DENSITY MEASUREMENTS OF SALINE ICE BY HYDROSTATIC WEIGHING IN PARAFFIN

Anna Pustogvar and Knut V. Høyland
Sustainable Arctic Marine and Coastal Technology (SAMCoT),
Centre for Research-based Innovation (CRI),
Norwegian University of Science and Technology,
Trondheim, Norway

ABSTRACT
In order to estimate the ice loads on marine structures in cold climate regions one should know how strong the ice is. Mechanical properties of ice are affected by a number of parameters and one of these parameters is ice density. The most common way to measure density is to evaluate the volume and the mass of the ice sample and calculate density directly as mass/volume. Despite its simplicity this technique is considered to be relatively inaccurate due to the difficulties in obtaining the true dimensions of the sample. An alternative way to do more precise density measurements is hydrostatic weighing in paraffin or in any liquid which has lower density than ice. This technique was applied for ice in a laboratory environment and proved to be very accurate. Present paper addresses a possibility of employing hydrostatic weighing technique in the field at ambient temperature. First, the paper presents density measurements performed in the Fram Strait during Oden Arctic Technology Research Cruise (OATRC2013) in August 2013. Ice density measured by a standard mass/volume method is compared with the results obtained by hydrostatic weighing technique. Moreover, a study on the effect of storing time on ice density results is reported. Second part of the test campaign is performed in the cold laboratory at Norwegian University of Science and Technology (NTNU). By applying factorial design of the experiment the effect of three factors: paraffin temperature, time of ice core storing and location of the sample in the core, and their interaction are studied. The results of the field and laboratory tests reveal no significant difficulties in performing density measurements by hydrostatic weighing in the field environment. Furthermore hydrostatic weighing method proves to be superior to the standard mass/volume technique.

INTRODUCTION
Field investigations of sea ice properties generally include collecting of temperature, density and salinity data (TDS) due to the strong effect of these parameters on mechanical properties of ice (Løset et al., 2006). Salinity and temperature measurements of ice are relatively straightforward. On the contrary there are several methods to measure ice density. The four most common techniques are reviewed in the paper by Timco and Frederking (1996):

mass/volume, displacement (submersion), specific gravity, freeboard and ice thickness technique.

The most applicable method for in situ measurements of sea ice density is mass/volume method. An extracted ice core is cut into a number of ice samples. Every sample is weighed to give the mass; the volume is calculated from the dimensions of the sample. Finally the density is calculated by:

$$\rho_{ice} = \frac{M}{V} \tag{1}$$

where ρ_{ice} is the density of sea ice, M and V are the mass and the volume of the ice sample respectively. Despite its simplicity mass/volume method has been argued to be relatively inaccurate due to the difficulties in obtaining the true dimensions of the sample (Timco and Frederking, 1996).

To avoid inaccuracy one can use one of the specific gravity techniques (Weeks, 2010) – hydrostatic weighing method. By now this technique has been applied for ice only in the laboratory conditions (Nakawo, 1980; Kulyakhtin et al., 2013). Hydrostatic weighing has an advantage over mass/volume method as no volume need to be measured. It is based on Archimedes' law and requires measurements of three parameters:

- ice sample mass in the air (M_{air});
- ice sample mass suspended in the liquid of lower density than ice (M_{liq}) (2, 2, 4 trimethylpentane – Nakawo, 1980; paraffin – Kulyakhtin et al., 2013);
- density of the liquid (ρ_{liq}).

