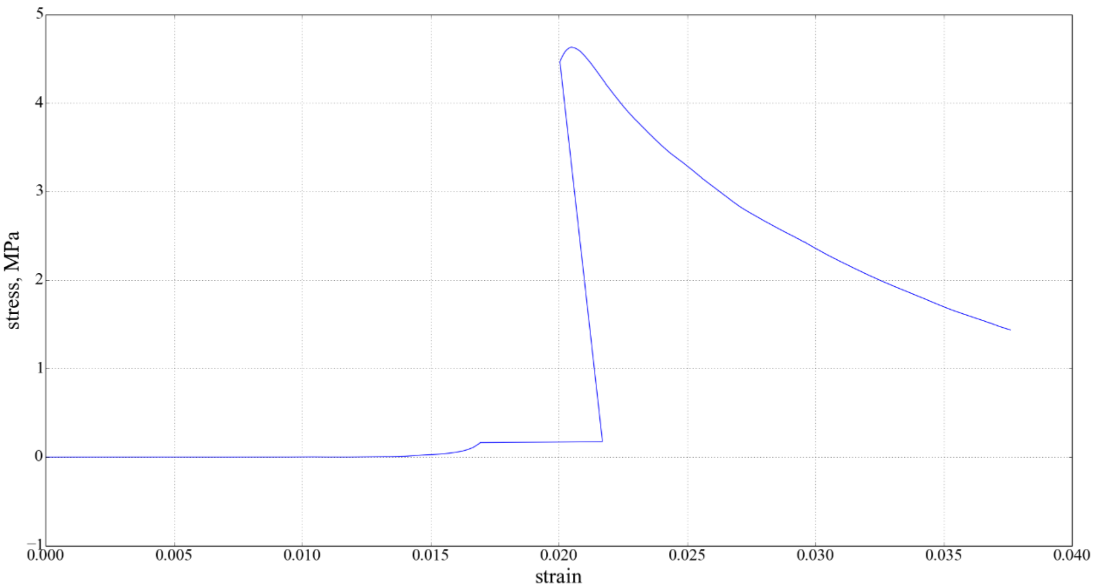


Figure 5.3.2a) - Stress vs strain for core 7.1 (20 - 56 cm)

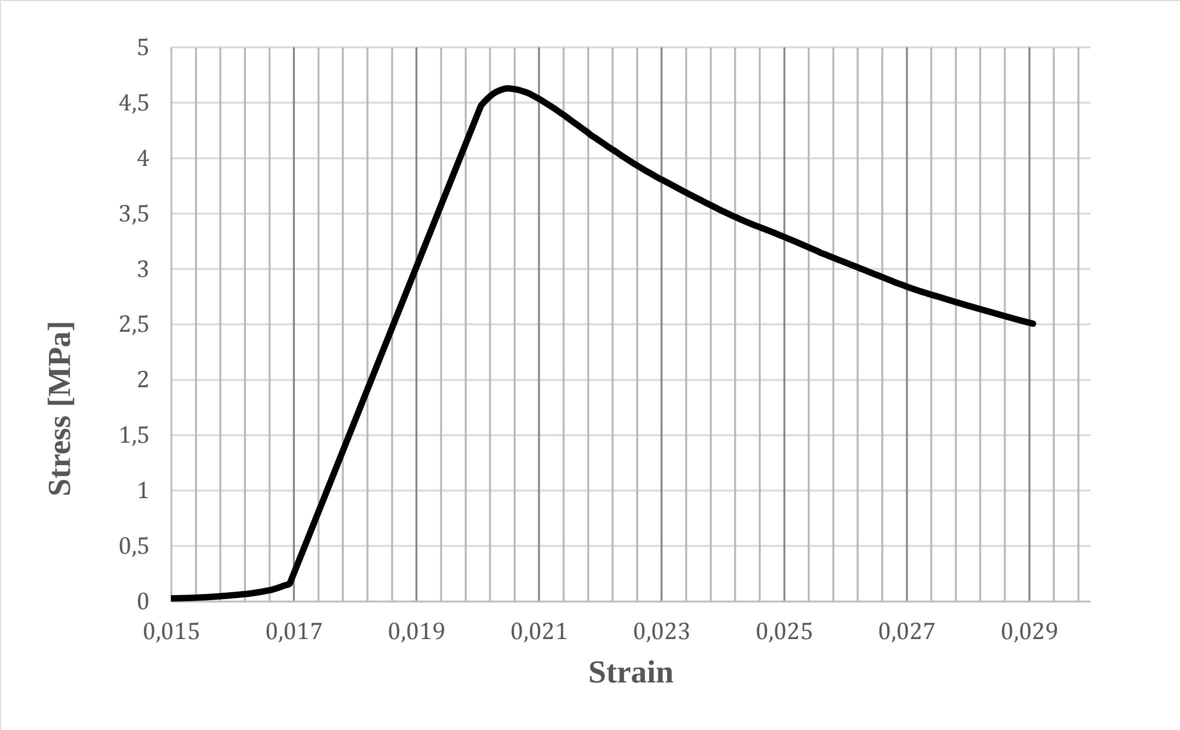


Figure 5.3.2 b) – Stress vs strain for core 7.1, with interpolated line, to calculate the E-modulus.

