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Field Tests of Ice Compressive Strength Using Thermally Balanced Samples

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The compressive strength of sea ice is one of the primary mechanical ice properties. This parameter can be found by tests on small (10 to 20 cm) samples picked from different layers across the ice sheet thickness as well as full-scale tests where the compressive ice strength is referred to the full ice thickness. Full-scale tests with loading of floating ice across its full thickness are preferable for compressive ice strength evaluations but involve more technical challenges in the field compared to tests on small-scale samples. However the relationship between the ice compressive strength values obtained by small- and full-scale tests is not yet sufficiently understood and needs further investigations. Sea ice has inhomogeneous structure, temperature and brine content across its thickness. The problem with strength evaluation procedures based on small samples picked from different horizontal layers of ice is that these samples fail to keep the layer-specific temperature of ice. This paper describes a special-purpose experimental technology that has enabled researchers to maintain the temperature of small-scale ice samples as close as possible to the original temperature up to compressive ice strength tests. These tests provided compressive strength distribution curves across ice thickness, and thus obtained average integral values of ice compressive strength are compared with the data from full-scale tests.

1. Introduction

Ice compressive strength is to be obtained to assess ice loads on offshore structures when a failure due to compression is the primary type thereof failure. One of two below methods is generally used for direct estimation of ice compressive strength in-situ:

- uniaxial compressive strength test on ice specimen afloat over the whole ice thickness in horizontal direction (full-scale tests);
- evaluation of ice strength based on uniaxial compression tests of small samples drilled off various horizontal ice layers (small-scale tests).

Indirect evaluation methods for full-thickness ice compressive strength are based on the below tests:

- Indentation tests of vertical cylinder into ice sheet (Karulina et al., 2013);
- loading of beam with two fixed ends with horizontal force applied mid-length (Marchenko et al., 2015).

Compression tests of ice sample over the whole ice thickness are labor-intensive and need powerful equipment. Application of small samples taken from various horizontal ice layers for the experiments makes the task technically easier. Alongside with that other issues are here:

- how can we maintain temperature and salinity of samples obtained from different layers up to uniaxial compression tests?
- what is the coincidence accuracy between ice compressive strength obtained with small samples and values thereof derived during direct measurements of strength over the whole ice thickness?

As well as other ice characteristics ice compressive strength depends on a number of factors: ice temperature, salinity, porosity, strain rate, etc. The inhomogeneity of these parameters over the ice thickness causes a corresponding change in ice compressive strength through the thickness.

The above dictated main purposes of this study:

1) development and implementation of compression test procedure for small samples ensuring maintenance of temperature and salinity of ice layers they are taken from;
2) experimental study of the ice compressive strength distribution over the ice thickness;
3) comparison of full-thickness ice compressive strength obtained from the tests with small samples and one from the full-scale tests.

This paper describes the offered procedure for uniaxial compressive strength test on small ice samples in-situ ensuring maintenance of samples' temperature as close as possible to the temperature of relevant horizontal layer they were taken from. The experiments were carried out on fast sea ice of Van Mijen fjord, Svalbard, Norway, in March 2019 and 2020. Small samples' strength averaged over ice thickness was compared with direct measurement results for ice strength over the whole ice thickness. The results of the performed tests revealed the discrepancy in ice compressive strength obtained with two above-mentioned methods. It's safe to assume that one of the reasons thereof is the effect of the sample dimensions in the full-scale tests.

2. Background

The necessity to convert from strength values obtained in small-scale tests to ice strength over the whole thickness is primarily dictated by inclusion of this parameter into computational formulae to assess ice loads on vertical structures; secondly, this parameter is to be specified for simulation in case model tests in ice basin are carried out. For objective reasons, measurement methods for compressive strength of model ice offered in ISO 19906 (2019) do not include compression tests on small samples.

