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Comparison of physical and mechanical properties of coastal ice and level ice

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Physical and mechanical properties of coastal and level ice were compared. The study is based on the results from horizontal samples taken in March 2007 in Van Mijenfjorden, Svalbard, Norway. The samples were tested in compression and relaxation in a cold laboratory at the University Centre in Svalbard and thin sections were prepared. The results show that the physical properties of the ice are essentially monotone functions of the distance from the shore and that the differences between the ice closest to land and the level ice are important. The porosity varies with a factor 6 while the brine fraction varies with a factor 17. The Young modulus is correlated with the porosity while the residual stress is correlated with the brine content although both correlations are weak. The microscopic analysis shows that the coastal ice is granular while level ice is S2 in the surface and S3 lower down. The size of the grains in the level ice is comparable with the size of the samples, therefore it is important to check their direction when sampling.

1. Introduction

There is a growing interest for constructing coastal structures in ice-infested Arctic waters. Several oil and gas projects are under planning. They will require infrastructure on land. At the same time the reduction of the Arctic ice cover prolongs the shipping season and puts harbour investments on the agenda. Arctic structures must resist ice loads from thermal expansion and tide (Smirnov and Sukhorov, 1994; Nikitin et al., 1992). When the sea ice cover is continuous, the time scale of ice movements is such that the viscosity has an important influence on the maximum loads.

The coastal ice forms in a different way than the level ice and is in addition subjected to important tidal stress variations (Caline and Barrault, 2008). We may therefore expect the physical and mechanical properties of the ice at both locations to differ.

Ice samples were taken at several locations and depths in order to measure physical properties and perform mechanical tests. The main interest was to perform relaxation tests in order to compare the viscous properties of the ice. It was the first time a study based on relaxation tests was made at UNIS, the University Centre in Svalbard.

2. Proposed terminology

The *ice foot* is determined as the ice frozen to the shore when gradual freezing of sea water from tide and wave spray occurs early in the season. It is in effect a block of ice that is fixed to the ground and does not move with the tide (WMO, 1970). At a certain distance from shore the ice, which is unaffected by the shore, is called *level (floating) ice*. In between is a transition zone which Croasdale (1980) calls *active zone*. The active zone is composed of *coastal ice* which forms simultaneously with the sea ice and is subjected to tidal forces significant enough to create tidal cracks (Caline and Barrault, 2008).

3. Site and measurement

The coastal ice and the level ice were surveyed during the winter 2006-07 in the innermost bay of Van Mijenfjorden, Svalbard, Norway (Figure 1). On 14 and 21 March 2007, 6 horizontal ice cores were sampled in level ice at three different depths (H1=10 cm from the ice surface, H2=30 cm, H3=50 cm). On 19 April, 23 horizontal ice cores were sampled in four locations in the coastal ice nearby a breakwater along a profile aligned normal to the shore at 316° from North (Figure 1 c) and e)). All samples had a diameter of 70 mm. They were put in sealed plastic bags and transported to a -20°C storage room at UNIS. The time from sampling to storing was about 3-5 hours and the temperature was kept below the freezing point all the time during transport. The samples were stored from up to three weeks before testing. All samples were tested at -10°C.

