MEASUREMENTS OF PERMEABILITY OF SEA ICE

Toshiyuki Kawamura¹, Masao Ishikawa¹, Toru Takatsuka¹, Shinsuke Kojima² and Kunio Shirasawa¹
¹ Institute of Low Temperature Science, Hokkaido University
² Department of Civil Engineering, Kitami Institute of Technology

ABSTRACT
Recently contribution of snow cover to sea ice growth has become of major interest. The contribution is partly due to snow-ice formation, which needs to infiltrate seawater through sea ice. Measurements on such an index, i.e. permeability, have scarcely been done in spite of a quite important factor. We measured the permeability of sea ice in both field and laboratory experiments. In the field studies, we obtained the values of the orders of -11 to -10. Definite relations between the permeability and the ice properties, e.g. temperature, salinity and structure, were not found. In the laboratory experiments, especially, we aimed to clarify difference of the permeability between ice types, i.e. granular and columnar ice. We obtained the values of the permeability of the same order of the magnitude as those in the field studies. The values were compared with those of the previous studies.

KEY WORDS: Sea ice; Permeability; Ice Types; Ice properties.

INTRODUCTION
The role of snow is usually perceived as negative during ice formation because of its low heat conductivity, which reduces bottom growth rates. Following recent studies conducted in the Antarctic Oceans, however, the positive contribution of snow cover to sea ice growth has become of major interest (e.g., Lange and others, 1990; Lange and Eicken, 1991; Jeffries and others, 1994). The contribution is due to two specific types of sea ice growth processes, i.e., snow-ice (e.g., Lange and others, 1990; Eicken and others, 1995; Worby and others, 1998) and superimposed-ice growth (Jeffries and others, 1994, 1997; Kawamura and others, 1997; Eicken, 1998; Haas and others, 2001). Snow ice is formed from a mixture of surface snow and infiltrating seawater (e.g., Lange and others, 1990; Jeffries and others, 1997). Superimposed ice is formed by the refreezing of fresh melt water that percolates through the surface snow cover onto the ice (Koerner, 1970). Both growth processes provide upward ice growth in contrast with ordinary downward congelation growth at the bottom. The processes can be very effective mechanisms for thickening, because the freezing interface is close to the cooling source.

Snow ice is created through a process of soaking of seawater into snow cover through sea ice
body, i.e., surface flooding of seawater. Therefore, snow ice formation needs the following two criteria that must be satisfied before flooding can occur (Crocker and Wadhams, 1989; Eicken and others, 1995):
1) A sea level is higher than a snow/ice interface or in a snow cover; the condition is so called “negative freeboard” or “positive hydrostatic water levels”.
2) Sea ice is permeable for seawater.

Sea ice permeability, a measure of the criterion 2) should depend on its temperature, salinity and structure. Although the permeability is a very important factor to understand snow ice formation, limited studies on it have been done as below. So, a little is known about the relationship between the permeability and the ice properties. Pounder and Little (1959) measured the permeability in a fieldwork. On the other hand, in laboratory studies, Saito and Ono (1978), Kasai and Ono (1984), Ono and Kasai (1985) and Saeki and others (1986) measured the value. Recently, Freitag and Eicken (2003) conducted a field observation to obtain the permeability, paying attention to meltwater percolation through the ice body in the summer melt season.

In this study, we present results of observation on sea ice permeability obtained in both field and laboratory studies. Especially, in the laboratory study, we aimed to clarify difference between granular and columnar ice.