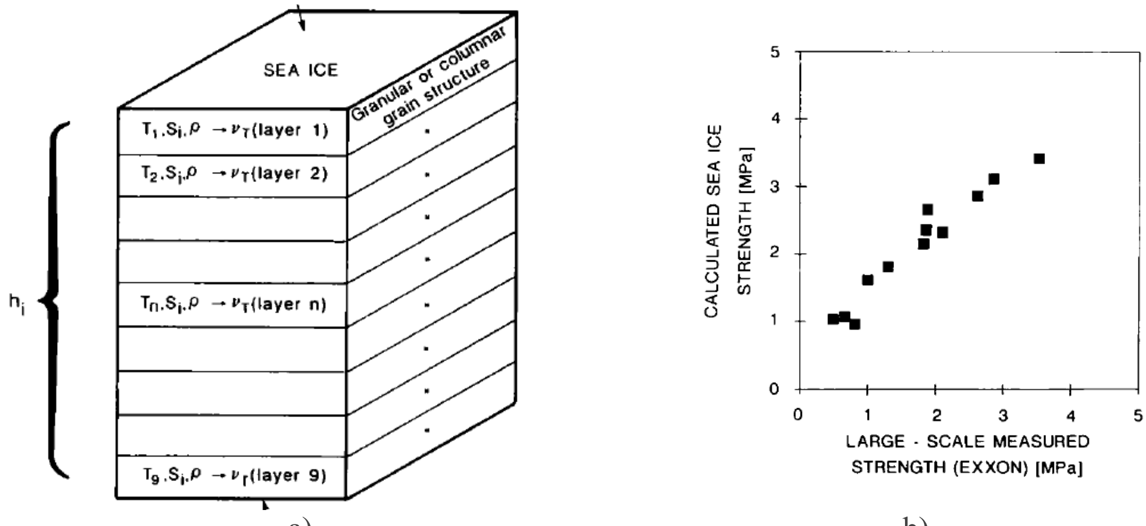
In passing to ice full-thickness compressive strength the results of small-scale tests may be used in a number of ways. As consistent with Russian regulatory document SP 38.13330 (2018) root-mean-square value of ice compressive strength taken from various ice layers shall be defined to assess ice compressive strength using formula:

$$\sigma_c = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\sigma_{c\_i}\right)^2\right]^{1/2} \quad \textbf{[1]}$$

where σ_{c_i} – uniaxial compressive strength of ice sample from i-th layer, n – number of layers ($n \geq 3$).

Some other researchers use arithmetic mean values of the small-tests results to assess full-thickness ice compressive strength. Major studies aimed at comparison of small samples' strength and full-scale ice strength were carried out in 1980-1981 in Beaufort Sea by EXXON order (Timko and Frederking, 1990). The full-scale tests on uniaxial compressive strength were performed in field condition, while the small-scale tests were carried out in laboratory conditions. The small samples were cut from different horizontal layers, packed in dry ice and shipped to the cold laboratory. One day prior the testing, the small samples were placed in the test room of temperature of relevant ice layer. Fig. 1a presents the scheme of ice fragmentation by layers wherefrom ice samples were taken. Ice strength over the whole thickness σ_c was defined as arithmetic mean value of strength obtained for each layer σ_{c_i} :

$$\sigma_c = \frac{1}{n}\sum_{i=1}^{n}\sigma_{c\_i}. \quad \textbf{[2]}$$



a) b)

Figure 1. a) Ice fragmentation by layers over thickness, and b) comparison of ice compressive strength obtained with small samples using formula (2) and measured during full-scale tests (from Timco and Frederking, 1990)

Strength values computed with formula (2) were correlated with results of compression tests on large-scale ice samples afloat (Chen and Lee, 1986). At that ice thickness achieved 1.2 – 1.8 m, samples were 3.05 m in width and 6.10 m in length. Strain rate $\dot{\varepsilon}$ in full-scale tests varied within 10^{-7}–$5\cdot10^{-5}$ s^{-1}. As seen in Fig. 1b close correlation of strength values obtained with two methods was obtained.

Small samples taken from different layers over ice thickness were repeatedly subjected to temperature variations during transportation to the laboratory, while the uniaxial compression tests were carried out at a significant time interval after the samples were taken from ice. This could affect the quality of the obtained results. This paper offers in-situ test procedure using small thermally balanced samples free from the above problems.

3. Tests description

Procedure of the uniaxial compression tests of small ice samples included several stages. First of all several holes were drilled in ice sheet. The depth of the holes was about 5 cm less than ice thickness. Round tubes with watertight bottom cap were inserted into the holes. The tubes with inner diameter of 110 mm and 90 mm were used in 2019 and 2020, respectively. The tubes were left for 24 hours to be frozen in ice. Cylindrical ice samples taken from various layers of ice sheet were used for tests. To obtain the samples block over the whole ice thickness was cut out in ice sheet and then it was extracted from water. Horizontal ice cores approximately 73 mm in diameter were drilled at four different levels over ice thickness (see Fig. 2). Ice thickness was in the range 0.75 – 0.82 м.