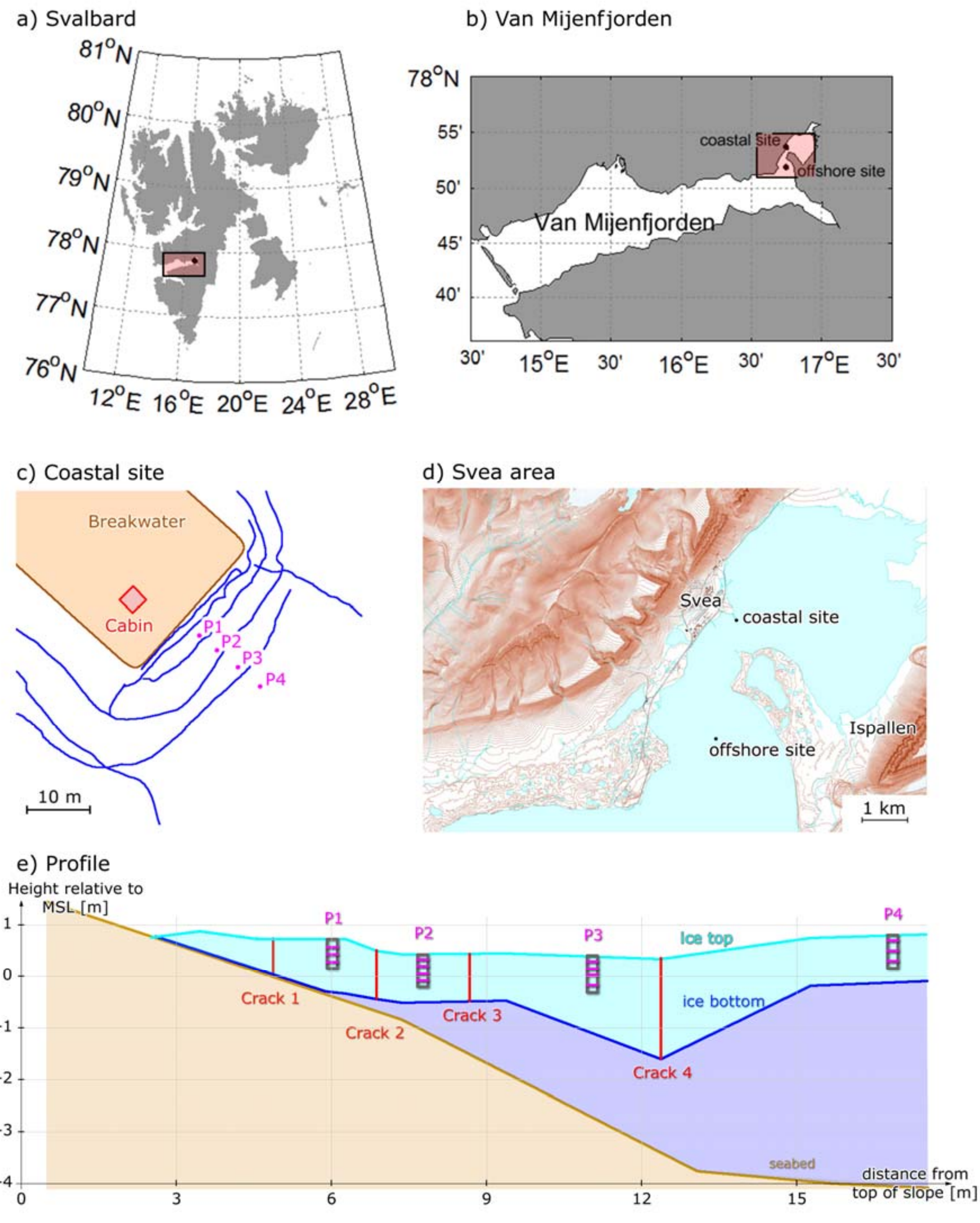

Figure 1. Map of the measurement site and profile in the innermost basin of Van Mijenfjorden

NTNU developed in 1996 a stationary uniaxial compression device, named Knekkis and installed at UNIS. The device can perform maximal strength, creep and relaxation tests. A piston moves upwards and a load cell placed in the upper part of the device records pressure. Data are recorded at a frequency of 0.5 Hz. The relaxation tests were performed by applying a start stress of 500 kPa and keeping the piston immobile for one hour. The compression tests were performed at a constant strain rate of 10^{-3} s^{-1}. For the level ice they were performed on the samples that had undergone relaxation tests. It was checked that the relaxation tests do not seem to affect the strength or the Young modulus of the samples. For the level ice the data is the average of two samples while for the coastal ice only one test was performed. Young's modulus was taken as the steepest slope of the stress-strain plot. After the tests the samples were melted to measure salinity. Porosity as a function of salinity, density and temperature were calculated from equations developed by Cox and Weeks (1982). Horizontal and vertical thin sections of all level ice samples and four coastal ice samples were made to analyze the ice texture.

4. Results

Formation of the coastal ice

From October to mid-December pancake ice accumulated onshore and consolidated into the ice foot. Below mean sea level the ground remained free of ice. In the end of December the sea was covered with ice which was connected to the shore. In the shore area the ice first moved up and down with the tide but by January it had grown thick enough that it stuck to the ice foot and to the sea bottom so much that it did not move with the same amplitude as the tide. On high tide it resulted in the flooding of the near-shore area and hence the formation of superimposed ice (Figure 2). The structure of the superimposed ice is different from that of the level ice as seen when comparing thin sections in Figures 3-6. The superimposed ice contains much smaller crystals and its porosity is one order of magnitude bigger. It is described as granular and contains more air bubbles. The ice with the lowest density looked more like a mixture of snow and ice. The ice grows faster the closer to the shore. The reasons are a greater heat transfer and the formation of superimposed ice. In the end of January, the ice thickness was 0.80 m at P1 and 0.50 m at P4. In the end of February it was 1.60 m and 0.60 m respectively. In the end of April it was 0.80 m at P4 and it reached 0.95 m in the middle of May.