METHODS

We measured permeability of sea ice with bail tests (e.g. Freeze and Cherry, 1979) on blind holes, drilled at different depths within the sea ice cover. The permeability of a porous medium is defined in the empirical law of Darcy, that describes the linear relationship between discharge and driving force, when a fluid is forced through the pores of a porous medium (Freitag and Eicken, 2003):

\[ u = (\kappa/\eta) \Delta p, \] (1)

where \( u \) (m s\(^{-1}\)) is specific discharge, \( \Delta p \) (Nm\(^{-3}\)) is imposed effective pressure gradient, \( \kappa \) (m\(^2\)) is permeability and \( \eta \) (kg m\(^{-1}\) s\(^{-1}\)) is dynamic viscosity. In the case of exclusively gravitational forces, the imposed pressure gradient can be expressed by the hydraulic gradient \( \rho g \Delta H/\Delta L \) in the direction of the main fluid flow, with density \( \rho \) (kg m\(^{-3}\)), gravitational acceleration \( g \) (m s\(^{-2}\)), and water-level difference \( \Delta H \) (m) between two selected observation points and their lateral distance \( \Delta L \) (m).

Assuming Darcy’s law (eq. (1)) for the laminar flow, the specific discharge \((= dh/dt)\) is expressed to be proportional to the driving force, the hydraulic head \( h(t) \). The recovery curve is given as

\[ h(t) = h(t_0) \exp\left[(-\kappa \rho g/\eta L) t\right] \] (2)

with hydraulic head \( h(t) \) (m), permeability \( \kappa \) (m\(^2\)) and ice thickness \( L \) (m) underneath the borehole. The exponent of the fitted function would thus provide a value for a vertical permeability under the assumption that sea ice is laterally impermeable.

Experimental data of the increasing water level have been expressed by an exponential curve,
approaching to the potential equilibrium water level (cf. Figure 3b). Therefore, the experimental hydraulic head curve to the water level agrees well with the exponential curve of Eq. (2). We can obtain the exponent \(-k\rho/\eta L\) and, consequently, calculate the permeability \(\kappa\).

If sea ice has lateral permeability, it should be taken into consideration. In his laboratory studies, Freitag (1999) indicated that the ice is laterally permeable also. On average, the lateral permeability is one order of magnitude lower than the vertical one. Freitag and Eicken (2003) derived a correction function from numerical simulations, which showed that the correction function \(\gamma\) depends linearly on the ice thickness under the blind hole with different ratios \(\kappa_l/\kappa_v\). In the case of \(\kappa_l/\kappa_v = 0.1\), \(\gamma(L)\) can be expressed by \(\gamma(L) = 0.17 + 10.7 L\). Thus the corrected vertical permeability \(\kappa_v\) (hereafter referred to as only permeability for simplicity) of sea ice is derived from measurements using eq. (2) and expressed by \(\kappa_v = \kappa / \gamma(L)\).

**MEASUREMENTS**

We investigated both field and laboratory studies to measure the permeability of sea ice. We carried out the field observations in the eastern part of Lake Saroma, Hokkaido, Japan (Figure 1) in the early February in 2003, and middle February and early March in 2004. Figure 2 shows a schematic drawing of the experimental set-up. Firstly we measured sea ice thickness at the hole drilled throughout the full depth with a CREEL type auger at each observation. We then measured sea ice temperature with a small drill and a thermistor, and sampled a sea ice core. Thereafter, we drilled a blind hole with fixed outer diameter of 105 mm near the sampling site. We installed a vinyl chloride pipe to effectively seal the perimeter of the core hole. Then, we put a float with a measure in the pipe as soon as possible. The vertical movement of the float was recorded with a video recorder. The change of the water level was measured on images in the video tape in the laboratory. Figure 3 shows an example of time series of a rise of the water level and ice properties.
In the laboratory experiments, firstly we grow sea ice in a cold room. A rectangular transparent acrylic water tank, whose inner sizes are 800 x 800 mm and 600 mm in height, was set in the cold laboratory at about -20°C. Figure 4 shows a schematic drawing of the tank with some accessories. Artificial seawater (tap water and salt) with a salinity of 32 psu was poured into the tank. The sidewalls and bottom of the tank were covered with insulation boards with 100 and 200 mm in thickness, respectively, to prevent ice growth from them. Belt-shaped heaters of 50 mm width were set around the sidewalls at the level of water surface to prevent growing sea ice from sticking to the walls. Temperature of air, ice and water was recorded using platinum resistance thermometers.

