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Antarctic sea ice properties on zero meridian side during Austral summers 2012-14 and 2018-19

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ABSTRACT

Polar Supply and Research Vessel S.A. Agulhas II has visited Antarctic continent annually since her maiden voyage 2012. Commonly, the voyage duration is from December to February or March. Aalto University and Stellenbosch University have been conducting ship and ice conditions related measurements with varying focus since the maiden voyage. The mechanical properties of sea ice (flexural and compressive strength) have been measured during voyages 2012-13, 2013-14, and 2014-15 while the focus in voyage 2018-19 was in physical properties, i.e. the salinity, density, temperature, and grain size of ice.

This paper presents the methods and results of these measurements to contribute to the relatively rare dataset of Antarctic sea ice properties. The mean flexural strength was around 280 kPa. The measured compressive strength of sea ice varied from 100 kPa to 3.0 MPa in the vertical direction, and from 100 kPa to 1.5 MPa in the horizontal direction, the averages being 740 kPa and 560 kPa, respectively. The shelf ice compressive strength varied generally from 100 kPa to 400 kPa with an average of 160 kPa. The measured ice temperature generally varies from air temperature on the top to -1.8 °C in the bottom. Ice salinity varies from around 1‰ to 8‰ and ice density is in the range from 830 to 940 kg/m^3.

KEY WORDS: Flexural Strength; Compressive Strength; Salinity; Density; Temperature; Antarctica; Sea Ice

INTRODUCTION

Due to the harsh ice conditions and dedicated focus on research exploitation only, the maritime transportation activities are rare in the vicinity of Antarctic ice shelf and on the drifting floe ice. Only few supply vessels annually visit Antarctic ice self to supply the research stations. Partly due to the low maritime activities and short access season, mechanical (flexural and compressive strength) and physical (salinity, density and temperature) ice property measurements on Antarctic sea ice are rare. However, these properties are important for ships designed for this region. Therefore, the full-scale measurement and results for these ice properties are needed.

Despite the measurements in Antarctic waters are rare, the measurements on saline sea ice has been conducted extensive in other seas and in laboratory in the past. Timco & O'Brien (1994) developed a formulation where the flexural strength can be determined from the porosity that can be calculated from the temperature and salinity as described by Frankenstein and Garner

(1967). A part of the utilized data was measured in Antarctic waters by Dykins (1968, 1971). Similarly, an effort to determine compressive strength of sea ice has been studied by several authors. However, according to the authors' knowledge, a similar formulation with validations by several authors has not been presented.

In order to provide additional information on the prevailing conditions, this paper presents the measured mechanical properties (flexural and compressive strength) from voyages 2012-2015, and physical properties (salinity, density, temperature) from voyage 2018-2019 on board S.A. Agulhas II during annual South African National Antarctic Expedition (SANAE) voyages. In addition, the measurement methods and more detailed description of the voyages are presented.

MEASUREMENT PROCEDURS AND METHODS

Sample Collection and Preparation

The samples for mechanical property measurements were collected from drifting ice floes, bay ice connected to the ice shelf, and ice shelf (only tested for compressive strength). In a case the samples were taken from a floe, larger floes were preferred to secure the safety of sample collection, i.e. the floe should be thick enough not to crack and large enough from diameter not to turn over easily. The scientists were lifted on the ice for sample collection from the ship with a crane of the ship.

Ice blocks were cut from the ice sheet with a chainsaw. After the ice blocks were cut out, the blocks were covered with snow and lifted on board together with the scientists. Once onboard the ship, the blocks were trimmed to the target dimensions for the mechanical property measurements. The measurement was conducted directly after the trimming. The aim of this procedure (cutting slightly extensive sample, covering the samples with snow, and testing it right after trimming) was to preserve the temperature of the sample as close to the condition on the field as possible for the testing.

A band saw was used for trimming the samples for the compressive strength of ice measurements. The compressive strength was measured both in the vertical and horizontal direction. The target dimensions of the samples were 0.1m*0.1m*0.15m (width*depth*height). After the sample was trimmed, the dimensions of the sample were measured, and the sample was weighed to determine the density of ice. After weighting, the sample was placed in a hydraulic clamp, where the sample was tested, see Figure 1. The sample was crushed with the clamp and the force was measured with a load sensor attached to the clamp above the sample. A metal plate was applied between the sample and load sensor to distribute the applied force evenly on the surface of the sample.