Figure 2. Pond of surface water close to shore that refreezes on top the coastal ice

Formation of the level ice

Sea ice extended to the offshore site in early January. During a first visit on 14 February the ice was 0.52 m thick. 14 March it reached 0.66 m and a month later ice was 0.58 m thick. The thin sections from level ice H2 and H3 indicate a predominant alignment of the c-axis at an approximate angle of 45˚ (Figure 6). For the H1 cores the orientation of the c-axis is more random. The vertical thin sections from all three levels clearly show an elongation in the vertical direction. According to these observations the ice from level H1 is characterised as S2-ice, while ice from level H2 and H3 is characterised as S3-ice.

Figure 3. Vertical thin section of P1-H1

Figure 4. Horizontal thin section of P4-H3

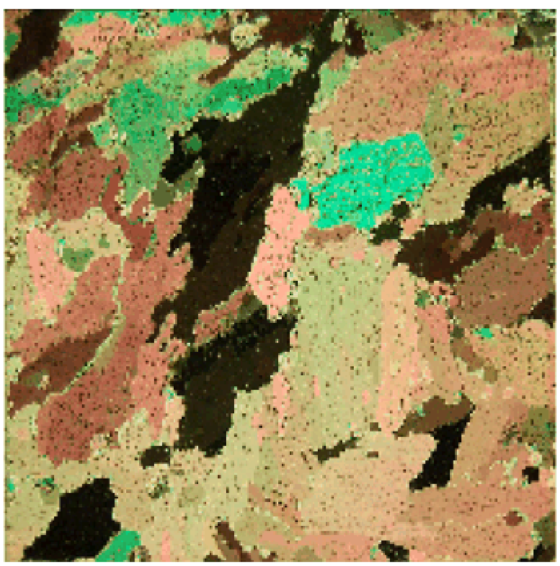

Figure 5. Horizontal thin section of P5-H1

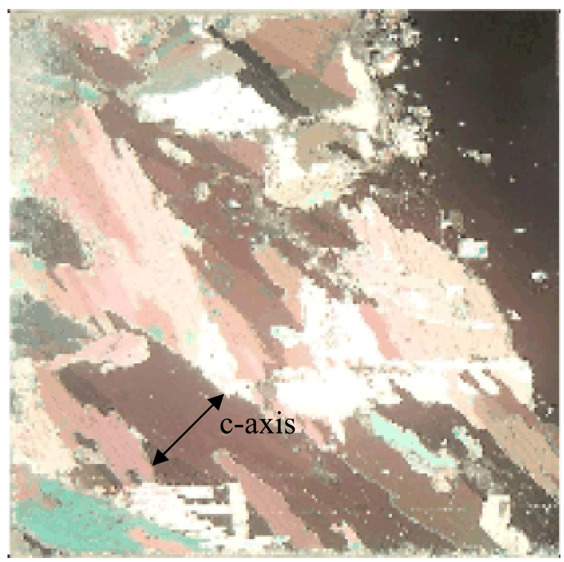

Figure 6. Horizontal thin section of P5-H3

N.B: The diameter of the circular sections and the width of the square sections is 70 mm (Figures 3-6).

Physical and mechanical properties

Table 1 summarises physical and mechanical results obtained in level and coastal ice. All data vary monotonously with the distance from shore. The porosity of coastal ice is decreasing from P1 to P4 and level ice (P5) is 6 times less porous than P1. Air fraction is decreasing as well. In P1 the air fraction is maximal with 99.4 % of the total porosity whereas it is 37 % in the level ice. The brine fraction is highest in the level ice. Ice has the lowest density in P1.

The Young modulus is somewhat higher in the level ice (up to 50% difference) while the residual stress is up to three times higher in the coastal ice than in the level ice.

The residual stress is the only analysed result kept from the relaxation tests. It was chosen not to study the relaxation function partly because it seems that it takes up to 30 minutes for its slope to stabilise after the initial loading and partly because ice is a non-linear visco-elasto-plastic material so no unique relaxation function exists.