Ice density can be thereafter calculated as:

$$\rho_{ice} = \frac{M_{air}}{M_{air} - M_{liq}} \cdot \rho_{liq} \tag{2}$$

The uncertainty ($\Delta\rho_{ice}$) associated with the ice density measurements (ρ_{ice}) performed by hydrostatic weighing technique can be estimated by the following expressions:

$$\Delta\rho_{ice} = \sqrt{\left(\frac{\partial\rho_{ice}}{\partial M_{air}}\Delta M_{air}\right)^2 + \left(\frac{\partial\rho_{ice}}{\partial M_{liq}}\Delta M_{liq}\right)^2 + \left(\frac{\partial\rho_{ice}}{\partial\rho_{liq}}\Delta\rho_{liq}\right)^2} \tag{3}$$

$$\Delta\rho_{ice} = \sqrt{\left(\frac{\rho_{ice} \cdot M_{liq}}{M_{air}\left(M_{air} - M_{liq}\right)}\Delta M_{air}\right)^2 + \left(\frac{\rho_{ice}}{M_{air} - M_{liq}}\Delta M_{liq}\right)^2 + \left(\frac{\rho_{ice}}{\rho_{liq}}\Delta\rho_{liq}\right)^2} \tag{4}$$

All laboratory tests using hydrostatic weighing were performed with control of the temperature. On the contrary field measurements usually have to be done at ambient conditions. But how can ambient temperature affect the precision of hydrostatic weighing method? Does storing time of the ice core at the ambient temperature have a strong influence on the results? These questions were first addressed during Oden Arctic Technology Research

Cruise (OATRC2013) and afterwards in the cold laboratory of NTNU in order to check applicability of hydrostatic weighing method in the field.

EXPERIMENTS

Field tests

During Oden Arctic Technology Research Cruise (OATRC2013) which was carried out by the Norwegian University of Science and Technology (NTNU) in collaboration with Statoil and the Swedish Polar Research Secretariat (SPRS) in the Fram Straight in August 2013 we studied applicability of the hydrostatic weighing technique in the field. First, two ice cores were drilled next to the standard TDS measurement cores corresponding to the points 4.2 and 5.1 of the Ice Station polygon (a paper about ice properties of Ice Station polygon is currently under preparation). Ice density data obtained by hydrostatic weighing (4.2 HW, 5.1 HW) were compared with the results obtained by mass/volume method (4.2 MV, 5.1 MV). Salinity of the ice was in average 1.2 ppt, and temperatures varied from the top to the bottom of the ice sheet from 0 to -1.3°C.

Hydrostatic weighing technique is a time-consuming method. This disadvantage rises up a question about effect of storing time on the results. In order to investigate this effect two cores from an ice floe out of the Ice Station were taken 10 cm apart from each other. Ice samples from the first core were cut starting from the top of the core; samples from the second core were cut starting from the bottom (referred as top-bottom (TB) and bottom-top (BT) respectively in further text). After each TB sample a BT sample was measured so that measurements of both cores were performed simultaneously but in inverse manner, therefore they are referred to as inverse measurements.

The procedure of all density measurements was following: after drilling the cores were cut into samples: 36 samples of 4.2 HW and 5.1 HW with the length equal to 0.062 ± 0.016 m and 27 samples of TB and BT with the length equal to 0.072 ± 0.01 m. While density of one ice sample was being measured the rest of the core was kept horizontally in a plastic mold outside of the sun to reduce brine drainage and melting. For each sample both masses – in the air (M_{air}) and in the paraffin (M_{par}) were recorded by hanging the sample by a thin thread (effect of which was considered to be negligible) on a hook of electric weight scales (Fig. 1) first in the air and afterwards suspended in the paraffin. The density of the paraffin was measured by aerometers; it varied around 812.9 ± 0.5 kg/m^3.

Measurements were performed in a container on deck of Oden in order to avoid effect of wind on the accuracy of the measurements. Air temperature during the measurements was equal to the ambient temperature and varied from 0.2 to 3.4°C.

