Compressive strength and structure of sea ice in the Weddell Sea, Antarctica

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Abstract

The field experiments on Antarctic sea ice physical properties were performed in the Weddell Sea during the Finnish Antarctic Expedition in 1989-1990. The examined ice included shorefast ice and pack ice floes. Altogether 61 ice cores were drilled from 12 test sites. The temperature, salinity and density distributions in the ice cores were measured. Ice thin sections were prepared and photographed through crossed polaroids to study the structural characteristics of Antarctic sea ice. The unconfined uniaxial compressive strength of ice was tested with 165 samples in the ambient temperatures of the examined ice floes. The tests were made in the brittle range with high strain rate both in-situ and in the cold laboratory container on board R/V Aranda. The sampling techniques and testing procedures are described. Typical profiles of ice salinity, density, temperature and uniaxial compressive strength in the ice floes are presented. The results of genetic and textural classification of ice samples are given. Ice unconfined uniaxial compressive strength versus ice total porosity is illustrated.

1 Introduction

Antarctic sea ice undergoes a large seasonal variation annually. The extent of the total sea ice cover in the Antarctic Ocean varies from the austral summer minimum of $3 \times 10^6 \text{ km}^2$ to the austral winter maximum of $20 \times 10^6 \text{ km}^2$ (Zwally et. al [10]). Most of Antarctic sea ice is drifting pack ice. At its peak extent in late winter fast sea ice covers roughly an area of $0.55 \times 10^6 \text{ km}^2$ (Panov & Fedotov [9]). The Weddell Sea is the main source of pack ice formation in Antarctica. It is estimated that the pack ice area affected by Weddell Sea processes is $8 - 10 \times 10^6 \text{ km}^2$ (Ackley [1]). Every year a polynya starts to open on the eastern coast of the Weddell Sea in November-December. It widens towards the west up to the mid February, when the ice cover is smallest. An unmelted ice massive remains over the austral summer in the southwestern part of the Weddell Sea on the coast of the Antarctic Peninsula. This ice mass drifts northwards by the influence of the Weddell Gyre.
In the austral summer from 8th December, 1989 to 27th February, 1990 Finland arranged the first large scientific expedition FINNARP-89 to Antarctica with a new research vessel, R/V Aranda (Mälkki et. al [8]). Fig. 1 presents the route of R/V Aranda in the Weddell Sea during the two voyages from South America to Antarctica.

The main targets of the sea ice research in the expedition involved collecting basic data on ice physical properties, ice strength, pack ice formations and ice mass balance in the Weddell Sea. This kind of ground data have been rather limited from the Antarctic Ocean ice zone. Especially the sea ice mechanical properties such as ice strength have been poorly known. The ground data are needed for basic geophysical investigations, remote sensing, development of sea ice mathematical models and ship ice navigation. This paper concentrates to the ice research made during the FINNARP-89 expedition by analysing ice cores.
drilled from the ice fields with a CRRELL-type ice coring auger (core diameter 10.5 cm). The examined ice properties were the unconfined uniaxial compressive strength, ice crystal structure, temperature, salinity and density. The properties were determined as vertical profiles in the studied ice floes. Three different type of ice cores were collected and analysed: salinity ice cores, texture ice cores and compressive strength ice cores. The basic idea in the compressive strength tests was to obtain the ice strength in the ambient temperatures of the ice floes.

The ice cores were collected altogether from 12 test sites. Fig. 1 illustrates the test site locations. In Table 1 are presented the positions of the test sites, date and ice field description. The principal research area was between the latitudes 70° 33' S - 73° 50' S and the longitudes 110° 42' W - 29° 06' W. The main part of the samples were collected in the pack ice zone of the eastern Weddell Sea. Two test sites located at the shorefast ice zone on the coastline of the Queen Maud Land and a couple samples were picked up in the western Weddell Sea. Most of the ice floes consisted of first year sea ice. The thickness of the thinnest rather level ice floe was 0.8 metres, whereas the thickness of the ridged floes exceeded 3.5 metres. A few samples were taken from multiyear floe and a growler of glacial ice. In the course of the expedition altogether 61 ice cores were collected giving 82 metres of ice core sample.

Table 1. The positions and general properties of the tested ice floes.

