POAC'11
Montréal, Canada
POAC11- 008

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

FIELD EXPERIMENTS ON ICE-ICE FRICTION

Sergiy Sukhorukov[1,2] and Sveinung Løset[1, 2]

[1] Norwegian University of Science and Technology, Trondheim, Norway

[2] The University Centre in Svalbard (UNIS), Spitsbergen, Norway

ABSTRACT

This article presents initial results from field experiments on the friction between sea ice and sea ice. The experiments were performed near Akselöya Island at Svalbard (77˚43.664 N, 14˚46.565 E) in early May 2010. Ice blocks were pulled on level, snow-free ice. The friction force was measured, and the kinetic coefficient of friction was derived. Two ice blocks were used in the experiments; the first was obtained from a rubble ice field, and the second was cut from nearby level ice. The dependence of the kinetic friction on normal pressure (2.4 - 7.5 kPa) and sliding velocities (0.12 - 0.32 m/s) was investigated using the first ice block. Tests with short time stops were also performed while the block was sliding. The hold times (i.e., the duration of the stops) were 1 s, 2 s and 4 s. The influence of the ice block's orientation on the friction coefficient was studied using the second ice block. In total, 68 ice block runs were performed. The results demonstrated that the kinetic coefficient of friction did not change with increases in the normal load. However, the coefficient decreased with increasing velocity. The static and kinetic friction coefficients were independent of the hold time in the experiment with intermediate stops.

INTRODUCTION

An understanding of the phenomena associated with ice friction is an important problem for several engineering applications. When ice interacts with sloping structures, friction is a significant factor for calculation of ice forces on structures. Friction from ice and snow limits the performance of icebreakers and ships in ice-covered waters. A number of investigations have been performed to study the friction between ice and different construction materials under various conditions (Tusima and Tabata, 1979; Forland and Tatinclaux, 1985; Saeki et al., 1986; Frederking and Barker, 2002). In contrast, ice-ice friction phenomena have received considerably less attention. Friction between pieces of ice is an important factor that must be considered during the ridge building process and the brittle compressive failure of ice (Schulson and Duval, 2009).
Oksanen and Keinonen (1982) performed lab tests of ice-ice friction at sliding velocities between 0.5 m/s and 3 m/s. They obtained small values for the friction coefficient, which they attributed to the presence of a liquid melt film on the ice surface. Kennedy et al. (2000) studied ice-ice friction in the laboratory for both freshwater and sea ice under a range of velocities (5×10^{-7} m/s - 5×10^{-2}

m/s), temperatures and contact pressures. Generally the coefficient of kinetic friction decreased with increases in the velocity and increases in the temperature. At the lower temperatures (-30ºC and -40ºC) the kinetic coefficient of friction exhibited a peak value at intermediate velocities. They attributed their results to frictional heating, creep and fracture. Maeno et al. (2003) studied ice-ice friction in the laboratory using flat surfaces of pure ice to exclude the effect of ploughing. They discussed two physical mechanisms of ice friction: water lubrication and the adhesion shear deformation of ice.

Most investigations of ice-ice friction have been conducted using small-scale experiments and artificially produced ice. Frederking and Barker (2002) studied the friction between sea ice and various construction materials (including ice) in mesoscale laboratory tests. The values obtained for the friction coefficient were small. Lishman et al. (2009) studied ice-ice friction with meter-scale ice basin experiments.

The friction coefficient values measured in the field can differ from those measured in the laboratory. Therefore, field data are valuable.

Ryvlin (1967) conducted field experiments on ice friction with both freshwater ice (near St. Petersburg) and sea ice (in the Tiksi Bay). Although the main focus of this study was the friction between ice and steel, some results were reported for ice-ice friction.

In this article, we report the results from mesoscale field tests in Svalbard on the friction between sea ice and sea ice. The influences of sliding velocity, normal load and ice block orientation on the friction coefficient were investigated and are discussed in this manuscript.

TEST EQUIMPMENT AND PROCEDURES

Tests were performed in a field near Akselöya Island at Svalbard (77˚43.664 N, 14˚46.565 E) on the 4th and 5th of May 2010. The air temperature during the test period, which was sufficiently stable, was -3ºC ± 2ºC.