Table 1. Comparison of physical and mechanical properties of the floating ice and the coastal ice

		Coastal ice				**Level ice**
Tested at -10 °C	**Depth**	**P1**	**P2**	**P3**	**P4**	**P5**
Residual stress [kPa]	H1 (10 cm)	170	162	156	156	103
(after one hour relaxation,	H2 (30 cm)	128	150	149	127	76
initial stress 500 kPa)	H3 (50 cm)	132	151	-	104	57
Strength [MPa]	H1	2.7	3.7	2.6	5.1	4.3
(strain rate = 10^{-3} s^{-1})	H2	3.2	3.0	4.2	4.3	4.1
	H3	3.0	4.3	5.2	6.0	3.3
Young's modulus [GPa].	H1	1.1	1.2	1.1	1.2	1.5
	H2	1.1	1.0	1.2	1.2	1.5
	H3	1.0	1.3	1.4	1.6	1.5
Salinity [psu]	H1	0.3	1.0	0.9	2.5	4.6
	H2	0.4	0.9	2.6	6.1	4.6
	H3	0.3	0.7	3.3	4.4	3.7
Density [kg/m^3]	H1	724	789	806	842	916
	H2	720	731	818	861	915
	H3	703	777	-	894	900
Brine fraction [%]	H1	0.13	0.47	0.44	1.26	2.53
	H2	0.17	0.40	1.28	3.15	2.53
	H3	0.13	0.33	-	2.36	2.00
Air fraction [%]	H1	21.2	14.2	12.3	8.6	0.8
	H2	21.6	20.5	11.2	7.0	0.9
	H3	23.5	15.5	-	3.2	2.5
Porosity [%]	H1	21.3	14.7	12.8	9.9	3.4
	H2	21.8	20.9	12.5	10.1	3.5
	H3	23.6	15.8	-	5.5	4.5

As shown in Table 2 ductile failures were observed in all samples except P3-H1 and P5-H3.

Table 2. Failure type of the different samples

	P1	**P2**	**P3**	**P4**	**P5 (level ice)**
H1	Ductile	Ductile	Brittle	Ductile	Ductile
H2	Ductile	Ductile	Ductile	Ductile	Ductile
H3	Ductile	Ductile	Ductile	Ductile	Brittle

5. Discussion

Ice texture analysis

The size and orientation of the crystals have an influence on the results from the mechanical tests. For samples P5-H2 and P5-H3, the crystal size is comparable with the sample size, and the inclination of 45° between loading direction and basal plane direction causes the maximum shear stresses to act along one single basal plane. When the strength of the basal plane is reached through a stress build up, the sample fails in a brittle way.

For samples where crystals have a predominant direction, Peyton (1966) showed that the strength will be lowest when this direction is 45° to the direction of compression while it reaches local maxima at 0° or 90°. It can be seen in Lainey and Tinawi (1984) (after Peyton, 1966 and Wang, 1979) that ice loaded in compression perpendicular or parallel to the c-axis is 2 to 3 times stronger than ice loaded at 45° to it. Since the direction is 45° in the samples analysed in this paper, higher strengths would have been obtained if the samples had been taken in any other directions.

In the coastal ice the size of the crystals compared to the diameter of the samples varies from very small (factor 100) to small (factor 10) as seen in Figures 3 and 4. The unequal grain size originates from the ice formation. Core P1-H1 represents ice formed by snow that gets soaked in sea water at high tide. At low tide the brine is drained, and this causes the ice to be low-saline and very porous. Core P4-H3 represents ice formed directly from sea water.

Residual stresses

In Figure 7 the residual stresses are plotted against the brine content. The two lowest residual stresses (stars) correspond to P5-H2 and P5-H3. As discussed above with strength, the residual stress values would have been expected higher if the samples had been taken with the predominant crystal orientation at 0° or 90° to the direction of compression. It was observed that the residual stress tends to decrease with the brine content, especially when P5-H2 and P5-H3 are not considered. This trend is in accordance with Cole (1997).