Laboratory tests

There are several factors which might affect ice density measurements by the hydrostatic weighing. Before making any conclusions about applicability of the method in the field at the ambient temperature, one needs to check effects of these factors. We can highlight some of them:

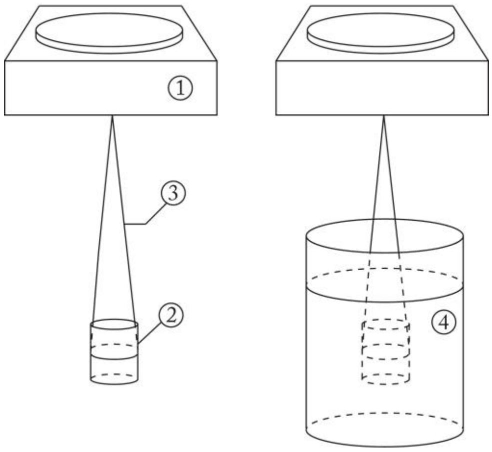

Figure 1. Sketch of the test set up:
1 – weight scales, 2 – ice sample,
3 – thread, 4 – paraffin

1. In previous laboratory studies paraffin and ice were in isothermal equilibrium, which is not a case for field measurements when the ambient temperature control is not possible. Therefore, the importance of isothermal equilibrium is to be checked.

2. The ice core taken for density measurements in the field can be up to one meter which makes it impossible to perform density measurement at once, the core must be split into the samples. While performing measurements on one sample, the rest of them have to be put aside. Time can cause brine drainage from the ice and other processes, which can affect density measurements. Therefore, effect of storing time is to be studied.

3. The ice properties may vary significantly through the core. The importance of this factor should be questioned in order to avoid wrong judgment about ice density basing only on specific part of the core.

The most efficient way to study effects of several factors on the response is to apply factorial design. Moreover factorial design helps in revealing interaction between the factors. We chose full 2^3 factorial design (three factors at two levels) with 16 ice samples as experimental units as the most appropriate way to screen effects of the factors (Table 1).

Each of the factors has two levels (Table 1) and the levels are chosen based on the following:

1. In order to reveal importance of ice and paraffin being in isothermal equilibrium, the low level of factor A represents the case when ice and paraffin are in isothermal equilibrium. High level corresponds to the case when the temperatures of ice sample and paraffin are different.

2. Levels for time of storage were chosen in order to check how fast the measurement should be done in the field, and if there is a difference between measurements which are done immediately after drilling the core (Factor B, low level) and postponed measurements (Factor B, high level).

3. Levels for part of the core were chosen because the crystal structure of the top part of the core and bottom part can differ significantly, due to slowing down in the ice growth process.

Ice for the test was produced in the cold laboratory ice tank FRYSIS II. Eight ice cores were drilled out of the ice sheet. The thickness of the cores was 0.181 ± 0.014 m. After the ice cores were extracted, they were sawed into halves and put in a container filled with water from the ice tank in order to reduce brine drainage. Samples assigned for high level of Factor B (storing time 30 min), were taken out from the container and put on a plastic tray 30 min before the measurements. Ice salinity was approximately 4 ppt, and the ice temperature varied between -2.6 to -1.3°C.

Table 1. Factor levels in 2^3 factorial design of the density experiment

Factor A Temperature of paraffin	Low (-1) High (+1)	-3°C -12°C
Factor B Storage time of the ice sample	Low (-1) High (+1)	0 min 30 min
Factor C Part of the ice core	Low (-1) High (+1)	bottom top

Ice samples were assigned to 8 treatment combinations, twice replicated. It was not necessary to use a blocked design in this specific case, because all observations were made by one person at the same day on the same ice and with the same equipment.

The test set up was the same as in the field tests (Fig. 1) apart from a thread. In laboratory tests a metal carrier was used to suspend an ice sample in the air and in the paraffin. The ice sample was put inside the carrier at weight scale reading equal to zero, therefore effect of the carrier was eliminated.

RESULTS

Field tests

Results of the field density measurements are summarized in Table 2 and plotted in Figures 2 and 3. By Eq. 4 the uncertainty of performed ice density measurements is estimated to be equal to 0.08% (Table 3).