Snow was removed from an area of level sea ice that was 3 m long and 0.6 m wide, and a sliding track was prepared. Ice blocks were slid along the track using a pulling mechanism, which was driven by an electrical motor and operated at two speeds: 350 rpm and 1200 rpm. The motor was geared down using a system of gearing wheels, and three different pulling velocities were used in the tests. The pulling force was measured using a load cell attached between the pulling chain and the ice blocks. The load cell used in the tests, RSCAC1, exhibited a nominal load of 1960 N (200 kg). Data were collected using a Campbell CR1000 data logger at a sampling rate of 10 Hz. To prevent displacement of the pulling mechanism during the test, the apparatus was attached to the sea ice with four screws. The mean velocity was estimated by dividing the sliding length by the elapsed time. Figure 1 shows the test arrangement.

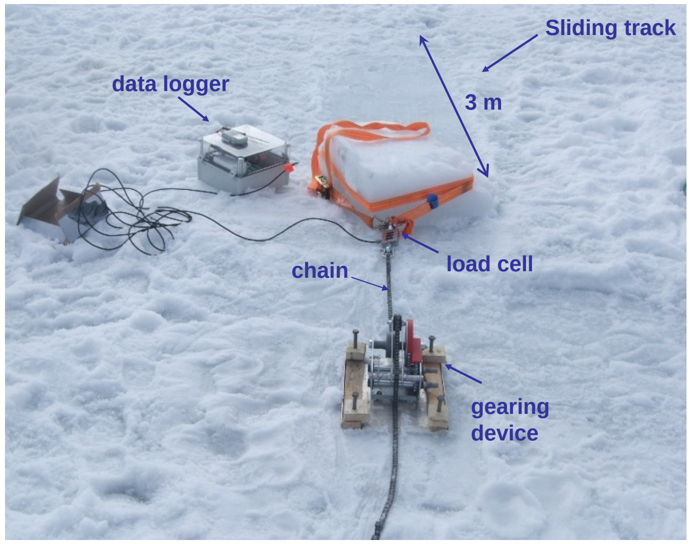

Figure 1. Test arrangement with the ice block at the end of the sliding track.

Two ice blocks were used in the experiment. The first was removed from the top part of the rubble ice field, and it exhibited a bulk salinity value of 0.4 ppt (Figure 2).

Figure 2. Extracting the first ice block from the rubble field.

The block resembled a rectangular prism with a mean height of 0.24 m and horizontal dimensions of 0.54 m and 0.41 m. The block was used to study the dependence of the kinetic coefficient of friction on the sliding velocity, normal load and duration of stationary contact. Tests were performed for three contact times: 1 s, 2 s and 4 s.
The second block, obtained from the level sea ice, also resembled a rectangular prism with the following dimensions: height - 0.53 m (sea ice thickness), length - 0.58 m and width - 0.5 m. This block was used to study the effect of the ice block orientation on the friction. The block was placed on its various sides and pulled along the track. Three different block orientations are shown schematically in Figure 3. First, the surface of the block that was in contact with the sea was placed on the sliding track. The sliding configuration in which the bottom surface of the ice block slid on the top surface of the level ice was denoted as *top-bottom*. Brine was allowed to drain onto the track, and friction occurred on the wet surface. The slush that formed on the track

was allowed to remain maintained during the two subsequent runs but was removed from the track prior to the next experiment.

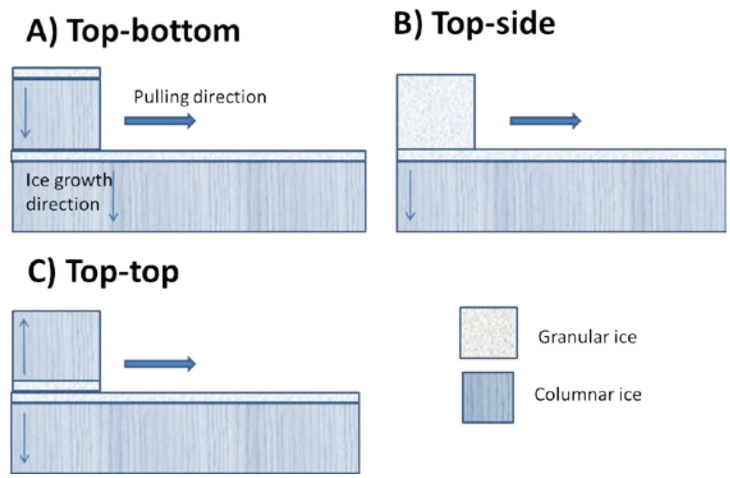

Figure 3. Orientations of the ice block during the sliding experiment.