<table>
<thead>
<tr>
<th>SITE</th>
<th>DATE</th>
<th>LAT</th>
<th>LON</th>
<th>Ice floe type</th>
<th>Floe size [m x m]</th>
<th>Ice type</th>
<th>Thickness [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>24-26.12.89</td>
<td>72 23 S</td>
<td>16 19 W</td>
<td>Shorefast, level</td>
<td></td>
<td>Firstyear</td>
<td>1.3 - 1.5</td>
</tr>
<tr>
<td>S2</td>
<td>31.12.89</td>
<td>72 49 S</td>
<td>27 32 W</td>
<td>Pack ice</td>
<td>300 x 600</td>
<td>Firstyear</td>
<td>0.8</td>
</tr>
<tr>
<td>S3</td>
<td>1.1.90</td>
<td>72 32 S</td>
<td>28 46 W</td>
<td>Pack ice, ridged</td>
<td></td>
<td>Firstyear</td>
<td>&gt; 1.3</td>
</tr>
<tr>
<td>S4</td>
<td>1.1-2.1.90</td>
<td>72 51 S</td>
<td>28 33 W</td>
<td>Pack ice, ridged</td>
<td>2000 x 2000</td>
<td>Firstyear</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>S5</td>
<td>3.1.90</td>
<td>73 50 S</td>
<td>28 43 W</td>
<td>Pack ice</td>
<td>1000 x 1500</td>
<td>Firstyear</td>
<td>2</td>
</tr>
<tr>
<td>S6</td>
<td>4.1.90</td>
<td>72 26 S</td>
<td>16 29 W</td>
<td>Shorefast, ridged</td>
<td></td>
<td>Firstyear</td>
<td>3</td>
</tr>
<tr>
<td>S7</td>
<td>5.1.90</td>
<td>70 33 S</td>
<td>11 42 W</td>
<td>Pack ice</td>
<td>2000 x 3000</td>
<td>Firstyear</td>
<td>0.9 - 1.0</td>
</tr>
<tr>
<td>S8</td>
<td>18.1.90</td>
<td>64 28 S</td>
<td>51 56 W</td>
<td>Pack ice</td>
<td></td>
<td>Multiyear</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>8.2.90</td>
<td>72 01 S</td>
<td>28 22 W</td>
<td>Pack ice</td>
<td>30 x 30</td>
<td>Firstyear</td>
<td>1.2 - 1.4</td>
</tr>
<tr>
<td>S10</td>
<td>8.2.90</td>
<td>71 40 S</td>
<td>29 06 W</td>
<td>Pack ice, ridged</td>
<td>200 x 200</td>
<td>Firstyear</td>
<td>1.8 - 2.3</td>
</tr>
<tr>
<td>S11</td>
<td>9.2.90</td>
<td>71 42 S</td>
<td>29 02 W</td>
<td>Pack ice, ridged</td>
<td>150 x 150</td>
<td>Firstyear</td>
<td>2.3 - 3.5</td>
</tr>
<tr>
<td>S12</td>
<td>20.2.90</td>
<td>57 30 S</td>
<td>39 32 W</td>
<td>Drifting growler</td>
<td></td>
<td>Glacial</td>
<td></td>
</tr>
</tbody>
</table>

2 Sampling and analytical techniques

2.1 Ice temperature, salinity, density and uniaxial compressive strength measurements

The temperature profile of the ice cores was measured with FLUKE 50 k/j Thermometer in-situ immediately after the cores were lifted on the ice field. The distance between measurement points was 10 cm. The ice cores to be used to determine the salinity distribution were sawed to 10 cm thick pieces, put into plastic bags or boxes and transported to R/V Aranda. There they were melted and the salinities were measured by the Guildline Autosal 8400 salinometer.
The temperature profile of the ice cores which were used in the compressive strength tests was measured first in-situ. On the shorefast ice field the compressive strength was also tested in-situ. From the pack ice floes the ice cores were transported by helicopter to the ship, where the tests were performed in the cold laboratory container. The weights of the samples were measured before the test to determine the ice bulk density. Also the sample temperature was measured just before the compressive strength test in order to obtain the correlation to the ice field temperature. In addition, salinities of the tested compressive strength samples were analysed. The ice unconfined uniaxial compressive strength tests were made with a electro-hydraulic testing machine. The diameter of the cylindrical samples was 10,5 cm and sample lengths varied from 20 cm to 25 cm. The loading strain rate was in brittle range being approximately $10^{-3}$ 1/s. A total of 165 uniaxial compressive strength samples were tested during the FINNARP-89 expedition.

