SOME PHYSICAL PROPERTIES OF ARTIFICIAL SEA ICE

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Introduction

During the months of February, March, and April, 1959, several techniques for increasing the thickness of an existing ice sheet were investigated by NCEL in cooperation with the Arctic Research Laboratory at Point Barrow, Alaska. To assist in evaluating the relative merits of each technique, some of the physical properties of the resultant artificial ice and of the natural sea ice were studied.

The three artificial ice types which were studied were:

(1) Flooded sea ice--formed by alternately flooding and freezing layers of sea water on to the existing ice sheet.

(2) Sprayed sea ice--formed by the accumulation of frozen sea water sprayed into the air through a fire hose spray nozzle.

(3) Flooded snow-ice--formed by alternately saturating and freezing layers of uncompacted snow with sea water.

Three different flooding techniques were investigated, involving 3 inch, 5 inch, and 7 inch flood layer thicknesses. In addition, a few ice specimens were obtained from two specially constructed plots built by a field party from MIT directed by Dr. M. Adams. These two plots consisted of approximately 1/8 and 1/2 inch layers, respectively, which were given a "squeegee" treatment after each flooding.

All the artificial ice was made between 17 February and 31 March. During this period the air temperature at the test site ranged from a high of +20°F to a low of approximately -46°F. The mean temperature was -21°F.

Temperatures through three of the flooded test plots were measured daily. Unconfined compression and ring tensile strength tests were made on 3-inch diameter core specimens taken from the various types of ice. Ice salinities and densities were also determined. This paper presents some of the preliminary results obtained from these data.

Ice Temperatures

One of the important phases of the Point Barrow ice study program was to observe the thermal effects which accompany the flooding method. To do this, ice temperatures through three of the flooded plots were measured periodically. Prior to the first flooding, 24-gage copper-constantan thermocouples were spaced 6 inches apart through the natural ice sheet at the centers of these plots. Before each flooding, additional couples were tied to the thermocouple pole to furnish a temperature record for each flooded layer. A portable potentiometer was calibrated to read temperature directly over the range from -100 to +100°F. It was read to the nearest 1/2°F and was accurate to ±1°F.

Figure 1 shows four typical gradients obtained from the temperature data from a 3-inch increment flooding plot. Temperature in °F is indicated on the abscissa and thermocouple locations in inches above or below the original ice surface are indicated on the ordinate. The feathered line at the 41-inch depth level locates the bottom ice boundary at the time the thermocouples were installed. The ice surface is indicated by the dotted area above each gradient. Gradient #1 was obtained on 6 March, just prior to the first flooding. A practically linear condition existed through the natural ice between the air and water boundary temperatures. Gradients #2 and #3 were obtained on 18 March, 23 hours after the sixth flooding and 5 1/2 hours after the seventh flooding, respectively. These two gradients show the warming effect of a new flooding on the underlying ice. Initially the ice surface is brought to the temperature of the flooding water, and subsequently, as the layer freezes, the interior of the ice sheet is warmed. Gradient #4 was obtained on 4 April, 12 days after the eleventh and final flooding. Note the persistence of the higher than normal temperatures in the interior of the ice sheet.

Ice Density, Salinity and Brine Content

To supplement the ice strength and temperature data, a number of density and salinity determinations were made for each type of ice. Average values are shown in Table 1. Salinities were determined with a set of hydrometers, read to the nearest 1/10 ‰ and corrected to salinity at 15°C. Densities were calculated from weight and volume determinations. The maximum uncertainty in the density calculations is 2 or 3 per cent.