The ice block was then placed on its side surface, perpendicular to the ice growth direction. This configuration was denoted as *top-side* (Figure 3B). In this case, the columnar ice slid on the granular ice. In the final configuration, which was denoted as *top-top*, the top surface of the ice block (granular ice) was placed on the track surface.
The same sliding track was used in all tests. Thus, each test produced incremental surface smoothing. The ice block was pulled along the track several times prior to data collection to obtain a relatively level track.

RESULTS AND DISCUSSION

Figure 4 shows an example of the temporal variations in the frictional force observed in the tests with the first ice block. The first peak load was associated with the force needed to initiate motion (inertia and static friction). Thereafter, the frictional force decreased and oscillated around a mean value of 170 N.

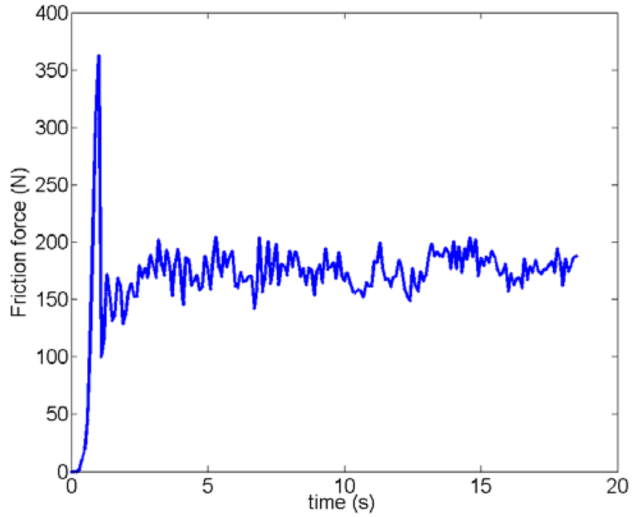

Figure 4. Temporal variations of the friction force. The normal force was 540 N (corresponding to a normal pressure of 2.43 kPa), the sliding velocity was 0.12 m/s and the ice temperature was -3ºC.

Effect of velocity on the friction coefficient

The friction tests were performed at three sliding velocities: 0.12 m/s, 0.23 m/s and 0.31 m/s. The tests were repeated seven times for each velocity, and averages were obtained. The results are shown in Figure 5. As shown in the graph, the kinetic friction coefficient decreased with increases in the sliding velocity.

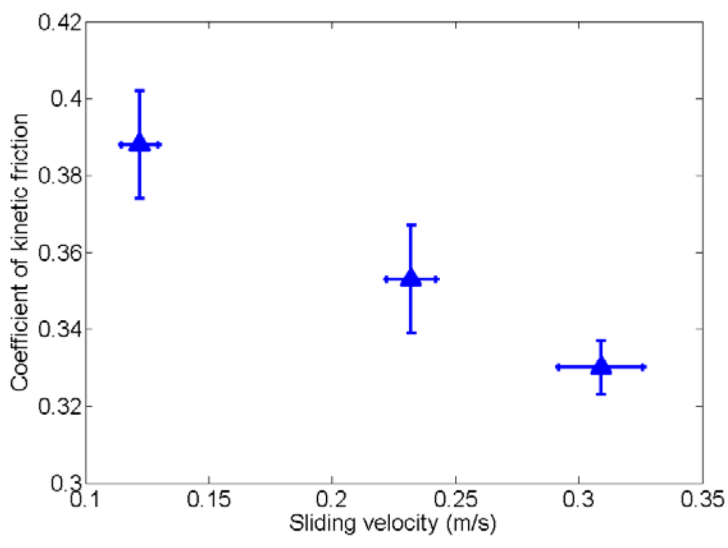

Figure 5. Kinetic friction coefficient versus sliding velocity. The normal pressure was 2.43 kPa, and the ice temperature was -3ºC.

The error bars in Figure 5 indicate uncertainty in sliding velocity measurements caused by the relatively rough measuring technique. The tests were first performed in increasing order of velocity. Therefore, the smoothing of the track surface may have influenced the results.

Effect of normal pressure on the friction coefficient

To study the effect of the normal load on the friction coefficient, ice blocks of different sizes were placed on top of the sliding block (Figure 6). The sliding velocity was maintained constant. A slight decrease in the sliding velocity (i.e., from 0.13 m/s to 0.11 m/s) was observed when the normal load was increased from 540 N to 1660 N.