2.2 Ice structure characterization

The texture ice cores were cut to approximately 0,5 metres long pieces, packed in plastic bags, put in styrox boxes, and transported immediately to the freezers in the cold laboratory container on board R/V Aranda. There vertical thick sections were made with a band saw and further thin sections were prepared with a microtome. The rest of the samples were stored in the freezers and used later to prepare horizontal thin sections. Every thin section was photographed between crossed polaroids. Altogether 130 thin sections were examined.

The ice was classified by using the thin sections into two main classes: the genetic and the textural class. The genetic classes describe the oceanographic conditions when the ice was formed. The genetic classification consisted of frazil and congelation ice. The frazil ice is formed in upper part of water column by surface accumulation of frazil slush. The congelation ice is formed by congelation of seawater at the ice-water interface under stable conditions (tranquil congelation) resulting in formation of columnar ice texture or it is formed of seawater at the ice-water interface under unstable conditions (distributed congelation), resulting in formation of intermediate columnar/granular ice texture.

The textural class was recognised on the basis of the grain size and the shape of the brine inclusion, similar way as Eicken and Lange [3]. They divided samples into five distinct classes at the textural level: granular, columnar, intermediate columnar/granular, mixed columnar/granular and platelet ice. Further distinction was made between polygonal granular and orbicular granular ice. Eicken and Lange describe in [3] different ice textures in detail. In Fig. 2 can be seen examples of different basic textures (granular, intermediate columnar/granular, columnar, platelet) collected in the FINNARP-89 expedition.
Fig. 2a. Polygonal granular ice from the site S4.

Fig. 2b. Intermediate columnar/granular ice from the site S1.

Fig. 2c. Columnar ice from the site S7.

Fig. 2d. Platelet ice from the site S2.
3 Typical profiles of the examined sea ice properties

3.1 Shorefast ice field

In Fig. 3 are presented the vertical salinity and texture profiles in a level shorefast ice field. This sampling site S1 (72° 23' S, 16° 19' W) located few nautical miles from the continental ice shelf. The ice cores were drilled and tested there 24th-26th December, 1989. Ice field thickness was 130 cm - 151 cm having a snow cover of 22 cm - 27 cm. The minimum salinity 2.22 ppt (parts per thousand) was recorded close to the centre part of the core at 80-90 cm and the maximum salinity 7.25 ppt at the bottom of the core at 140-151 cm. The average salinity of the salinity core was 5.17 ppt. This shorefast ice field was composed mainly of gongelation ice. The texture ice core consisted 76.5 percent of gongelation ice and 23.5 percent of frazil ice. The top 21 cm of the ice core had orbicular and polygonal granular ice texture. Below this layer began 114 cm thick intermediate columnar/granular ice layer. At the bottom of the core there was 14 cm thick layer of platelet ice. From the depth 120 cm to the bottom there was a brown algae layer. Some ice crystals which thickness was 1-2 mm and diameter 20-40 mm were attached to the the bottom of the ice core. Similar loose ice crystals were found also in the coring holes. The thickness of this sub-ice platelet layer below the ice cover was 50-70 cm.

Fig. 3. The vertical profiles of ice salinity and texture in the shorefast ice field at the site S1.
The uniaxial compressive strength tests were performed on this shorefast ice field in-situ. The results of seven ice cores are presented in Fig. 4. The ice field temperature $T_f$ was $-3.0^\circ C$ in the surface layer and it increased rather linearly towards the bottom of the ice field to $-1.5^\circ C$. The testing temperature $T_t$ of the samples followed closely to the ice field temperature $T_f$. The average ice field temperature was $-2.3^\circ C$. The compressive strength sample salinities varied between 3.04 ppt and 7.74 ppt. The average ice density was 0.885 g/cm$^3$.

The maximum unconfined uniaxial compressive strength was 4.5 MPa. The compressive strength profile shows clearly a stronger layer in the centre part of the floe (= 70-90 cm). The microstructure of this strong layer was classified as intermediate columnar/granular. The average compressive strength of the tested samples, which describes the overall ice field strength, was 2.35 MPa.

![Fig. 4](image)

**Fig. 4.** The unconfined uniaxial compressive strength $S_c$, ice field temperature $T_f$, testing temperature $T_t$, salinity $S_a$ and density $\rho_o$ profiles by seven ice cores in the shorefast ice field at the site S1.