Table 1

ICE DENSITY AND SALINITY

Ice Type	Salinity (‰)		Density (gm/cm^3)	
	No. of Specimens	Average	No. of Specimens	Average
Natural	150	6.6	71	0.899
Flooded A	161	17.0	74	0.866
Flooded B	8	21.6	6	0.904
Sprayed	28	14.1	13	0.844
Flooded Snow	12	12.8	9	0.824

Natural ice specimens represented in Table 1 include those from the undisturbed ice surrounding the test area and from the ice sheet beneath the various flooded test plots. Group A of the flooded ice specimens includes all the ice from the six plots which were flooded in 3 inch, 5 inch, and 7 inch increments. Variations in the salinity averages for these plots were found but were not significant

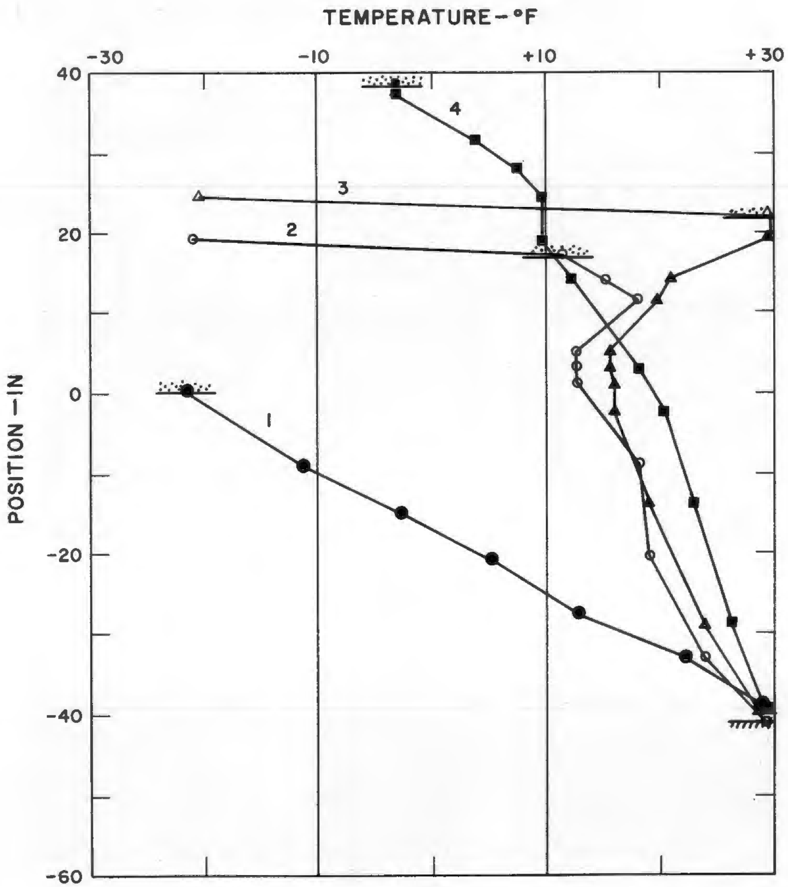


Fig. 1. Typical temperature gradients for Test Plot #1, a three-inch flooding increment test plot.