The ice beam for the bending strength of ice measurements was trimmed using the chainsaw. The target length of the beam was 1.2 meters and the target width and height were 0.15 m. After the beam was trimmed, it was placed in the steel frame. The beam was simply supported on both ends by the steel frame and was loaded downwards from the middle. The force needed to break the beam was measured with a load sensor, see Figure 1.

During the investigation of physical properties in voyage 2018-19, the ice samples were extracted from the ice field with a Covacs ice core drill. The temperature is measured immediately after ice coring on the ice field. The salinity, density and grain measurements are conducted onboard. All measurements were conducted from various depths of the extracted ice sample cores.

Determination of Properties

The compressive strength, σ_{Comp}, is determined by dividing the measured maximum force, F

[N], at the time of failure by the nominal cross-sectional area of the sample, A [m^2]:

$$\sigma_{Comp} = \frac{F + m_p g}{A} \tag{1}$$

Where m_p [kg] is the mass of the metal plate placed over the sample, and g [m/s^2] is the gravitational acceleration. In order to determine the flexural strength, the beam was assumed to behave as an Euler-Bernoulli beam. Assuming the first failure in a bending situation occurs on the surface in tension, the equations for flexural strength can be determined from:

$$\sigma_x = \frac{My}{I} \tag{2}$$

Where σ_x [Pa] is the axial stress, M [Nm] is the moment affecting the cross-section, y [m] is the distance from the neutral axis, and I [m^4] is the second moment of area. Inserting the moment equation in Equation (2), the flexural strength in 3-point bending (σ_{3Point}) is obtained from:

$$\sigma_{3Point} = \frac{3x}{bh^2}\left[F + \left(L_{sup} - x\right) g \rho_i bh\right] \tag{3}$$

Where L_{sup} [m] is the length of the span, x [m] is the distance from the support to the location where the ice failed, b [m] is the breadth of the beam, and h [m] is the height of the beam, and ρ_i [kg/m^3] is the density of ice.

Figure 1. Test setup for the bending strength (left) and compressive strength (right) of ice measurements (Suominen, et al., 2013).

Ice temperature along the ice core is directly measured by a thermometer (DLTOHM-HD2307-0) when inserting the probe into the ice cores through a hole drilled by a 3 mm diameter drill head at different depth. Ice salinity is measured from the melted ice samples with a salinity meter.

On voyages 2012-15, the density of ice was determined by measuring the dimensions of the samples (height h [m], breadth b [m], and depth d [m]) in order to determine the volume of the sample V [m^3]. After the volume was measured, the weight of the sample m [kg] was measured with a scale and the density determined with formula:

$$\rho_i = \frac{m}{hbd} \tag{4}$$

On voyage 2018-19, the density of ice was determined by following the ITTC Guidelines (ITTC, 2014). The procedure is that firstly tap water is poured in a measuring cup and the weight is recorded as w_1. Then, one ice piece cut from the ice cores is placed in the cup and the second weight is recorded as w_2. Lastly, the ice sample is submerged, and the third weight is recorded as w_3. The ice density can be calculated with the formula:

$$\frac{\rho_i}{\rho_w} = \frac{w_2 - w_1}{w_3 - w_1} \quad (5)$$

where ρ_w [kg/m3] is the density of water, assumed to be 1000 [kg/m3].

The grain structure of ice was investigated from horizontal and vertical thin sections of ice. An ice core is cut horizontally into thin pieces by band saw at different depths. These ice sections are referred as horizontal thin sections. In addition, ice pieces cut from the middle of the ice core vertically are referred as vertical thin sections. The thin sections are then placed in-between two crossed polarizers on a light table with rulers to observe the structure of ice and grain sizes.

DESCRIPTION OF VOYAGES AND MEASUREMENT LOCATIONS

General Description of Voyages

SANAE voyage commonly departures from Cape Town late November or early December. The voyage can be coarsely divided into three sections: 1) voyage to Antarctic ice shelf along zero Meridian (reached around mid-December), 2) voyage from Antarctic ice shelf to South Georgia and the South Sandwich Islands and back (early to late January), 3) return voyage from Antarctica to Cape Town along zero Meridian (start early February), see Figure 2. The expedition commonly returns Cape Town late February or early March. The voyage 2018-19 was an exception as the ship visited the Weddell Sea after reaching the Antarctic continent.