### 3.2 Pack ice floe

The sampling site S4 (72°51' S, 28°33' W) is introduced as an example of the examined pack ice floes. The measurements were made there 1st-2nd January, 1990. The floe included many pressure ridges which were formed of rafted ice sheets. The ice sheet thickness was 150 cm on the level part of the floe, but close to the pressure ridges the thickness of the floe exceeded five metres. There was great brine drainage in the top layer of the floe, where the minimum salinity was only 0.20 ppt. The maximum salinities were measured in the bottom part of the salinity ice core. The average salinity was 2.56 ppt. The texture ice core included granular, intermediate columnar/granular, mixed columnar/granular and columnar structures in thin layers altering each other. The contents of frazil and gongelation ice were correspondingly 45.1 % and 54.9 %.

The compressive strength, density and temperature profiles from the site S4 are illustrated by Fig. 5. The ice field temperatures were high through the examined
ice cores. In the surface layers temperatures were close 0.0 °C and the minimum temperature -1.6 °C was measured 90-110 cm below the surface. The average temperature was -0.9 °C. The minimum uniaxial unconfined compressive strength of 0.36 MPa was measured in the top layer. The maximum compressive strength 2.58 MPa was obtained in a sample 65-94 cm below the surface. The average uniaxial compressive strength of this pack ice floe was 1.35 MPa. The average density was 0.861 g/cm³. The ice floe was porous and clearly in melting condition. However, this pack ice floe was so thick that it did not not melt during the season. The installed Argos buoy in an other FINNARP-89 project (Launiainen & al. [7]) was operating on the floe still on the 3rd of September, 1991 which means that the ice floe survived at least one summer season after the expedition. So it became actually a multiyear ice floe.

![Graph](image_url)

**Fig. 5.** The uniaxial unconfined compressive strength $S_c$, ice field temperature $T_f$, testing temperature $T_t$, salinity $S_a$ and density $\rho_{oo}$ profiles by four ice cores in the pack ice field at test site S4.

### 3.3 A growler

On the 20th of February, 1990 a small freely drifting growler of glacial ice was picked up on board R/V Aranda by a grane. The dimensions of the growler were approximately 3 m x 3 m x 1 m. An interesting feature was that the temperature of the growler was very low despite the small size being from -5.1 °C to -3.8 °C inside. Altogether 13 compressive strength samples were prepared from the growler. The compressive strength varied between 1.2 MPa and 6.1 MPa and the average strength was 3.2 MPa. The densities of the measured samples were from 0.882 to 0.921 g/cm³.

### 4. Discussion of the results

#### 4.1 Ice internal structure

Genetically congelation ice was the dominant component in our ice cores. 62.1% of the total length of the texture ice cores was composed of congelation ice and 37.9% was frazil ice. The percentage of frazil was typically higher in the
heavily ridged ice floes compared to the more level floes. However, the frazil ice content exceeded the content of congelation ice only at two test sites. The content of congelation ice was clearly higher in the examined ice cores during FINNARP-89 expedition than the results from other expeditions in the Weddell Sea, presented in Table 2. The reason for the difference to the former expeditions may be explained by the spatial variation of different ice types. Intermediate columnar/granular ice was the dominant component in the crystal structure and 35.8% of the examined material was intermediate columnar/granular ice. 22.4% of the analysed ice had clear columnar structure.

Table 2. Observed sea ice growth during a number of expeditions into the Weddell Sea, Antarctica.

<table>
<thead>
<tr>
<th>Expedition</th>
<th>Observed Growth</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PolSea</td>
<td>57.4 frazil, %</td>
<td>Gow et al., 1987 [4]</td>
</tr>
<tr>
<td>WWSP-1</td>
<td>57.1 frazil, %</td>
<td>Lange et al., 1989 [5]</td>
</tr>
<tr>
<td>WWSP-2</td>
<td>51.7 frazil, %</td>
<td>Eiken and Lange, 1989 [3]</td>
</tr>
<tr>
<td>EPOS-I</td>
<td>63.8 frazil, %</td>
<td>Lange, 1989 [6]</td>
</tr>
<tr>
<td>FINNARP-89</td>
<td>37.9 frazil, %</td>
<td></td>
</tr>
</tbody>
</table>

PolSea = Polar Sea Expedition, WWSP = Winter Weddell Sea Project (Leg 1 and 2), EPOS-I = The European Polarstern Study (Leg 1)

Table 3. Frequency of textural classes in the sea ice samples from the Weddell Sea during FINNARP-89.