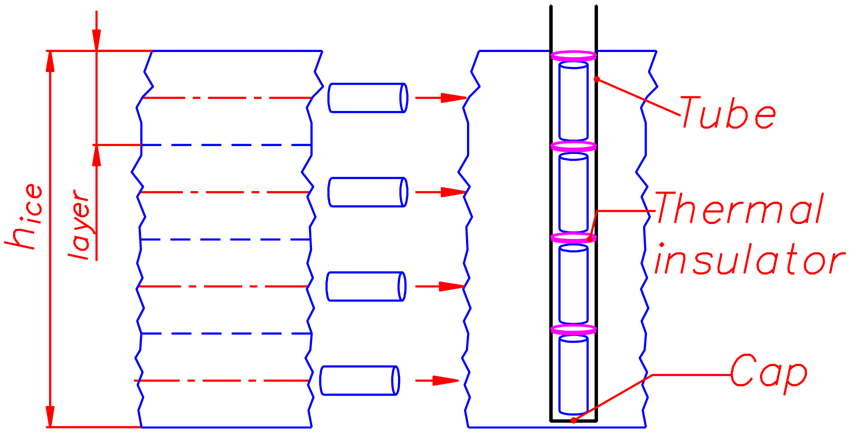


Figure 2. Preparation of thermally balanced ice samples

Two series of the tests were carried out: 3 tubes were used in 2019 and 4 tubes in 2020. Depths of axes of drilled horizontal cores are given in Table 1.

Table 1. Location of layers small samples are taken from

No. of horizontal layer	Distance from ice top to the horizontal axis [mm]	
	Year: 2019	Year: 2020
1	115	100
2	265	300
3	415	500
4	565	700

After the samples of required dimensions (73 mm in diameter and 180 mm in height) were prepared they were placed in plastic bags. The bags were placed into the earlier prepared tubes to depth corresponding to that of layer they were taken from. Vertical spaces between samples were filled with thermal insulation material (see Fig. 2). Then the tubes with samples were left for several days in natural environmental conditions to ensure thermal balance for the whole system (see Fig. 3). Thus the samples maintained the temperature close to that of layer they were taken from.

Figure 3. Workplace with tubes frozen into the ice cover. Next to the red stick is a thermistor string

7 days later the samples were sequentially extracted from pipes and subjected to uniaxial tests. The tests were performed with the Kompis rig designed for the use in the field conditions (Moslet, 2007). Strain rate during all the tests was the same $\dot{\varepsilon} = 10^{-3}\mathrm{s}^{-1}$. The load and displacement in the small scale tests were recorded with sampling frequency of 10 Hz in the field laptop connected to the Kompis rig.

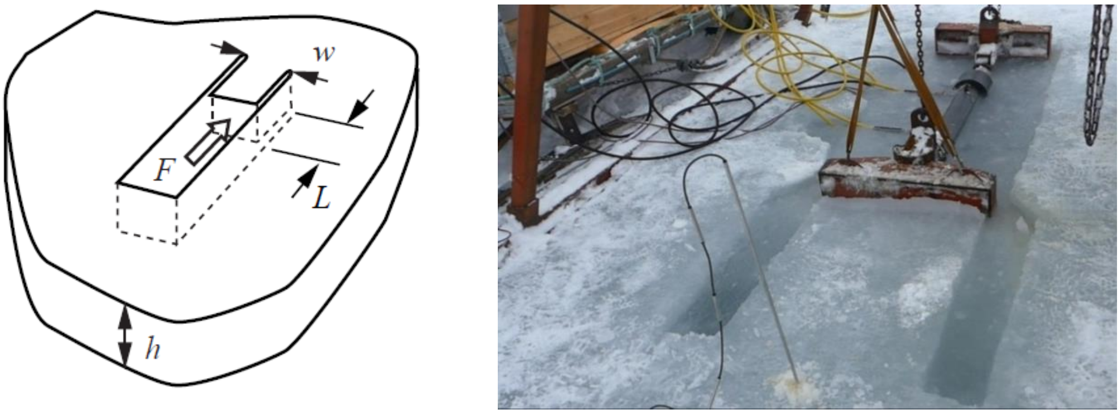
The tests with each sample were carried out as quickly as possible so that the temperature of sample remained stable. Ice temperature in the small scale tests was registered with temperature probe immediately after each test. For the measurement of salinity the ice samples were taken and delivered in a warm place in plastic boxes for the melting. Then salinity of melt water was measured with salinometer Toledo.