The time between the sections is used for logistic operations (cargo on- and off-loading, and personnel transportation between the research station and the ship). During this time, the ship operates next to the ice shelf between Penguin Bukta (the closest point to the South African Antarctic research station SANAE IV) and Neumayer III (the German research station), see Figure 2.

As voyages are conducted during the summer season, the sea ice extent diminished greatly during the voyage as the majority of the thinner first-year ice melts and only the thicker multi-year ice remains. On the voyage to Antarctica on December (voyage section 1), the ship encounters the first ice around 60^{O} Latitude. When the return voyage is started in early February, the ice exists only close to the Antarctic shelf and open water conditions start close after 70^{O} Latitude. More detailed description of ice conditions during voyages 2012-2015 are given by Lensu et al. (2015) and Suominen et al. (2017), and for the voyage 2018-19 by Kujala et al. (2019), Bekker et al. (2019) and Lu et al. (2019).

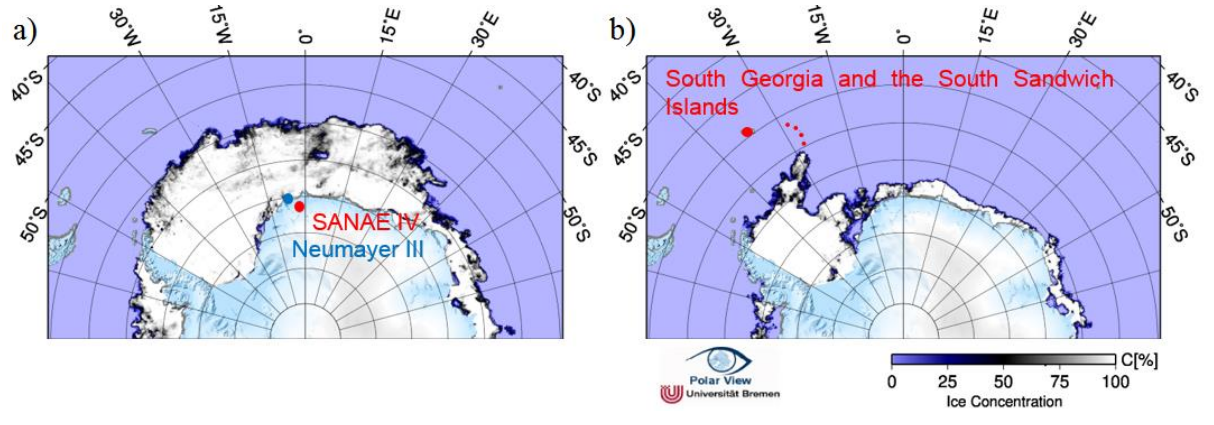

Figure 2. The sea-ice extent in Antarctica on (a) December 6, 2013, and (b) February 2, 2014. Pictures reproduced from Suominen et al. (2015), ice maps produced by Spreen et al. (2008).

Measurement Locations

The samples for flexural and compressive strength measurements were taken from the sea ice and on the shelf ice. The thickness of the sea ice in the locations from which the samples were taken during December was commonly over one meter. Therefore, the blade of the chainsaw was not long enough to cut through the total ice thickness and the ice blocks were cut from the top part of the sea ice. The samples were in many cases porous which decreases the strength of ice. The description of ice conditions on sample extraction locations for flexural and compressive strength are given below:

Dec 15, 2012 - 69º06'S, 00º13'W: The samples were taken from an ice piece, which the ship had broken from the ice field and lifted on top of the ice floe. Thickness was 96 cm.

Dec 17, 2012 - 70º05'S, 05º10'W: The sample was taken from the ice floe whose thickness was approximately 1 m. The ice was "snow ice" as its salinity was close to zero.

Dec 20, 2012 - 70º30'S, 08º11'W: The samples were taken from the bay ice next to Neumayer III. The ice was porous and had big air pockets. Snow thickness was 30-40 cm and ice thickness approximately 1 m.