Table 2. Ice density results obtained by hydrostatic weighing technique

		OATRC2013				Laboratory
		4.2 HW	5.1 HW	TB	BT	
Mean, $\overline{\rho_{ice}}$	[kg/m^3]	905.5	910.4	896.2	897.0	902.7
SD, $\sigma_{\rho_{ice}}$	[kg/m^3]	17.9	12.5	15.6	15.8	12.0
Number of samples		22	14	13	14	16

Laboratory tests

Results of the ice density measurements performed in the cold laboratory at NTNU are reported in Table 4. Main effects and interaction plots are presented in Figures 4 and 5. Equation 4 gives us uncertainty of performed measurements equal to 0.07% (Table 3). Analysis of the variance is presented in Table 5. These results were also plotted on a Pareto type chart to visualize the main effects and interaction easier (Fig. 6).

DISCUSSION

Field tests

The density of the ice samples taken from the Ice Station polygon (Fig. 2) tends to be lower on the top and higher on the bottom of the ice sheet, which can be explained by the processes taking place during melting period in summer (Shestov et al., 2012). Outliers from the core 4.2 corresponding to the 20-60 cm depth were noted to be very porous even by visual studying.

Results from the inverse measurements presented in Figure 3 show that hydrostatic weighing technique can be applied in field environment. Even though simultaneous measurements of two one meter thick ice cores took two hours no significant difference was found in obtained density values. The latter statement is supported by two-sample t-test performed on the inverse measurements (p-value=0.898).

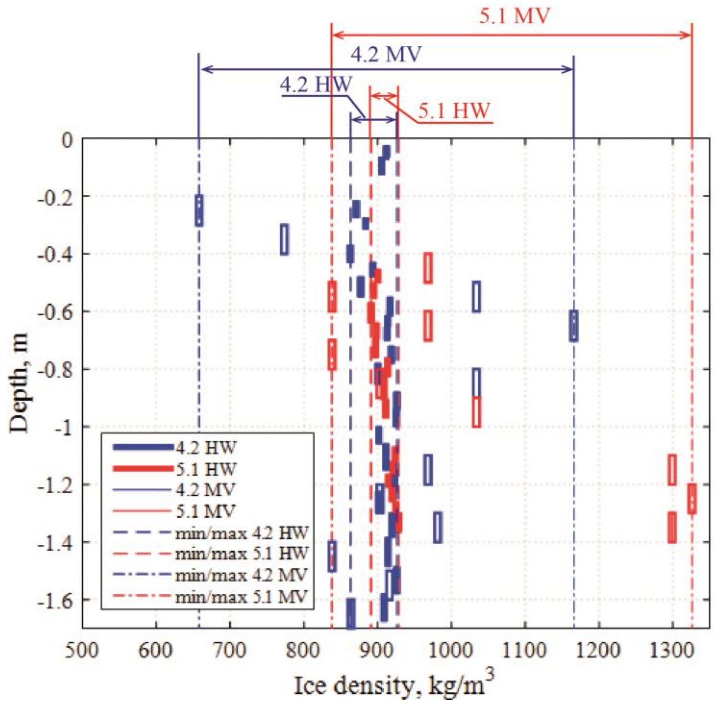

Figure 2. Ice density measured during OATRC2013,
HW - hydrostatic weighing method, MV - mass/volume method