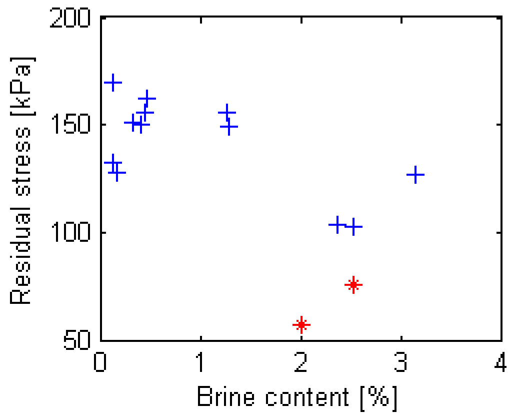

Figure 7. Residual stress vs. brine content

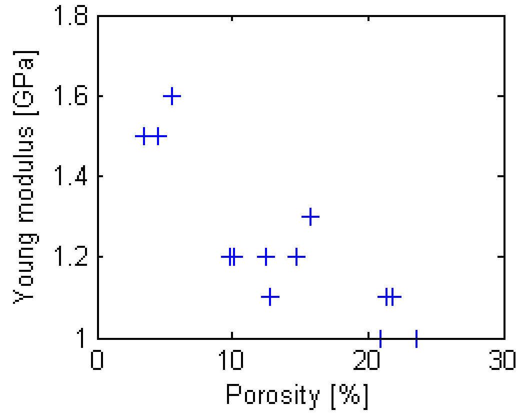

Figure 8. Young modulus vs. porosity

Young modulus

As seen in Figure 8, Young's modulus is decreasing with porosity in accordance with Moslet (2007) and Timco and Frederking (1990). The physical mechanism for elastic deformation is in fact strain of the atomic structure, which is denser the smaller the porosity.

Strength

In Figure 9 the data is split in 3 groups: level ice (star), P3-H1 (circle) and the rest of the coastal ice (cross). The reason why P3-H1 was plotted differently is that it is the only coastal ice sample which failed in a brittle way. It was taken as an indication that its structure is different from that of the other coastal ice samples where, based on the four thin sections, the crystal orientation is random. One good reason why the structure of the ice in P3-H1 would be different is that P3 is located in a place that remained flooded for a couple of weeks in the middle of March and the water froze completely undisturbed. The strengths of the level ice samples are a bit lower than the porosity alone would indicate but the large grains in the level ice reduce its strength (Lee and Schulson, 1986).

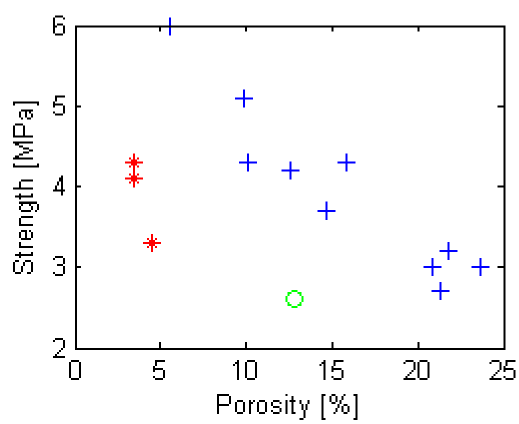

Figure 9. Strength vs. porosity

Mechanical response

Tidal fluctuations have a time constant of 6 hours therefore the ice behaves viscously and the maximum stresses are lower than for a pure elastic material.

Data quality
The margin of error is unknown because of the small number of samples (one per location in the coastal ice). However the strong geographical data dependence is coherent with on-site observations of ice formation and structure. In addition other samples were taken to perform creep and then strength tests and the results show a satisfactory consistency. The storage conditions varied to some extent and the effect of storage time is not well known. Finally note that the coastal ice cores were taken in the top 50 cm while the coastal ice is up to 1.6 m thick (P1). Therefore the results are not fully representative of the coastal ice.

6. Conclusion

Ice was sampled from the level ice and the coastal ice in Van Mijenfjorden on the West Coast of Svalbard, Norway and tests were done to investigate its physical and mechanical properties. The strength, the elastic and the viscous properties were examined by uniaxial compression tests. The strength tests were performed with a nominal strain rate of 10^{-3} s^{-1}. The relaxation tests were done by quickly applying a load of 500 kPa and then allowing the samples to relax. The elastic modulus was taken as the steepest slope of the stress-strain plot.

The level ice has higher density, salinity and brine fraction but lower air fraction and total porosity. It is also stiffer, but significantly more viscous than the coastal ice. The main results are as follows:

- Young's modulus is decreasing with the total porosity as one could expect from the well-known physical mechanism behind elastic deformation
- the strength is also decreasing with porosity but is in addition a function of grain size. The level ice is weaker than the coastal ice even though it is less porous because its grains are up to 100 times bigger.
- the residual stress depended on the brine volume however the orientation of the crystals in the level ice samples may exaggerate this trend in the presented data.

This means that the coastal ice is stronger than level ice when loaded slowly, as with tidal fluctuations, but weaker when loaded faster, as when the wind or a ship pushes the level ice towards the shore.

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