Dec 21, 2012 - 70º30'S, 08º11'W: The samples were taken on top of the ice shelf near Neumayer III. A hole was dug with the chainsaw, drill and shovels to get the samples from a deeper layer. Samples taken from depths 65-127 cm.

Dec 30, 2012 - 70º24'S, 03º27'W: The samples were taken from the bay ice. The ice thickness was over 1.3 m. The ice was really porous having big air pockets.

Jan 29, 2013 - 70º33'S, 07º54'W: The samples were taken from the bay ice near Neumayer III. The ice had frozen during the season as the iceberg had blocked the bay and ice was able to form in calm conditions. The ice was real level ice (smooth, flat and no ridges). Ice thickness was 0.65 m. The surface and bottom layers were harder ice, but the middle part was weaker snow ice.

Jan 31, 2013 - 70º31'S, 07º59'W: The samples were taken from the same location as on Jan 29. The ice thickness was 50 cm. On the surface there was approximately 15 cm layer of hard ice and below this surface the ice had rotted having significant holes in it.

Dec 26, 2013 - 70º09'S, 04º51'W: These measurements were done at the Penguin Bukta from the bay ice close to the ice shelf. Ice thickness was 1.5 m and snow thickness 0.5 m. Ice had a large porosity.

Jan 25, 2014 - 70º01'S, 02º23'W: These measurements were done on flat ice cover close to Penguin Bukta, ice thickness 1.75 m, snow 0.2 m.

Jan 29, 2014 - 70º32'S, 08º10'W: These measurements were done on the snow part of the flat ice cover close to Neumayer III. Ice thickness was 160 cm snow 90 cm.

Jan 30, 2014 - 70º30'S, 08º11'W: The samples were taken on top of the ice shelf near Neumayer III. A hole was dug with the chainsaw. Samples taken from top layer.

Dec 19, 2014 - 70º32'S, 08º10'W: The samples were taken from the bay ice near Neumayer III. The total ice thickness on the site was over two meters. The samples for the bending and compressive strength tests were taken from depths 25 - 90 cm.

The measurements during voyage 2018-19 focused on physical properties of ice, i.e. salinity, temperature, density and grain size. A brief description of the locations is given in the following chapter and in Table 5.

RESULTS

Mechanical Properties: Flexural and Compressive Strength

Table 1 presents the measured flexural strengths. The measured flexural strengths varied from 130 kPa to 510 kPa. The general trend in flexural strength follows the seasonal ice coverage. The flexural strength decreases during the December reaching the minimum on January. Towards the end of the January to early February, the temperatures begin to decrease and the strength of the top layer of ice increases. It is notified that bottom of ice is still porous and strength measurements from bottom layers were not possible.

The measured compressive strengths in vertical and horizontal direction of sea ice and shelf ice are presented in Figure 3 and Figure 4, respectively. The corresponding statistical parameters are presented in Table 2 to Table 4. As can be noted from Figure 3 and Figure 4, the compressive strength of ice has a clear increasing trend as a function of density. It is notified that in this case density gives an indication of porosity due to the measurement method. The density of ice was determined based on Equation (4). In this case, the method allows the water inside the sample to drain out. In a case of porous snow ice, this enables large air pockets inside the sample as the drain channels may extend through thickness. In a case the sample would be solid ice, the density would be approximately 900 kg/m3. Thus, a measured density of 600 kg/m3 indicates that 66% of the volume is ice and the rest is voids.

Table 1. Measured flexural strengths.

	Dec 15, 2012	Dec 17, 2012	Dec 20, 2012	Dec 30, 2012	Jan 29, 2013	Jan 31, 2013	Dec 26, 2013	Jan 25, 2014	Dec 19, 2014
Samples	2	1	2	1	2	2	2	3	2
Mean [MPa]	274	254	249	135	339	481	150	236	385
St.dev. [MPa]	57	NA	64	NA	72	45	31	77	19
Min [MPa]	233	254	204	135	288	449	128	150	366
Max [MPa]	314	254	295	135	390	513	172	337	405
Density [kg/m3]	889	800	877	727	835	870	825	777	883
Salinity [‰]	-	-	-	-	-	-	2.4	7.4	4.8
Temperature [°C]	-	-	-	-	-	-	-1.3	-0.4	-2.5