Uniaxial compressive strength of a sample from i-th layer was calculated using formula $\sigma_{c\_i} = \frac{4F}{\pi d^2}$ where F is breaking force of the sample, d is the sample diameter.

The setup of full-scale uniaxial compression tests is shown in Fig. 4*a*. For these tests, a floating ice cantilever was cut over the whole ice thickness. The load F is applied to the vertical face of the cantilever by flat plate of 60 cm width and 80 cm height. The equipment has been designed and manufactured under the support of SAMCoT project. The rig shown in Fig. 4b consists of flat plates connected by two horizontal hydraulic cylinders (Enerpack) equipped with displacement sensor and load cell. Upper cylinder A is visible in the Figure and another one is under water. The cylinders are connected to the electrical pump powered by three phase generator 400 V. The stroke of the hydraulic cylinder is 37 cm and it has a load capacity of 300 kN. Recorded after the test data included loads, stroke and oil pressure in each cylinder. The data were recorded with sampling frequency of 100 Hz on the hard disk of the field computer. The test rig ensured average strain rate $\dot{\varepsilon}$ of the sample equal to $\sim 10^{-3}\mathrm{s}^{-1}$.

Ice temperature (temperature profile) was registered with thermistor string GeoPrecision placed into the hole drilled in the beam (Fig. 4b). The salinity profile was obtained by measurement of ice samples salinity taken from different vertical layers of ice sheet.

Full-thickness ice compressive strength was calculated from these tests as $\sigma_c = \frac{F}{wh}$ where F is a breaking force of the ice cantilever (sample), w is the sample width, h is ice thickness.



a) b)

Figure 4. Full-scale compression test: a) layout, and b) set-up

To study the ice structure through entire thickness, horizontal and vertical thin sections were made, which were then analyzed in polarized light.

4. Test results and analysis

Table 2 gives uniaxial compression test results for small thermally balanced samples.

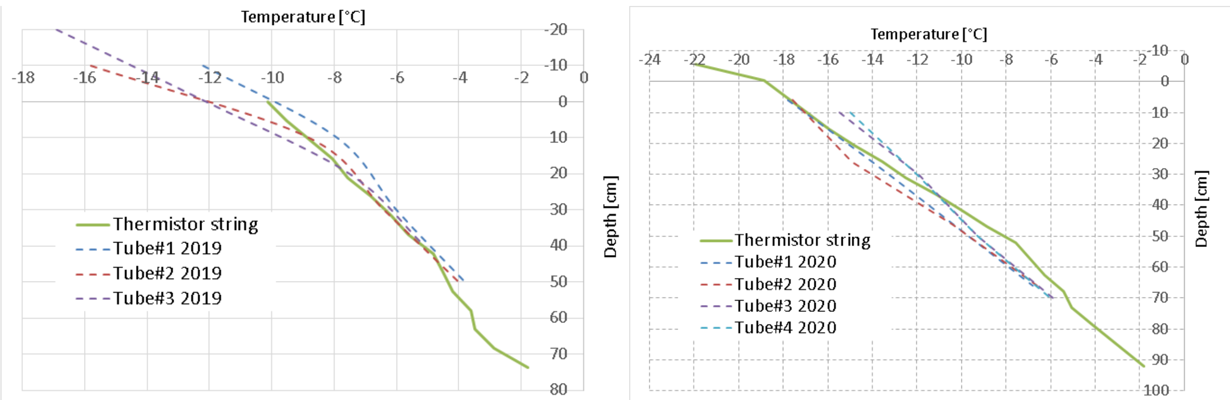
Fig. 5 shows temperature distributions of samples in tubes, as well as temperature profile over ice thickness, as measured by a thermistor string near frozen-in tubes (see Fig. 3). In 2019 some samples in tubes were somewhat above their parental ice layers, so the temperature profiles in Fig. 5 (left) are above ice surface. It can be seen that temperature distribution over small samples has rather good correspondence with temperature profile over ice thickness measured by a thermistor string, which confirms the applicability of suggested technology for sample temperature preservation till the moment of compression tests.