<table>
<thead>
<tr>
<th>Textural class</th>
<th>Frequency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granular</td>
<td></td>
</tr>
<tr>
<td>Polygonal</td>
<td>1.5</td>
</tr>
<tr>
<td>Orbicular</td>
<td>26.5</td>
</tr>
<tr>
<td>Intermediate c/g</td>
<td>35.8</td>
</tr>
<tr>
<td>Mixed c/g</td>
<td>9.1</td>
</tr>
<tr>
<td>Columnar</td>
<td>22.4</td>
</tr>
<tr>
<td>Platelet</td>
<td>4.7</td>
</tr>
</tbody>
</table>

4.2 Ice salinity, temperature and density
The salinity profiles were typical for the firstyear sea ice of the Weddell Sea. The salinity results were rather similar compared to those of Gow et al [4]. The average salinity was 3.9 ppt and the salinity range was from 0.2 ppt to 7.3 ppt in the actual salinity ice cores. In some ice cores rather great brine drainage was detected in the top layer. The ambient temperatures of the tested floes were high reflecting the midsummer conditions in the Weddell Sea. Three typical temperature distributions were obtained. In the shorefast level ice field close to the continental ice shelf the vertical temperature distribution was linear between the surface and the bottom. In the thin level ice fields rather constant temperature distributions were measured, where the temperature was close to the sea water temperature. In the thick pack ice floes the surface layer temperature was close to 0.0 °C. Typically the middle layer of these floes was coldest and the bottom layer temperature was close to the seawater temperature. The average density varied in general from 0.840 g/cm³ to 0.887 g/cm³. In a thin ice floe which was
clearly in melting condition, the average density was only 0.790 g/cm³. In the
growler the average density was 0.911 g/cm³.

4.3 Ice unconfined uniaxial compressive strength
The applied procedure to make the compressive strength tests immediately in the
ambient ice field temperatures is different from the previous compressive
strength tests for Antarctic sea ice (Urabe and Inoue, [11]). They stored ice
samples for a long time in a temperature of approximately -20 °C and tested
them after the expedition in different temperatures. An other difference was also
that Urabe and Inoue [11] examined only shorefast sea ice. During the
FINARP-89 compressive strength tests for shorefast ice were made in-situ.
The test temperatures of these samples were very close to the original ice field
temperatures. Also in the tests of pack ice floes the test temperatures were in
most of the cases close to the original field temperatures.

In general the measured strengths were rather low reflecting the midsummer
conditions, where temperatures of the floes are high and the ice structure is
porous. In the shorefast ice field the destruction of ice had not proceeded as far
as in the pack ice floes. The maximum unconfined uniaxial compressive
strengths of the shorefast ice and pack ice were correspondingly 4.50 MPa and
3.49 MPa. The highest uniaxial compressive strength of 6.09 MPa was
measured in the growler of glacial ice. In the tested pack ice floes no clear
difference could be noticed between the strength results measured in the
beginning of January compared to those measured in the beginning of February.

![Graph](image)

**Fig. 6.** The unconfined uniaxial compressive strength $S_c$ of the samples in pack
ice versus the ice total porosity $v_b+v_a$.

In Fig. 6 are presented the measured unconfined uniaxial compressive strengths
in the pack ice floes as a function of total porosity of the tested samples. The
porosity of ice is an important physical quantity in determining ice mechanical
properties. The porosity of sea ice contains both gas (\(v_a\)) and brine volumes (\(v_b\)). These are difficult to measure directly. Here the method of Cox and Weeks [2] has been applied in order to calculate the total porosities of the ice samples from measurements of salinity, temperature and density in the uniaxial compressive strength tests. In Fig. 6 can be seen that the uniaxial compressive strength decreases as the total porosity of the samples increases.

5. Concluding remarks

The paper concludes the results of the Antarctic sea ice physical properties research performed during the Finnish Antarctic Expedition 1989-1990. A lot of new field data were obtained on the original conditions of the ice floes in the Weddell Sea. The main success of this research was that Antarctic sea ice crystal structure and porosity analysis and ice strength measurements were integrated together.

Acknowledgements

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References