We can see that the results for core 7.1 (Figure 5.3.2a), is giving us some strange curve. This is probably because of some malfunction in the compression machine («knekkis»). We know that for core 7.1, there was a ductile deformation, and the curve should be smooth, as shown in the first part of figure 5.1.1. Since we know that the curve should have an inclination, it is possible to calculate the E-modulus, by taking two points were the inclination would be (Eq 5.1.3). We did this (Figure 5.3.2b), and obtained an E-modulus value. But this value would probably be larger, because we assumed a linear straight line that might be changing a bit in reality.

For core 7.2 we got a brittle deformation, which we can see clearly in figure 5.3.1. Up to the maximum strength of the ice, the stress increases, until it reaches failure and the stress decreases straight down.

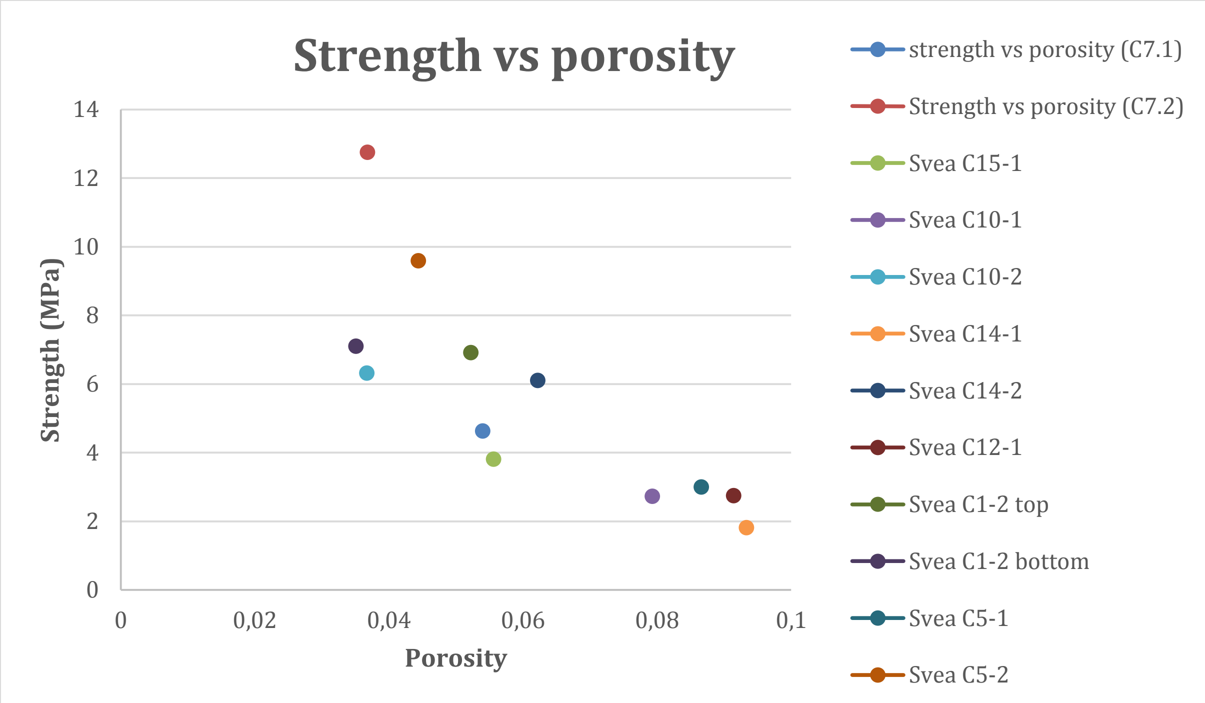


Figure 5.3.3 - Strength vs porosity for every core sample in Svea

As we can see in Figure 5.3.3, the strength of the ice increases with decreasing porosity. This makes sense, because more «free space» in the ice, means less compaction, and therefore less strength.