The profiles of ice salinity over the ice thickness are given in Fig. 6. It must be noted that, unlike the relatively stable temperature profile, salinity distribution varied from one test site to another. Still, average salinities of ice within the testing area in spring period belong to rather a narrow range of 5–6 ppt. Fig. 6 shows a trend towards a certain decrease in salinity of small samples, which might suggest partial outflow of brine during sample preparation.

The thin section analysis, carried out in the same field studies and given in Marchenko et al. (2020), showed that the upper layer of ice about 20 cm thick had a granular structure, and below it was columnar one. Thus, the top ice samples in each tube had a granular structure, whereas the other three samples below were columnar.

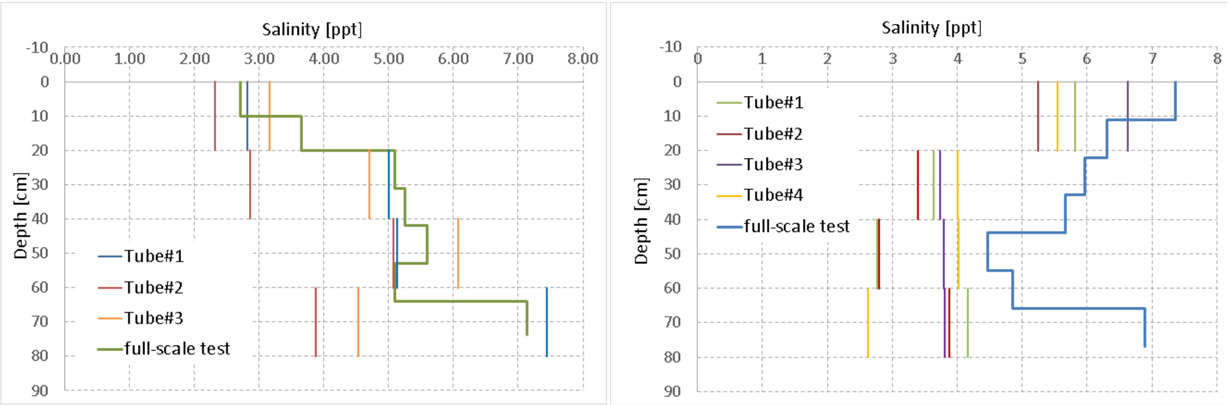
Table 2. Uniaxial compression test results for small thermally balanced samples

Sample Year_No. of tube_ No. of layer (from top)	Salinity [ppt]	Temperature [degree C]	Sigma, [MPa]
2019_1_1	2.82	-12.2	6.88
2019_1_2	5.00	-7.9	4.23
2019_1_3	5.13	-6.0	3.23
2019_1_4	7.45	-3.8	1.94
2019_2_1	2.32	-15.8	7.63
2019_2_2	2.87	-8.8	4.45
2019_2_3	5.08	-6.4	3.68
2019_2_4	3.87	-4.0	2.99
2019_3_1	3.17	-16.9	8.06
2019_3_2	4.70	-12.1	5.24
2019_3_3	6.07	-7.5	3.68
2019_3_4	4.53	-5.1	3.20
2020_1_1	5.82	-17.8	6.08
2020_1_2	3.63	-14.0	5.13
2020_1_3	2.77	-10.4	5.04
2020_1_4	4.16	-6.8	3.95
2020_2_1	5.24	-17.6	5.09
2020_2_2	3.39	-14.9	5.64
2020_2_3	2.79	-10.4	3.78
2020_2_4	3.88	-6.6	2.81
2020_3_1	6.63	-15.5	2.58
2020_3_2	3.73	-11.9	4.63
2020_3_3	3.80	-9.3	5.06
2020_3_4	3.81	-5.9	4.48
2020_4_1	5.54	-15.0	5.48
2020_4_2	4.01	-12.0	4.17
2020_4_3	4.02	-9.3	5.90
2020_4_4	2.62	-6.0	3.33



Year 2019 Year 2020

Figure 5. Temperature profiles over ice thickness, as measured on small ice samples and in ice cover using a thermistor string