Figure 3: An example of permeability measurements (Feb. 5, 2003 at Ice Station). (a) a side view of a blind hole in the ice body, (b) a rise of the water level, and (c) temperature and (d) salinity profiles in the ice.
We used two kinds of ice type to find their difference of the permeability in the laboratory study. In one growth experimental run, columnar sea ice was made in the calm condition. On the contrary, in other two runs, granular ice was created in the turbulent condition caused by stirring the water with a fan. In the both cases, sea ice was grown to about 150 mm thick. Measurements of the permeability were done by the same method as the field study. However, a small-sized core drill and pipe were used, i.e. 75 mm of outer diameter and 64 mm of inner diameter, respectively.

After the permeability measurements, structure of the collected sea ice samples was observed on the vertical thick and thin sections. The samples were cut to small pieces at about 10 mm intervals according to stratigraphic variability. The cut pieces were then melted and the chlorinity were determined by the titration method (TOA Electronics, SAT-210, accuracy of 0.1 psu). The chlorinity was converted to salinity by a formula (e.g., Bennett, 1976). Brine volume in the ice was calculated from the temperature and salinity of the ice (Frankenstein and Garner, 1967).

RESULTS and DISCUSSION
The corrected permeability obtained in the field study has the orders of -11 to -10 with a range of 1.06 x 10^{-11} and 1.33 x 10^{-10} m², respectively. Figure 5 shows the relations of permeability to (a) the ice temperature, (b) the ice salinity and (c) brine volume in the ice, classified by the different ice types. Systematic relations are not found in the figures. Columnar ice, which has higher temperature and lower salinity, and consequently lower brine volume, has lower permeability. The result might be affected by the structure of this ice type. Except for the two values of the columnar ice, it seems to be found that slightly negative correlations of the permeability to the salinity and brine volume. However, the tendency is contrary to a common thought that increase of the salinity and brine volume should cause ice more permeable. The
contradiction remains to be unresolved because of limited data and their narrow regions. Further works with wide ranges should be investigated. The air fraction of the samples ranged less than 3 %, since the bulk density was about 880 kg/m$^3$. Therefore, the effect of the air volume on the permeability seems to be very low. However, it should be considered in the further studies.

Figure 5: Relations of the permeability to (a) temperature, (b) salinity and (c) brine volume of the ice in the field study. g., g/c and c. ice denote granular, intermediate granular/columnar (Eicken and others, 1989) and columnar ice, respectively.
All the permeability measured in the laboratory experiment has values of the orders of -11 with 1.16 to 7.95 x 10^-11 m^2. Unfortunately, since no salinity data were measured, a relation between the permeability and the ice brine volume was not obtained. Figure 6 illustrates a relation between the ice permeability and temperature. The values of permeability are similar to those of the laboratory study although the ice temperature is in a very narrow range and slightly lower than those. The columnar ice might have the lower values than granular ice in spite of very limited data.

Freitag and Eicken (2003) carried out in situ permeability measurements in Arctic during the summers. Their data showed the value of a range from 10^-11 to 10^-8 m^2. The mean and modal values were the orders of -9 in 1995 and -10 in 1996, depending melting rates, which were one or two orders magnitude higher than ours. Such high permeability is probably explained by the fact that their measurements were done in a melting season, when the evolution and widening of the brine channeling system as a result of brine drainage and internal melting processes. The values from laboratory studies on artificial sea ice at temperatures of –5 to –20 °C by Saeki and others (1986) were in the order of –12, being one order of magnitude smaller than our values probably because of lower temperature.

SUMMARY
Measurements of the permeability of sea ice were conducted in both field and laboratory experiments. One of the objectives of this study is to obtain difference of the permeability between ice types, i.e. granular and columnar ice. The difference and comparison with the previous studies were described. However, definite difference and relations between the permeability and ice properties could not be found. The reason is caused by the limited data of the narrow regions of the ice properties. Therefore, further study of the wide range of the properties is required to clarify the relations.

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