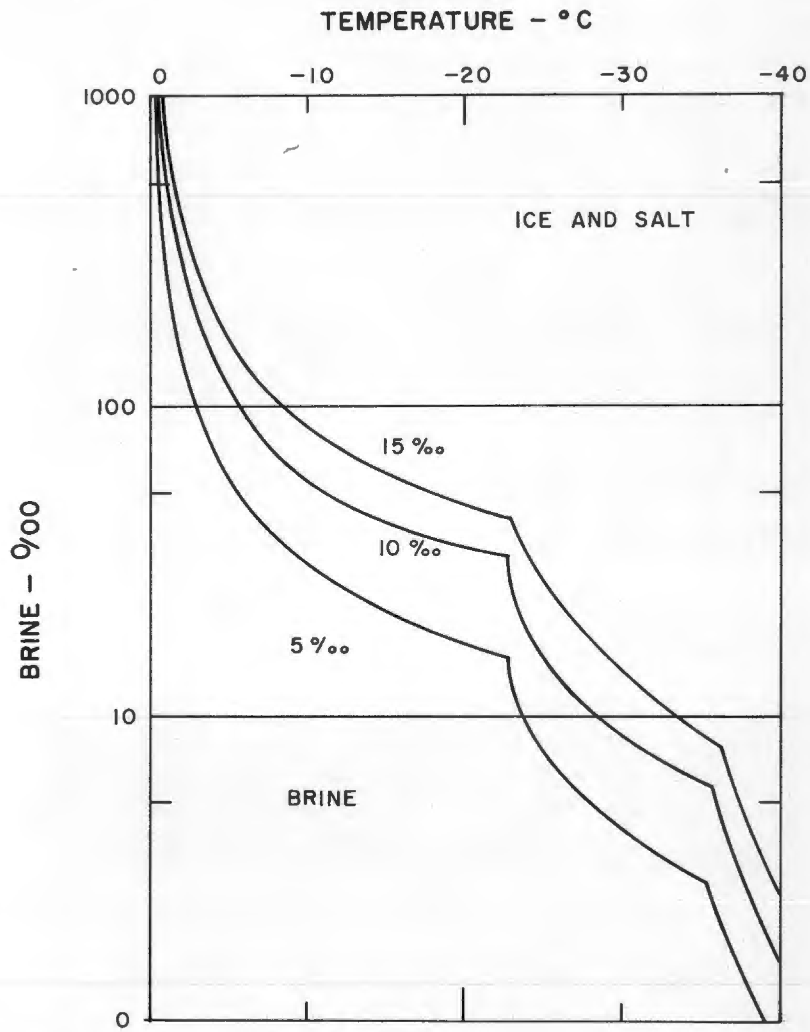
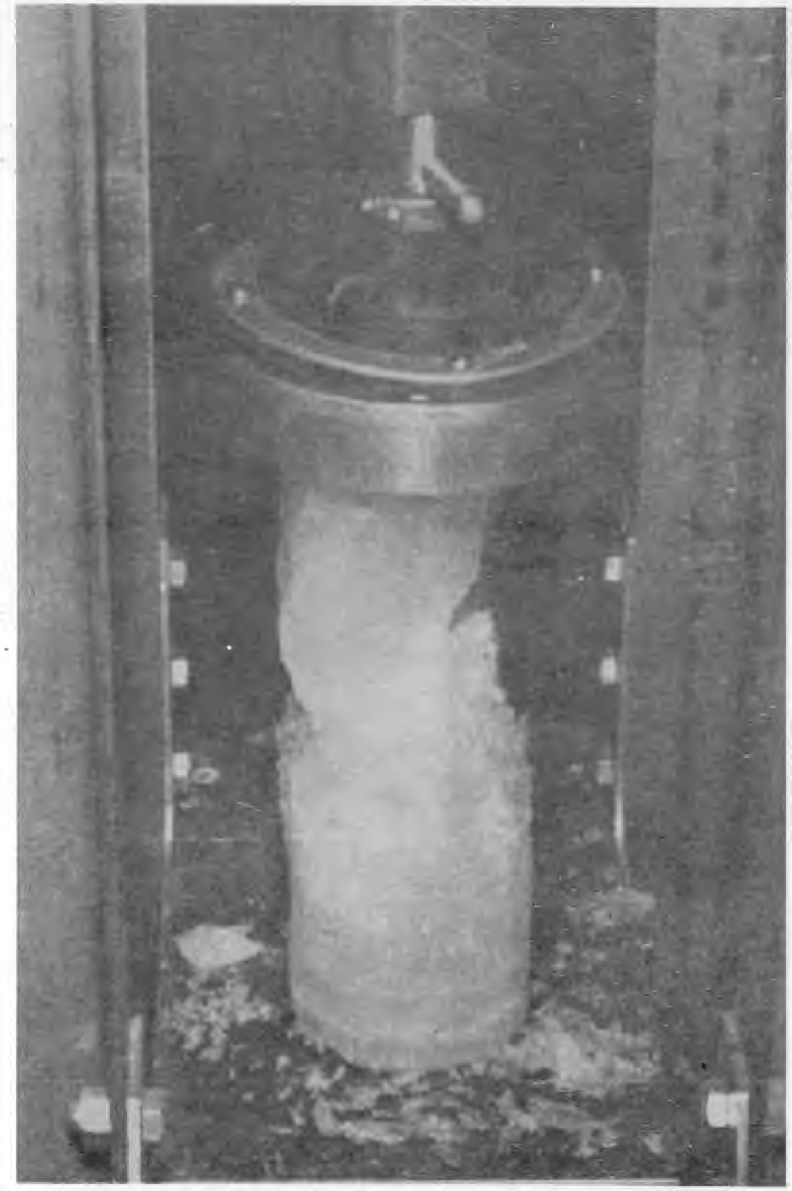