5.4 Discussion

The stress-strain curve shows brittle failure for core sample 7.2. For core sample 7.1, it should be ductile failure, but the data are inconclusive. For the ductile deformation, the curve should be smoothed out after reaching the highest strength. This test demonstrated that the ice has higher strength with lower salinity and lower porosity. We kept the strain rate equal for both of the tests. Therefore it shows that the bottom of the core (C7.2) has a higher strength than the upper part of the core (C7.1), due to the freezing process of ice. Water freezes fast at the top, leaving therefore more salt and air in the ice. Water freezes slower and slower, when more ice forms, and therefore the salt and air in the water «escapes» the ice more than on the top.

It is clear that the porosity plays a big role in the maximum strength of the Ice. Moslet executed several uniaxial compression tests from 2004 – 2005, and plotted the strength vs porosity for all the samples (Figure 29). In Figure 5.4.1, we have included our tests. Our results seem relatively good, compared to moslets distribution. We would however not rely to much on the result from core 7.1, since the data were inconclusive.

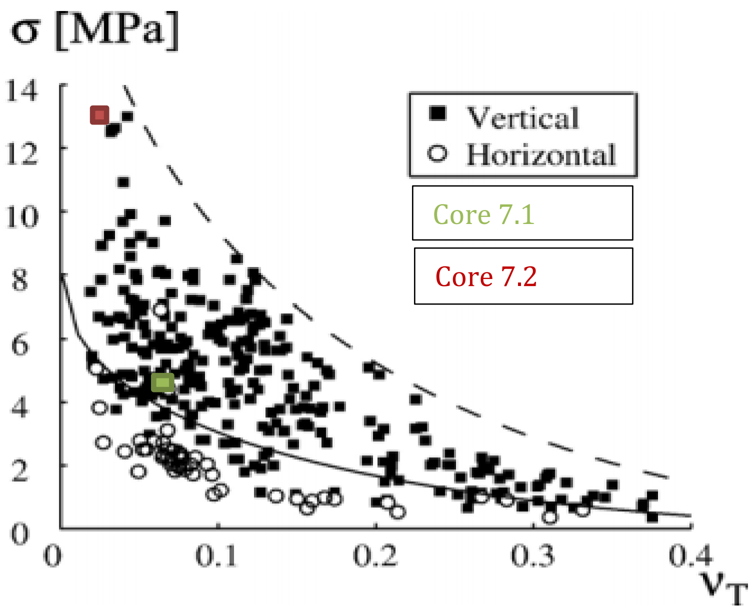


Figure 5.4.1 - Maximum strength vs total porosity. Tests are made by P.O. Moslet on Svalbard in 2006. Included Core sample 7.1 and 7.2 from tests taken 07.03.2015 at UNIS cold lab.

5.5 Conclusion

We have performed a uniaxial compression test on a vertical ice core sample taken from sea ice in Svea. We measured ice strength, deformation, physical properties, porosity, salinity and densities on the top and bottom of the ice core. Main results are as follows:

- Strength varied from 4,65 at the top, to 12,75 [MPa] at the bottom of the core.

- We observed ductile deformation at the top, and brittle deformation at the bottom.
- Salinity was higher at the top (5,78 ppt) than at the bottom (3,93 ppt)
- The densities was pretty similar, but the density is a bit higher at the bottom (917,1 kg/m^3) than at the top (913,7 kg/m^3).
- Porosity was higher in the top (5,4 %), than at the bottom (3,68 %).
- E-modulus was 1.38 GPa for the top of the core, and 5,18 GPa for the bottom.

Our results seem reasonable, because higher porosity and salinity at the top, decreases the strength of the ice, and also makes it more ductile. Lower porosity and salinity at the bottom, increases the strength of the ice, and also makes it more brittle.

6. Summary

To sum up, we have conducted four experiments in UNIS Cold Lab and obtained the following results.

During water cooling test there was convection all the way to freezing point at -2 C. After 5 hours of the experiment, ice started to form at the level of 1 cm below surface. The rest of liquid stayed at freezing point, which was slightly going down because of increasing of unfrozen water salinity. This happens due to the fact that salinity of ice is usually 2-4 times less than salinity of water it was frozen from.

Ice expansion test showed strain and temperature change near strain sensor within ice with time. The ice was contracting throughout the experiment, and the oscillations against the background contraction could also be observed. These oscillations occurred due to periodic temperature change in the Lab, which is connected to the work of cooling system. The period of oscillations was about 11 minutes.

Carrying out the thin section experiment we observed that the shape of grains increased with depth and ice is becoming more granular; the crystals with horizontal c-axis orientation tend to become larger as they are closer to the bottom of the sample.

The results of uniaxial compression test we got seem reasonable because higher porosity and salinity at the top of ice sample decreases the strength of the ice making it more ductile eventually. Lower porosity and salinity at the bottom of the sample increased the strength of the ice, and also made it more brittle.

7. References

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