Figure 6. Test arrangement to study the influence of the normal load on friction.

Three runs were performed for each normal load. The relationship between frictional stress and normal pressure is depicted in Figure 7. For these runs, the ice temperature and sliding velocity were -2.4ºC and 0.12 m/s, respectively. The results demonstrated that the coefficient of kinetic friction did not depend on the normal load.

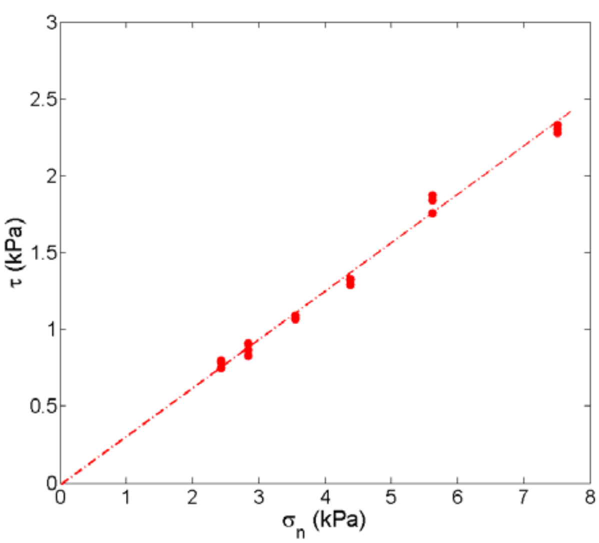

Figure 7. The relationship between frictional stress (τ) and normal pressure (σ_n). The ice temperature and the sliding velocity were -2.4ºC and 0.12 m/s, respectively.

Sliding with intermediate stops

In this test, the ice block was pulled for 4 s, stopped for a certain time (hold time), pulled for another 4 seconds and stopped again. This cycle was repeated several times until the block reached the end of the sliding track. The hold times were 1 s, 2 s and 4 s. Three runs were performed along the entire track for each hold time. Figure 8 shows the temporal variations of the friction coefficient for different hold times.

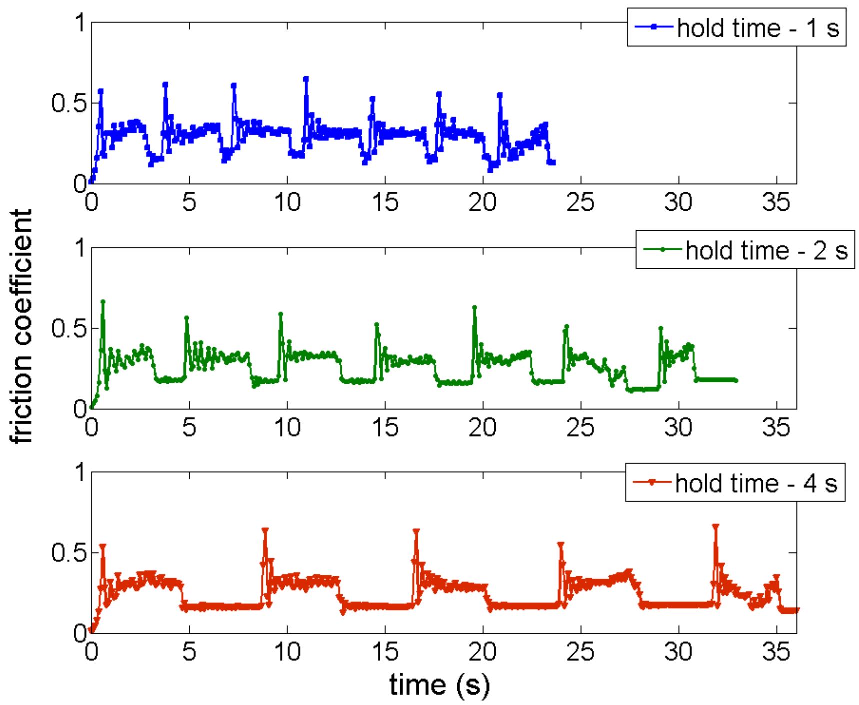

Figure 8. Temporal variations of the friction coefficient in the experiment with intermediate stops. The sliding duration was maintained constant at 4 s, and the durations of the stops (hold time) were 1 s, 2 s and 4 s. The normal pressure and ice temperature were constant and equal to 2.43 kPa and -2ºC, respectively. Sliding velocity during the tests was 0.12 m/s.