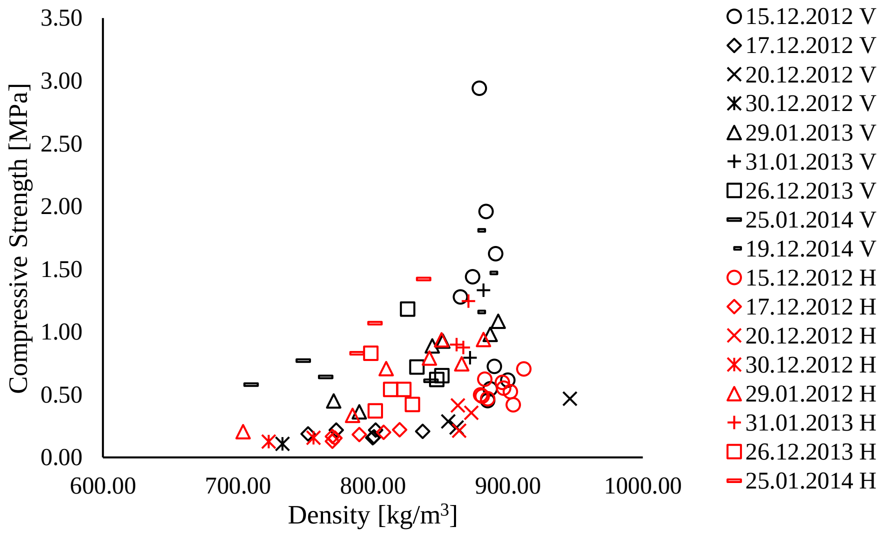

Figure 3. Compressive strength of sea ice as a function of density. V denotes vertical direction and H horizontal direction.

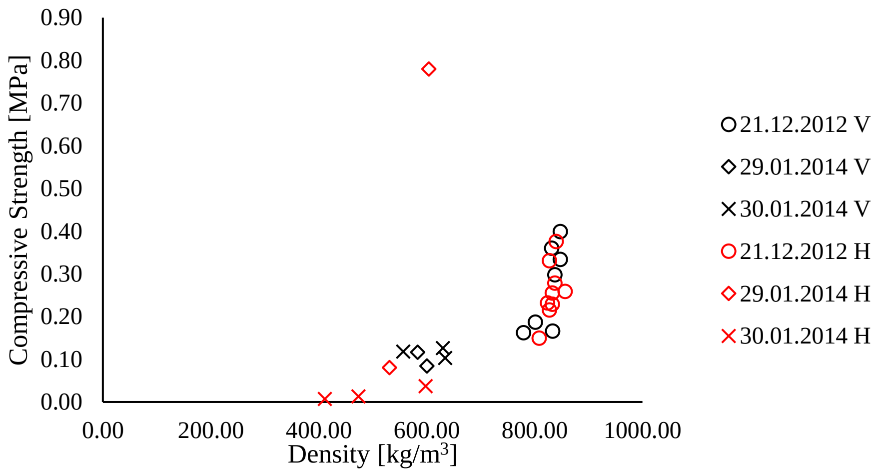

Figure 4. Compressive strength of shelf ice as a function of density. V denotes vertical direction and H horizontal direction.

Table 2. Measured compressive strengths of sea ice in the vertical direction.

	Dec 15, 2012	Dec 17, 2012	Dec 20, 2012	Dec 30, 2012	Jan 29, 2013	Jan 31, 2013	Dec 26, 2013	Jan 25, 2014	Dec 19, 2014
Samples	9	6	3	1	6	2	4	4	3
Mean [MPa]	1.29	0.19	0.33	0.11	0.78	1.06	0.79	0.65	1.48
St.dev. [MPa]	0.82	0.03	0.12	NA	0.3	0.38	0.15	0.05	0.27
Min [MPa]	0.45	0.16	0.24	0.11	0.36	0.79	0.62	0.58	1.16
Max [MPa]	2.94	0.22	0.47	0.11	1.08	1.33	1.18	0.77	1.81
Density [kg/m^3]	884	794	888	733	839	877	839	767	881
Salinity [‰]	-	-	-	-	-	-	2.6	7.4	4.81
Temperature [^{o}C]	-	-	-	-	-	-	-0.6	-0.6	-2.5

Table 3. Measured compressive strengths of sea ice in the horizontal direction.