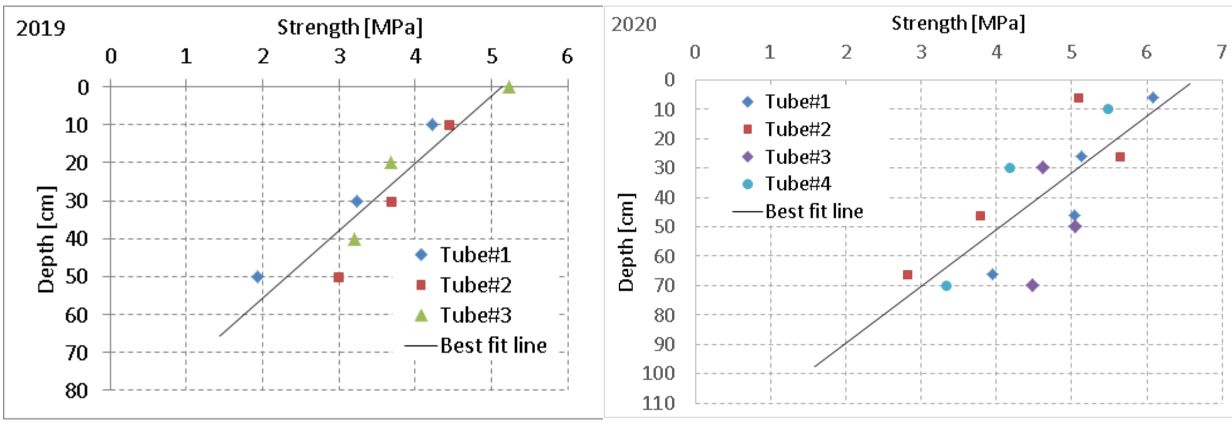
Year 2019 Year 2020

Figure 6. Salinity profiles over ice thickness, as measured on small ice samples and on ice cores drilled from ice cover next to full-scale tests

Fig. 7 shows test results for thermally balanced samples as distribution of uniaxial compression strengths over ice thickness. Some of the samples in tubes were above the surface of ice sheet, so these results only include the data for the samples within the ice sheet. Linear approximations of test data are given as follows:

Year 2019 $\sigma_c(depth) = 5.114 - 0.0565 \cdot depth,$ $R^2 = 0.8728$ **[3]**
Year 2020 $\sigma_c(depth) = 6.645 - 0.0518 \cdot depth$ $R^2 = 0.5815$ **[4]**

Here, $\sigma_c(depth)$ is in megapascals (MPa), and $depth$ is in centimeters (cm). Both test series have shown a trend towards weakening of deeper ice layers. The year 2020 as a whole and its winter and spring time in particular were considerably colder than 2019, which was reflected in ice strength.



Year 2019 Year 2020

Figure 7. Distribution of uniaxial compressive strength of ice over its thickness as per the test data for thermally balanced samples

It might be interesting to compare the test results for uniaxial compression strength of small ice samples with the estimates obtained as per the expressions recommended by ISO 19906 (2019). For calculations the following expressions suggested by Timco and Frederking (1990) were applied:

for columnar ice $$\sigma_c = 37\dot{\varepsilon}^{0.22}\left(1-\sqrt{\frac{\nu_t}{0.27}}\right)$$ **[5]**

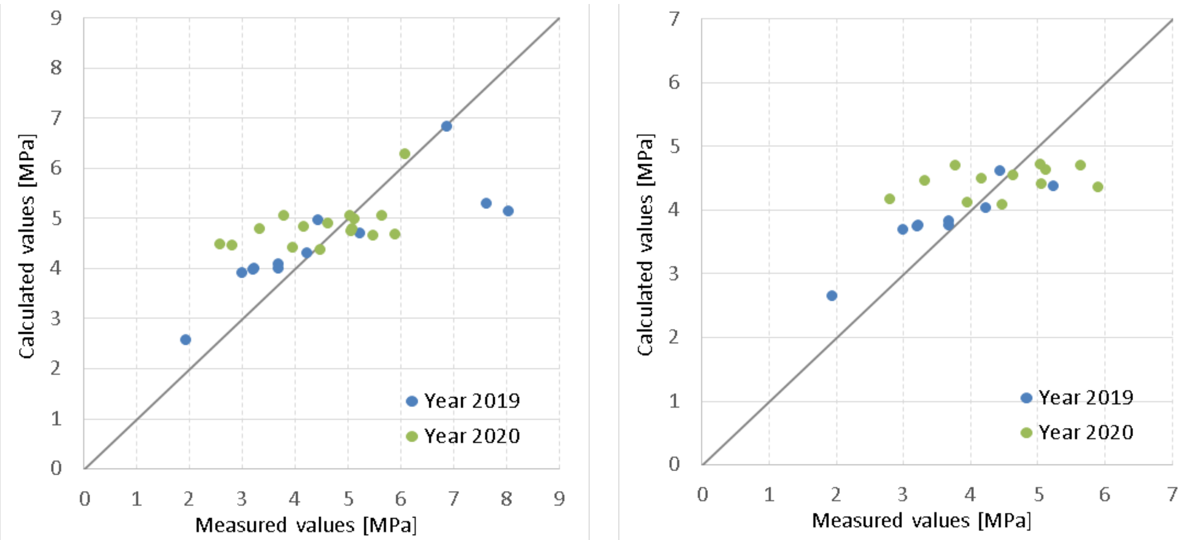
for granular ice $$\sigma_c = 49\dot{\varepsilon}^{0.22}\left(1-\sqrt{\frac{\nu_t}{0.28}}\right)$$ **[6]**