As shown in Figure 8, similar friction coefficient behaviour was observed in tests with different hold times. The average values of the static friction coefficient for hold times of 1 s, 2 s and 4 s are shown in Figure 9.

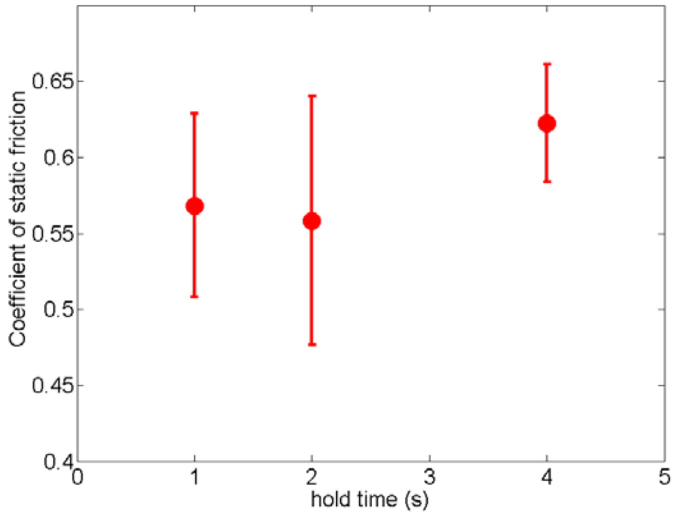

Figure 9. Coefficient of static friction versus hold time in tests with intermediate stops. The applied normal pressure was 2.43 kPa.

Effect of block orientation during sliding

To study the effect of block orientation on the friction coefficient, we used a second ice block, which was obtained from the level sea ice. As mentioned above, the three block orientations were tested: *top-bottom*, *top-side* and *top-top*. Three runs were performed for each configuration. The sliding velocity in the tests was 0.10 m/s. The normal load and contact area were slightly different in tests with different orientations due to the non-cubic form of the sliding ice block. For the *top-bottom* and *top-top* configurations, the normal pressure was 4.85 kPa. For the *top-side* configuration, the normal pressure was 4.58 kPa. The difference was not significant and did not affect our results considerably, which is demonstrated by the above-mentioned relationship between the normal pressure and the friction coefficient, i.e., the friction coefficient did not depend on the normal pressure.

Figure 10 shows the temporal variation of friction coefficient for the different sliding configurations.

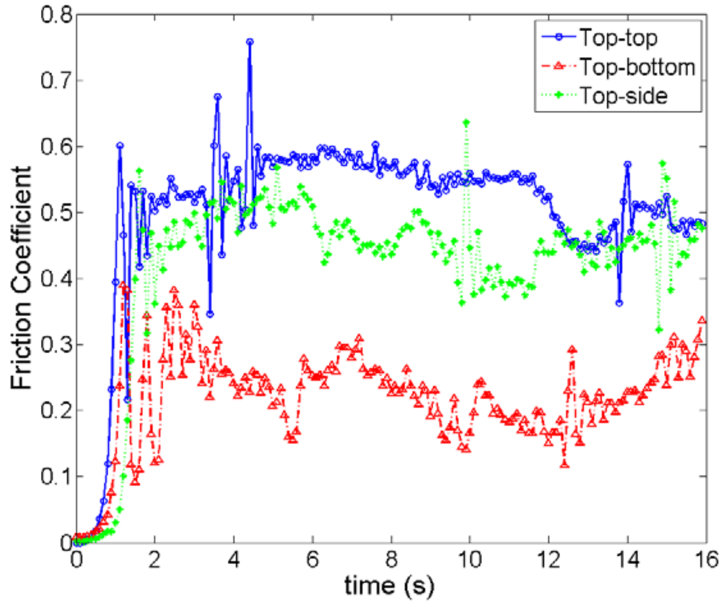

Figure 10. Temporal variations of friction coefficient (which is defined as the friction force divided by the normal load) for the *top-top*, *top-bottom* and *top-side* sliding configurations.

The average values of the coefficient of kinetic friction for different sliding configurations are presented in Table 1.

Table 1. Coefficient of kinetic friction for different sliding configurations.