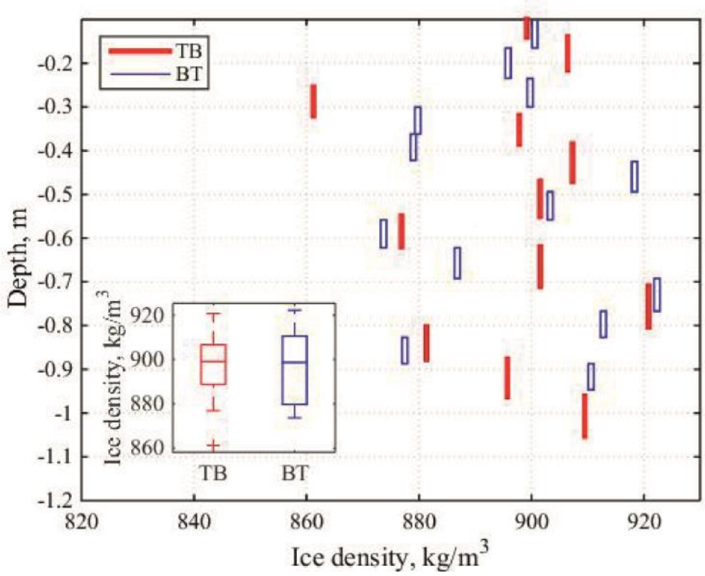

Figure 3. Inverse measurements of ice density during OATRC2013

Table 3. Uncertainty analysis of ice density measurements estimated by Eq. 4

		OATRC2013		
		4.2 HW, 5.1 HW	TB, BT	Laboratory
Estimate of ice density, ρ_{ice}	[kg/m^3]	907.42	896.62	902.70
Estimate of paraffin density, ρ_{par}	[kg/m^3]	812.60	813.23	766.20
Estimate of mass in the air, M_{air}	[g]	234.56	247.16	330.90
Estimate of mass in the paraffin, M_{par}	[g]	24.61	23.28	49.90
Uncertainty of mass measurements, ΔM	[g]	0.10	0.10	0.10
Uncertainty related to paraffin density, $\Delta\rho_{par}$	[kg/m^3]	0.50	0.50	0.50
Uncertainty related to ice density, $\Delta\rho_{ice}$	[kg/m^3]	0.71	0.68	0.67
$\frac{\Delta\rho_{ice}}{\rho_{ice}}\cdot 100$	%	0.08	0.08	0.07

Table 4. Results of ice density measurements performed by 2^3 factorial design

Run order	T_{par} [°C]	t [min]	top/bottom	ρ_{ice} [kg/m^3]	Run order	T_{par} [°C]	t [min]	top/bottom	ρ_{ice} [kg/m^3]
1	-12	0	top	900.4	9	-3	0	bottom	907.9
2	-3	0	top	900.1	10	-3	30	top	905.6
3	-3	30	bottom	902.5	11	-3	0	top	911.8
4	-3	30	top	894.4	12	-12	0	top	913.2
5	-12	30	top	909.3	13	-3	30	bottom	903.6
6	-12	30	bottom	912.2	14	-12	0	bottom	905.0
7	-12	30	top	865.0	15	-12	0	bottom	901.8
8	-12	30	bottom	916.4	16	-3	0	bottom	893.3

Table 5. Analysis of variance in ice density measurements performed by 2^3 factorial design studying effects of paraffin temperature, storage time and part of the core

Source	DF	Adj SS	Adj MS	F-value	p-value
Model	7	832.06	118.87	0.72	0.659
Temperature	1	1.05	1.05	0.01	0.938
Time	1	37.52	37.52	0.23	0.646
Part of core	1	115.03	115.03	0.7	0.427
Temperature × Time	1	6.89	6.89	0.04	0.843
Temperature × Part of core	1	169.65	169.65	1.03	0.339
Time × Part of core	1	379.28	379.28	2.31	0.167
Temperature × Time × Part of core	1	122.66	122.66	0.75	0.413
Error	8	1315.45	164.43		
Total	15	2147.52			

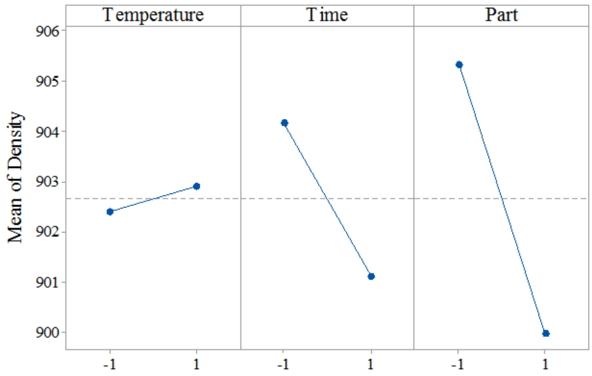

Figure 4. Main effects plot of paraffin temperature, storage time of the ice sample and part of the ice core