where ν_t is total porosity defined as the sum of the brine and gas fractions. Knowing the salinity, temperature and density of sea ice, the brine and gas fractions were calculated as given in Cox and Weeks (1983) for ice temperatures less than −2°C. Ice density was 900 kg/m^3.

Additional calculations have been performed for columnar ice using a formula suggested by Moslet (2007) and given in ISO 19906 (2019). The formula is based on results of field work on Svalbard in 2004 and 2005 when the same Kompis rig for small-scale compression tests was used. Strain rate during those tests was the same $\dot{\varepsilon} = 10^{-3}\text{s}^{-1}$. The formula provides an upper limit of the compressive strength for horizontally loaded ice samples:

$$\sigma_c = 8\left(1-\sqrt{\frac{\nu_t}{0.7}}\right)^2.$$ **[7]**

The results of this comparison are shown in Fig. 8. Calculated estimates mostly demonstrate a good correlation with experimental results obtained in presented research. Considerable discrepancies were found on rather cold (below -10°C) samples.



a) Calculation as per formulas [5] and [6] (Timco and Frederking, 1990)

b) Calculation as per formula [7] (Moslet, 2007)

Figure 8. Comparison of small-tests results and calculations based on ISO 19906

Expressions [5], [6] and [7] make it possible to estimate uniaxial compression strength of ice samples in the assumption that their properties, like structure, temperature, salinity, are uniform. As mentioned in Løset et al. (2006), these expressions do not yield ice compression strength over its entire thickness, so they are not suitable for ice load estimates. Two main factors must be taken into account when processing results of full-thickness uniaxial compression tests of ice samples: on one hand, growing pressure inside the sample due to

constrained compression and, on the other hand, non-uniform thickness-wise distribution of ice properties and the presence of lower layers with rather high temperatures.
In this study, full-thickness ice strength obtained through a certain averaging of the small-test results with samples from different layers was compared with compressive strength (pressure) measured directly in full-scale tests. The distribution of compression strength over ice thickness was calculated as per formulas [3] and [4]. The next step was the calculation of mean arithmetical, as per Timco & Frederking (1990), and root-mean-square (RMS), as per SP 38.13330.2018, full-thickness ice compressive strength. It must be taken into account that RMS calculation depends on the number of layers used to split the ice sheet. These calculations were performed for 4 ice layers of equal thickness. The results are given in Table 3 below.

Table 3. Full-thickness ice compressive strength [MPa] based both on small-scale and full-scale tests

Year	Calculations based on small-scale tests		Full-scale tests
	Arithmetical mean	RMS	
2019	3.00	3.25	1.29
2020	4.18	4.43	1.95

In contrast with similar field tests undertaken in 1981 under EXXON program (Petrie and Poplin, 1986), see Fig. 1b, these tests have not shown any close correspondence in full-thickness compressive strength based on small-scale tests and measurements in full-scale tests. The latter gave compressive strength more than 2 times less than averaged results for small samples.

Probable reasons for this discrepancy could be as follows. In the full-scale tests of 1981 performed under EXXON program (Lee et al., 1986), the proportions in size of large ice sample (thickness × width × length) were approximately 1×2.5×5, whereas in the presented studies these proportions were approximately 1×0.8×1. Such dimensions of full-scale sample in our tests were adopted so as to suit the capabilities of the test rig (plate size and maximum achievable load). Larger samples are likely to have stronger effect of constrained compression (see above) and, accordingly, exert greater pressure on the loading plate, and it is the key criterion in determination of ice strength during full-scale tests. So, the full-scale tests of 1981 demonstrated high values of compressive strength, which was close to the values in small-scale tests. This outcome means that dimensions of ice sample in the full-scale compression tests is an important factor.