	Dec 15, 2012	Dec 17, 2012	Dec 20, 2012	Dec 30, 2012	Jan 29, 2013	Jan 31, 2013	Dec 26, 2013	Jan 25, 2014
Samples	9	6	3	2	7	3	5	3
Mean [MPa]	0.54	0.17	0.33	0.14	0.67	1.01	0.54	1.11
St.dev. [MPa]	0.09	0.03	0.1	0.02	0.29	0.21	0.09	0.21
Min [MPa]	0.42	0.13	0.21	0.13	0.2	0.88	0.37	0.83
Max [MPa]	0.7	0.22	0.41	0.16	0.94	1.25	0.83	1.42
Density [kg/m^3]	893	788	867	739	820	867	813	809
Salinity [‰]	-	-	-	-	-	-	2.6	7.4
Temperature [^{o}C]	-	-	-	-	-	-	-0.7	-0.6

Table 4. Measured compressive strengths of shelf ice in the vertical (V) and horizontal (H) direction.

	Dec 21, 2012		Jan 29, 2014		Jan 30, 2014	
	V	H	V	H	V	H
Samples	8	9	2	2	3	3
Mean [MPa]	0.27	0.26	0.1	0.16	0.12	0.02
St.dev. [MPa]	0.09	0.06	0.02	0.11	0.01	0.01
Min [MPa]	0.16	0.15	0.08	0.08	0.13	0.01
Max [MPa]	0.4	0.38	0.12	0.24	0.1	0.04
Density [kg/m^3]	826	832	592	567	607	494
Salinity [‰]	0	0	0	0	0	0
Temperature [^{o}C]	-	-	-0.3	-0.3	-0.4	-0.4

Physical Properties: Ice Temperature, Salinity, Density and Grain Size

Table 5 summarizes measured range of temperature, salinity, density and mean grain size in each horizontal section from different locations. It covers period from December to February and wide range in both longitude and latitude. The ice thickness varies from 60 to 521 cm. Detailed results of these physical properties from different locations along the ice thickness are synchronized in Table 5. With the increase of ice dept, the temperature of ice converges to around -1.8 ^{o}C, which is roughly the freezing temperature of sea water. The temperature from the top part is influence by the air temperature which makes the temperature starts from different values in different locations. 'C' type ice temperature is also observed, e.g. in L2. Salinity of ice is in the relatively wide range from 1 ‰ to 8 ‰, and there is no obvious trend is observed. Similarly, in density of ice, no clear changing trend of density can be concluded. The density varies from 830 to 940 kg/m^3. A growing trend of mean grain size in each horizontal section along the ice thickness can be found, from around 3 to 20 mm from investigations in L1 and L2.

Table 5. Physical property results from different locations

Time (UTC)	Location	L	Activity	N	H (cm)	T (°C)	S (‰)	D (kg/m^3)	MGS (mm)
2018.12.21 13:30	70°09.800'S, 2°07.083'W	L1	Ice coring	2	60	(-3.1) – (-2.9)	4.5-6.1	870-923	3-15
2019.1.1 14:36	70°10.333'S, 2°07.817'W	L2	Ice coring	3	153	(-2.7) – (-1.8)	4.3-5.8	892-921	3-20
2019.1.16 22:00	65°49.512'S, 60°49.440'W	L3	Ice coring	1	521	0 – (-1.7)	0.7-7.8	833-939	-
2019.2.14 10:00	69°02.677'S, 50°10.024'W	L4	Ice coring	7	83-127	(-1.3) – (-1.7)	2.6-7.4	894-911	-

Note: L-abbreviation of location (applied also in Figure 5), N-number of samples, H-thickness, T-temperature, S-salinity, D-density, MGS-mean grain size.