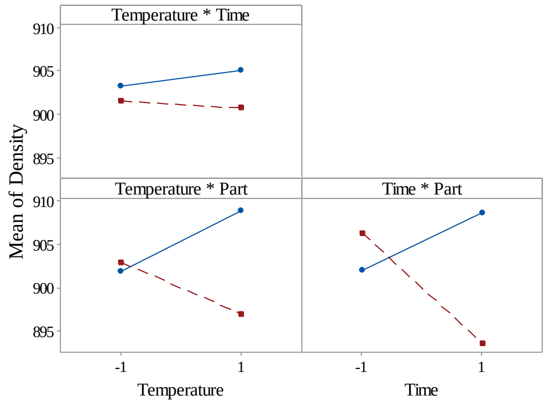

Figure 5. Interaction plot of three factors: paraffin temperature, storage time of the ice sample and part of the ice core

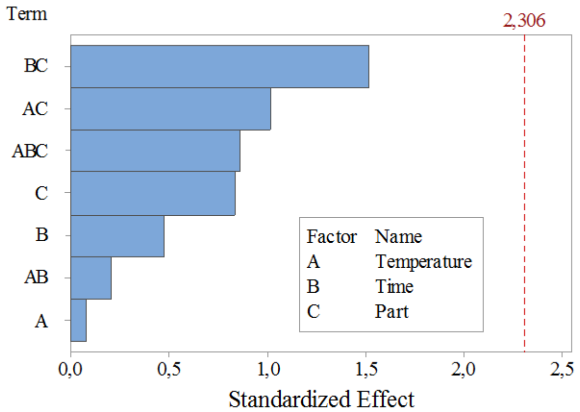

Figure 6. Pareto chart of standardized effects of paraffin temperature, storage time of the ice sample and part of the ice core (α =0.05)

Laboratory tests

Judging by calculated main effects we can make the following conclusions (Fig. 4):

1. Temperature of the paraffin has the least effect on the density measurements.

2. Time of storage has larger effect, this effect is reversed which means that when the measurements are done straight after taking the ice core the density values are higher than after waiting for 30 minutes. This result is reasonable, because while keeping the sample for 30 minutes the draining process can take place, so the brine in the brine channels will be replaced by air which is lighter than brine and this will lead to lower density values.

3. Part of the ice core. Part of the ice core has even larger effect than the storage time. The effect is also reversed. The upper part had a higher density than the lower part, and this may be reasonable for a young first-year ice cover. If we assume a perfect c-shaped salinity profile and that the gas volume is equally distributed, the warmer ice in bottom part will give higher brine fraction and higher density.

4. Pareto chart (Fig. 6) offers no statistically significant effects on the density measurements by any of the studied factors, which is supported by F-test and corresponding p-values (Table 5).

CONCLUSIONS

Ice density is one of the main input parameters in calculations of ice loads on marine structures. Field investigations of ice features should include collecting of ice density data. Present study was targeted to check applicability of hydrostatic weighing technique for ice density measurements in the field environment as a potential alternative to the standard mass/volume method.

The main results are:

- Field tests performed during Oden Arctic Technology Research Cruise (OATRC2013) in the Fram Straight in August 2013 showed superiority of the hydrostatic weighing technique above the mass/volume method.
- Effect of ambient temperature together with storing time didn't have significant effect on the density results.
- As laboratory tests showed neither paraffin temperature, storage time of the ice sample nor part of the ice core has a statistically significant effect on the density measurements. The variance in the measurements is larger than effect of any of the studied factors or their interaction.

Further investigation can be done in the field keeping in mind that there is natural spatial distribution of the density values through the thickness of the ice sheet and that the storage time might have a minor effect, so the measurement should preferably be done as soon as possible after extracting the ice core.

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