Another reason is a non-uniformity of ice properties, which leads to the differences in strength over the thickness. In addition to temperature and salinity, the presence of defects in the ice that reduce its strength should be considered. In our study, we assumed a uniform distribution of defects in the ice structure over its thickness. In this case, the uniform arrangement of the small ice samples over the ice thickness made it possible to take into account the presence of defects to some extent. However, the total thickness of ice layer subjected to the small-scale tests is determined by the sum of the sample diameters, and it is approximately 35% of total ice thickness. If the distribution of defects over the ice thickness is uneven, then the presence of larger defects in other layers of ice can lead to a decrease in compression strength related to entire ice thickness. When the full-thickness sample is loaded, the contribution of specific layers to the total load is hard to estimate unambiguously.

5. Conclusion

This paper studies methods for determination of ice full-thickness compressive strength based on small ice samples and full-scale tests. One of the challenges in conducting small-scale tests in field condition is preserving the ice sample properties for a long time. The paper suggests a method which can be used for this: preparation of thermally balanced ice samples. The described field tests on sea ice have demonstrated the feasibility of this method and showed a good correlation in the temperature of ice samples immediately before the tests and the temperature profile over the ice thickness. However, the salinity of samples was slightly less than in their respective parental layers, which might mean that the samples lost some of their brine.

The tests with thermally balanced samples made it possible to obtain the distribution of uniaxial compression strength over ice thickness. Strength results for small samples were averaged by thickness and compared with the results of compression strength measurements performed on full-scale specimens over their entire length. In contrast to EXXON 1980-1981 experiments, these studies have shown the discrepancies in averaged compression strengths of small samples and the results of full-scale measurements. Apart from thickness-wise variations in strength and other properties of ice, these discrepancies could also be due to the size and proportions of the ice sample tested afloat in full-scale test.

Acknowledgments

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References

Chen, A.C.T. and Lee, J., 1986. Large-scale ice strength tests at slow strain rates. Proc. OMAE'86, Tokio, Vol. 4, pp. 374–378

Cox, G.F.N. and Weeks, W.F., 1983. Equations for determining the gas and brine volumes in sea ice samples*, Journal of Glaciology*, Vol. 29, No. 102, pp. 306–316

Lee, J., Ralston, T.D. and Petrie, D.H., 1986. Full-thickness sea ice strength tests. Proc. IAHR Ice Symposium, Iowa City, Vol.1, pp. 293–306

Loset, S., Shkhinek, K.N., Gudmestad, O.T. and Hoyland, K.V., 2006. Actions from ice on Arctic Offshore and Coastal Structures, St. Petersburg, Publisher "LAN", 272 p.

Marchenko, A., Karulin, E., Frederking, R., Cole, D., Brown, J., Karulina, M., Sakharov, A., Chistyakov, P., Sodhi, D., Markov, V., Lishman, B., M. Shortt, and Sliusarenko, A., 2020. Influence of vibrations on indentation and compression strength of sea ice. Proc. of the 25th IAHR Symposium on Ice, Trondheim, Norway

Marchenko, A., Karulin, E., Karulina, M., Sakharov, A., Chistyakov, P., Sodhi, D. and Sliusarenko, A., 2018. Scale effects in compressive strength of sea ice. Proc. of the 24th IAHR Symposium on Ice, Vladivostok, paper 18-004.

Moslet, P.O., 2007. Field testing of uniaxial compression strength of columnar sea ice. *Cold Regions Science and Technology*, 48 (1), pp. 1–14.

Petrie, D.H. and Poplin, J.P., 1986. Comparison of small scale and large-scale sea ice strengths. Proc. IAHR Ice Symposium, Iowa City, Vol.1, pp. 265–277

Petroleum and natural gas industries – Arctic offshore structures. ISO/FDIS 19906, 2019

SP 38.13330.2018, 2018. Construction norms and rules: Loads and influences on hydrotechnical constructions (due to waves, vessels and ice), Moscow.

Timco, G.W. and Frederking, R.M.W., 1990. Compressive strength of sea ice, *Cold Regions Science & Technol.*, Vol. 17, pp. 227–240