Fig. 4. Brine content vs temperature curves for sea ice with 5, 10, and 15‰ salinity.



Figs. 2 and 3. Typical compression test specimen failures.

in view of the large scatter in the salinity data. Note that in spite of the high salinity of this ice, its density is less than that of the natural ice. This was probably caused by aeration of the flood water as it was pumped onto the test plots. The group B flooded ice specimens were obtained from the two test plots built by the MIT field party at Point Barrow. This thin-layer method appears to produce ice with slightly higher salinity and density.

The sprayed ice specimens tended to have a slightly lower salinity and density than the flooded ice and also had the visual appearance of being more uniformly aerated. Flooded snow-ice specimens had the lowest salinity and density averages of the artificial types of ice studied. Uniform saturation of the snow layer with the flood water was not achieved and it was not unusual to find small snow pockets encased in this ice.

Probably the most surprising feature of these data is that the salinity of the flooded and sprayed ice is from 30 to 60 per cent less than the salinity of the water used to make this ice. Either the sampling technique was missing a highly saline portion of the ice or else this highly saline brine was escaping from the ice. There is evidence from two laboratory studies and another field study at Thule, Greenland, last year that this brine escapes through the underlying ice into the ocean within 1 or 2 days after flooding.

Some interesting observations were made regarding the brine content of the flooded ice. Whenever a hole was drilled through the flooded ice but not through the underlying natural ice sheet, a concentrated brine would almost immediately begin collecting. This was apparently caused by the pressure of the upper ice expressing brine from the warmer lower layers. This process would continue until 1 or 2 ft of brine had collected in the hole, then would stop. If the brine was removed, the hole would refill to the same level. Samples of these brines averaged about 200 ‰ salinity. After 2 or 3 days, several of these brine collection holes were found to have developed smaller holes in their bottoms, about 1 inch in diameter and extending through the underlying 3 or 4 feet of ice. When hydrostatic contact was made with the ocean, sea water would flood into the original hole, and it would then freeze up. From a brine content profile made up from the temperature and salinity data for one of the test plots, it appears that the region of brine drainage corresponds with that stratum in the profile where the brine content is greater than 10 per cent by volume.

Crushing Strength Test Results

About 130 unconfined compression tests were performed on 3 inch-diameter core specimens of the various types of ice. Specimen lengths ranged from 5.5 to 8.25 inches and averaged 7.5 inches. After the specimens had been cut in a miter box, they were stored for 1 to 7 days and allowed to reach equilibrium with the ambient air temperature. Low temperature tests were obtained from specimens stored in an outdoor shelter. Higher temperature results were from specimens stored and tested in a partially heated utility garage.

Loads were applied with a hand operated mechanical jack mounted on top of a rigid aluminum testing frame. A 10,000-lb load cell was located between the jack and the upper bearing plate and connected to a Brush Analyzer and Recorder to give a load vs time recording. Constant Load rates, which averaged about 5 psi per second, were obtained by adjusting the turning rate of the jack handle to obtain a constant slope on the recording. All of the specimens were loaded to failure or until the maximum load could not be maintained because of excessive plastic yielding. Figures 2 and 3 show some typical compression test failures.