	Top - bottom	***Top - side***	***Top - top***
Coefficient of kinetic friction	0.22	0.49	0.54

Figure 10 and Table 1 show significant differences in the friction coefficient values between the different block orientations. Several factors may have led to this behaviour. As discussed previously, the first three runs were performed using the *top-bottom* configuration. The brine from the ice block was allowed to drain onto the track surface, and sliding occurred on the wet surface. The slush that formed on the track during the tests with the *top-bottom* configuration was removed before the remaining configurations were tested. Therefore, the presence of slush on the track may have reduced the coefficient of friction. Another factor that may have contributed to differences in the friction coefficient for different configurations is surface roughness.

The friction coefficient values obtained in this research are higher than those presented in the literature. Frederking and Barker (2002) performed tests at a similar range of velocities, i.e., from 0.01 m/s to 0.7 m/s, and at an ice temperature of -5ºC; however, they used a normal pressure of 65 kPa. They found that the coefficient of kinetic friction for ice on ice ranged from 0.022 to 0.090. Ryvlin (1973) reported that the average values of the coefficients of kinetic friction for ice on ice and ice on steel ranged between 0.08 and 0.13, respectively, at sliding velocities of 0.5 m/s and greater and at a normal pressure of 10 kPa. Lishman et al. (2009) reported friction coefficient values between 0.3 and 0.4 at sliding velocities between 0.8 cm/s and 2.84 cm/s and a normal pressure of 10 kPa. These values are similar to our results.

CONCLUSIONS

Field tests were performed to investigate the friction between ice and sea ice. The influences of sliding velocity, normal load and block orientation during sliding were studied. The air temperature during the tests, which was sufficiently stable, was -3ºC ± 2ºC.

The main results of this study are summarised as follows:

- The kinetic coefficient of friction values ranged between 0.22 and 0.6. These values were significantly higher than values reported in laboratory tests.
- The friction coefficient did not depend on contact pressure in the range from 2.4 to 7.5 kPa.
- The friction coefficient decreased as the sliding velocity increased from 0.12 m/s to 0.32 m/s.
- Repeated sliding on the same track smoothened the surface and decreased the friction coefficient.
- The static friction coefficient did not change significantly when the stationary contact time increased from 1 s to 4 s.
- The friction coefficient depended on the block orientation.

ACKNOWLEDGEMENTS

We would like to express our gratitude to the students from the University Centre in Svalbard who assisted us in these tests.

REFERENCES

Forlad K.A. and Tatinclaux J.-C. P.,1985. Kinetic friction coefficient of ice, CRREL report 85-6 (1985), 45 p.

Frederking, R. and Barker, A., 2002. Friction of sea ice on various construction materials. *Proceedings of the 16th IAHR International Symposium on Ice*, Dunedin, New Zealand, 2002, pp. 442-449.

Kennedy, F.E., Schulson, E.M., Jones D.E., 2000. The friction of ice on ice at low sliding velocities. Philosophical Magazine A., 2000, Vol. 80, No.5, pp. 1093-1110.

Lishman, B., Sammonds, P., Felthan, D., and Wilchinsky, A., 2009. The Rate - and State-Dependence of Sea Ice Friction. *Proceedings of the 20th POAC Conference*, Luleå, Sweden, 2009. 9 p.

Maeno, N., Arakawa, M.,Yasutome, A., Mizukami, N., Kanazawa, S., 2003. Ice-ice friction measurements, and water lubrication and adhesion-shear mechanisms. Canadian Journal of Physics, 81(2003), pp. 241-249.

Oksanen, P. and Keinonen, J., 1982. The Mechanism of Friction of Ice. Wear, 78(1982). pp.315-324.

Ryvlin, A. Y., 1973. Experimental study on ice friction. Trudy AARI, 309, GIDROMETIZDAT, pp.186-199 (in Russian).

Saeki, H., Ono, T., Nakazawa, N., Sakai, M. and Tanaka, S., 1986. The coefficient of friction between sea ice and various materials used in offshore structure. Journal of energy resources technology, 108(1986). pp. 65-71.

Schulson, E.M. and Duval, P., 2009. Creep and Fracture of the ice. Cambridge University Press, 416 p.

Tusima, K. and Tabata T., 1979, Friction measurements of sea ice on flat plates of metals, plastics and coatings. *Proceedings of the 5th POAC Conference*, Trondheim, Norway, pp.741-755.