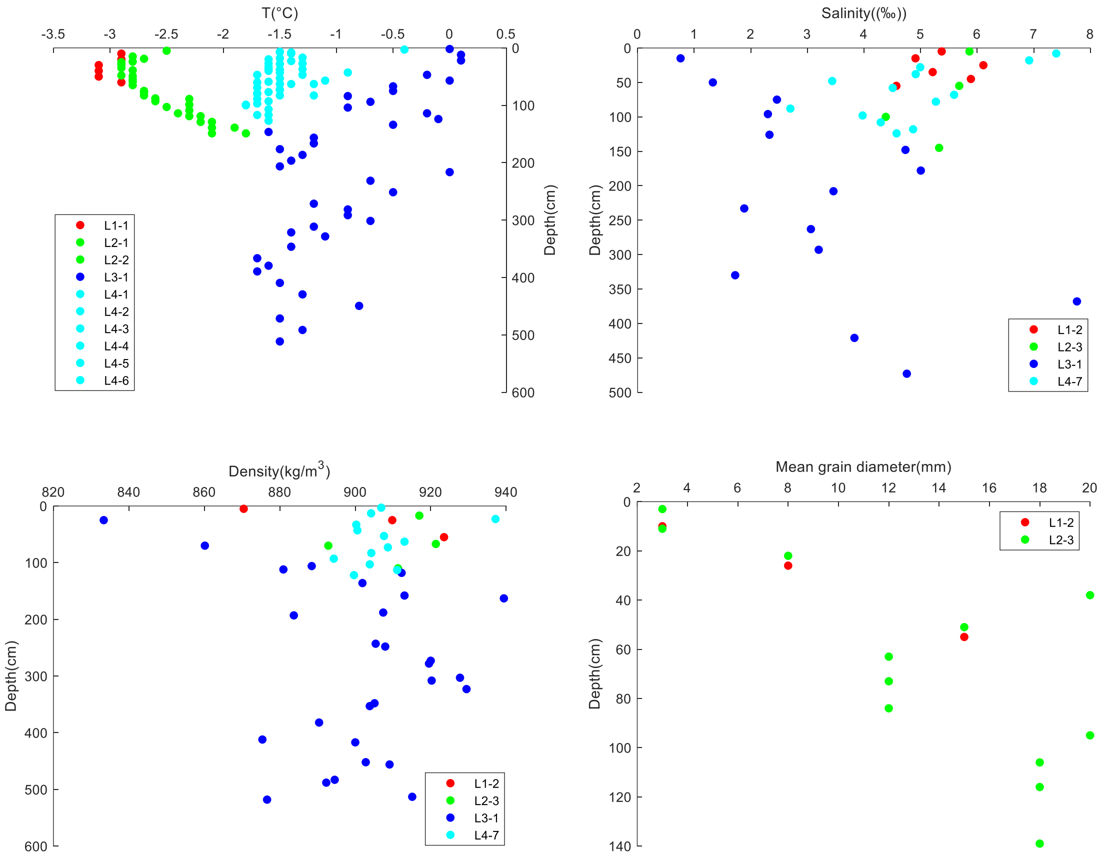

Figure 5. Distributions of physical properties along depth (ice thickness).

CONCLUSIONS AND DISCUSSIONS

The study presented the measured mechanical and physical properties of sea and shelf ice. The measurements show that the flexural strength of the sea ice is relatively weak during the summer season ranging from 130 kPa to 510 kPa with a mean value around 280 kPa. This is somewhat expected as the ice is in melting stage during the summer season and the Antarctic waters are known for high salinity. However, the number of samples is small and should be verified with additional measurements.

The measured compressive strength of sea ice varied from 100 kPa to 3.0 MPa in the vertical direction, and from 100 kPa to 1.5 MPa in the horizontal direction, the averages being 740 kPa and 560 kPa, respectively. The shelf ice compressive strength varied generally from 100 kPa to 400 kPa with an average of 160 kPa.

The measured ice temperature generally varies from air temperature on the top to -1.8 °C in the bottom. Ice salinity varies from around 1‰ to 8‰ and ice density is in the range from 830 to 940 kg/m^3. Uncertainties from both the measurement and equipment are not fully taken into consideration, which should be noticed.

The samples were mainly taken from the surface layer of sea ice. This was due to the limitation in cutting length. In the future, it would be beneficial to utilize chain saws with extraordinary dimensions.

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