A summary of the crushing strength data is given in Table 2. These results show that at the same test temperature, the crushing strength of the natural sea ice is approximately 100 per cent greater than any of the artificial types of ice. The "t" test for determining the significance of these differences (See Croxton and Cowden, "Applied General Statistics") indicates they are all highly significant in spite of the large scatter in the data. The differences in the mean strengths of the various artificial types of ice at the same temperature are not highly significant.

Table 2

RESULTS OF COMPRESSIVE STRENGTH TESTS

Ice Type	No. of Tests	Mean Test Temp. (^{o}C)	Mean Max. Stress (psi)	St. Dev. (psi)
Natural	15	-28	1427	433
Natural	48	-17	792	187
Flooded	16	-27	654	107
Flooded	44	-16	334	99
Sprayed	2	-26	608	20
Sprayed	3	-20	381	151
Flooded Snow	4	-13	214	37

Each type of ice was found to have a significantly higher strength at the lower test temperature. This temperature dependence is undoubtedly due to the lower residual brine content of the ice at lower temperatures. From the curves shown in Figure 4 we see that the brine content of 10 ‰ salinity sea ice, for example, drops from 40 ‰ at -15^{o}C to 10 ‰ at -28^{o}C.

Ring Tensile Strength Test Results

One hundred and five ring tensile strength tests were made on 3-inch diameter core specimens following the general recommendations made by SIPRE. (See Transactions Engineering Institute of Canada, Vol. 2, No. 3, Sept. 1958). Each specimen was cut to 3 inches in length (±1/32 inch) and a 1-inch diameter hole drilled through its center. Loads were applied and recorded in the same manner as described for the compression tests. The average loading rate was about 21 psi per second, and the range of loading rates was considerably larger than in the compression tests.

A summary of the ring tensile test data is shown in Table 3. In comparison with the crushing strength data, the scatter and the mean strength differences in the tensile test data are considerably smaller. The difference in the mean strengths of the natural and the flooded ice specimens is the only one which the "t" test indicates is highly significant. As in the compression tests, the specimens tested at the lower temperature are significantly stronger than the warmer test specimen group.

Table 3

RESULTS OF RING TENSILE STRENGTH TESTS

Ice Type	No. of Tests	Mean Test Temp. (°C)	Mean Max. Stress (psi)	St. Dev. (psi)
Natural	9	-28	116	20
Natural	18	-15	80	10
Flooded	52	-16	51	15
Sprayed	19	-14	69	26
Flooded Snow	7	-15	67	12

Conclusions

Results from the Point Barrow studies indicate that the strength of artificial sea ice is about 50% that of natural sea ice in compression and about 80% in tension. The primary cause for the lower strengths is believed to be the higher salinity, hence higher brine content, of the artificial ice for any specified temperature. Higher porosity may also have a detrimental effect on the strength of artificial ice; however, its magnitude is not known.

It is anticipated that further analysis of the Point Barrow data will provide information on the following characteristics of artificial ice making techniques and ice properties:

(1) Empirical relationships between the brine content of natural and artificial sea ice and their compressive and tensile strengths.

(2) Porosity and its effect on the strength of sea ice.

(3) Young's Moduli for the various artificial ice types from the compressive strength data and the apparently constant strain rate information also available from the 'load vs time' record for each specimen.

(4) Thermal properties of flooded ice and possibly the establishment of a criterion for an optimum flooding technique and time schedules.

(5) Brine migration rates through the bottoms of brine collection holes.

(6) Correlations between the location of cracks which occurred around several of the flooded plots and the existing theory for the deflection of ice sheets under loads of the same magnitude and distribution as represented by each flooded test plot.