THE PHYSICAL PROPERTIES OF SNOW AND SEA ICE*

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A great body of empirical information has been gathered over the years on the physical properties of snow and ice, but only recently has any systematic attempt been made to analyze theoretically properties other than flow. Encouraging success in the prediction of sea ice strength based on studies of structure and composition has led to the analysis of other properties of sea ice such as thermal and electrical conductivity, elasticity, latent and specific heat, and permeability. Electrical and elastic properties are particularly interesting since they can be measured in situ by geophysical means. Because the amount of unfrozen brine is the controlling factor in determining the condition of sea ice, all of the physical properties are closely related and show similar temperature dependencies. For instance, it is possible to determine approximately the bearing capacity of a sea ice sheet from seismic or vibration studies alone. Directly determined are elasticity and thickness, and tensile strength is determined indirectly.

Most of the physical properties of sea ice are complicated functions of temperature and salinity because of the continuous change of phase taking place as it freezes. Figure 1 is a photomicrograph of typical sea ice sections showing the brine-ice relationship. The density of sea ice is a unique and basic property. Figure 2 is the result of recent calculations, and indicates that the density goes through two minima as the temperature is lowered. The coefficient of thermal expansion (Fig. 3) varies over several orders of magnitude and even reverses. Figures 2 and 3 indicate the need for careful sampling techniques and careful temperature control when density measurements are made. The initial expansion of sea ice explains the absence of thermal cracks, in contrast to lake ice which is full of cracks.

The heat required to lower the temperature of sea ice is taken up in the freezing of ice; the crystallization of salts; and the specific heat of ice, brine, and salt. The heat of crystallization of the salt hydrates over certain temperature ranges is an appreciable fraction of the total heat involved and cannot be ignored. The "specific heat" and "latent heat" of sea ice have been calculated to facilitate calorimetric verification of the phase relations. The heat required to melt 1 gram of sea ice completely, for example, is shown in Figure 4. Figure 5 is perhaps the best documented sea-ice growth curve ever obtained. It is the result of approximately 5 to 30 measurements a day on natural ice sheets and artificially opened ponds which had undergone many kinds of thermal histories. The theoretical growth curve for pure ice would be a straight line on this double log plot. The departure from linearity is due to the absence of a unique freezing temperature and the associated temperature dependence of the thermal "constants".

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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. (^oC)	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.

A model consisting of intergrowing spheres of ice has been used to calculate such properties of snow as dielectric constant, elasticity, strength, and thermal conductivity. The agreement with observed data encouraged the use of this information to determine the principal process of material transfer. It can be shown that a rearrangement and packing of grains can only lead to a density of about 0.58 g/cm^3 in the absence of water, and that further densification proceeds due to migration of molecules, probably along the liquid surface film. It is suggested (Anderson and Benson, 1959) that this "critical density" is the dividing line between snow and firn. Most of the physical properties of glacier material change at the critical density, making this concept more fundamental than the firn-ice boundary, at which point permeability alone changes. Figure 6 shows experimental and calculated values of strength and elasticity for a packing of spheres, and a homogeneous mass with isolated spherical holes. Both theoretically and experimentally the strength and elasticity are almost the same function of density.

The ideas expressed in this paper are more fully developed in the following papers:

Anderson, D. L. (1958) A model for determining sea ice properties. Arctic Sea Ice, National Academy of Sciences Publication 598.

Anderson, D. L. (1958) Preliminary results and review of sea ice elasticity and related studies. Trans. Eng. Inst. of Canada, 2, no. 3.

Anderson, D. L. (1959) The physical constants of sea ice. (In preparation).

Anderson, D. L. and Benson, C. S. (1959) The densification of snow. (In preparation).

Anderson, D. L. and Weeks, W. F. (1958) A theoretical analysis of sea-ice strength. Trans. Am.Geophys. Union, 39, no. 4, 632-640.

Weeks, W. F. and Anderson, D. L. (1958) An experimental study of strength of young sea ice. Trans. Am.Geophys. Union, 39, no. 4, 641-647.

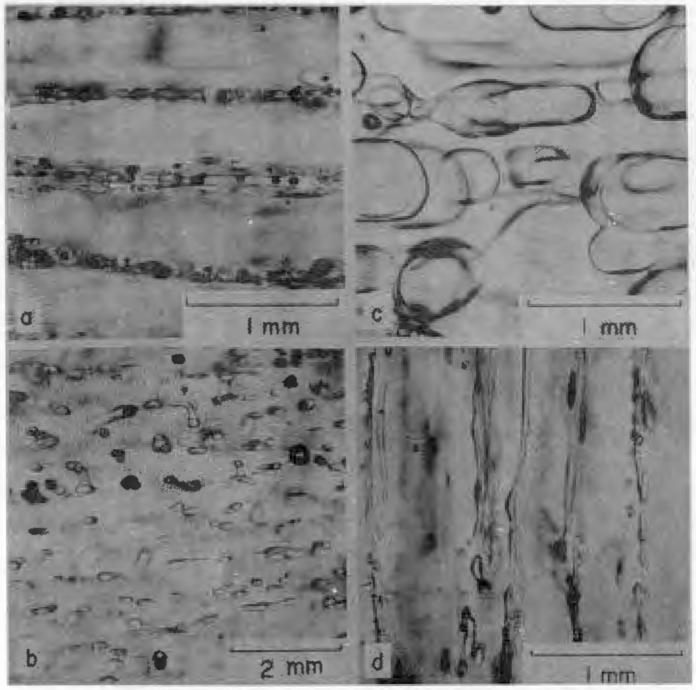

Fig. 1. Photomicrographs of thin sections of sea ice showing the brine, ice relationship (photo by W. F. Weeks).

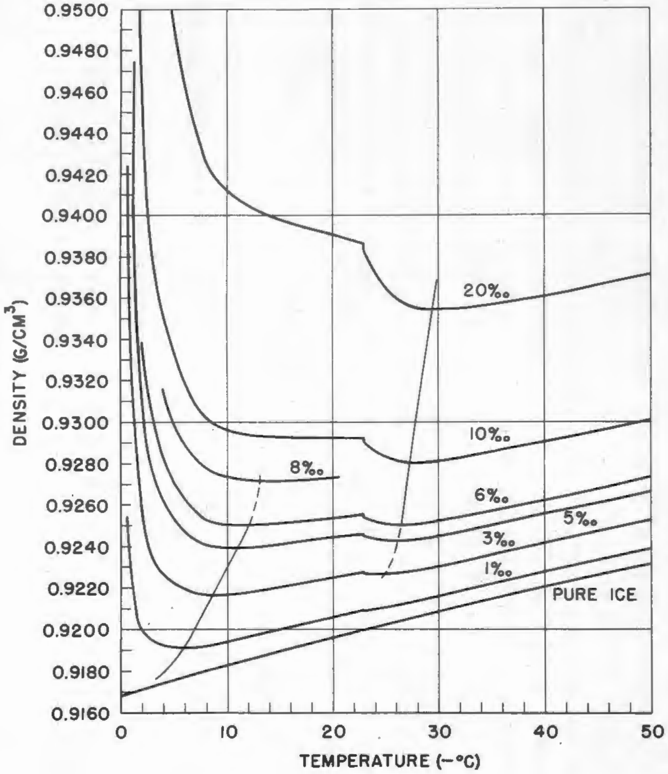

Fig. 2. Density of air free sea ice vs temperature and salinity.

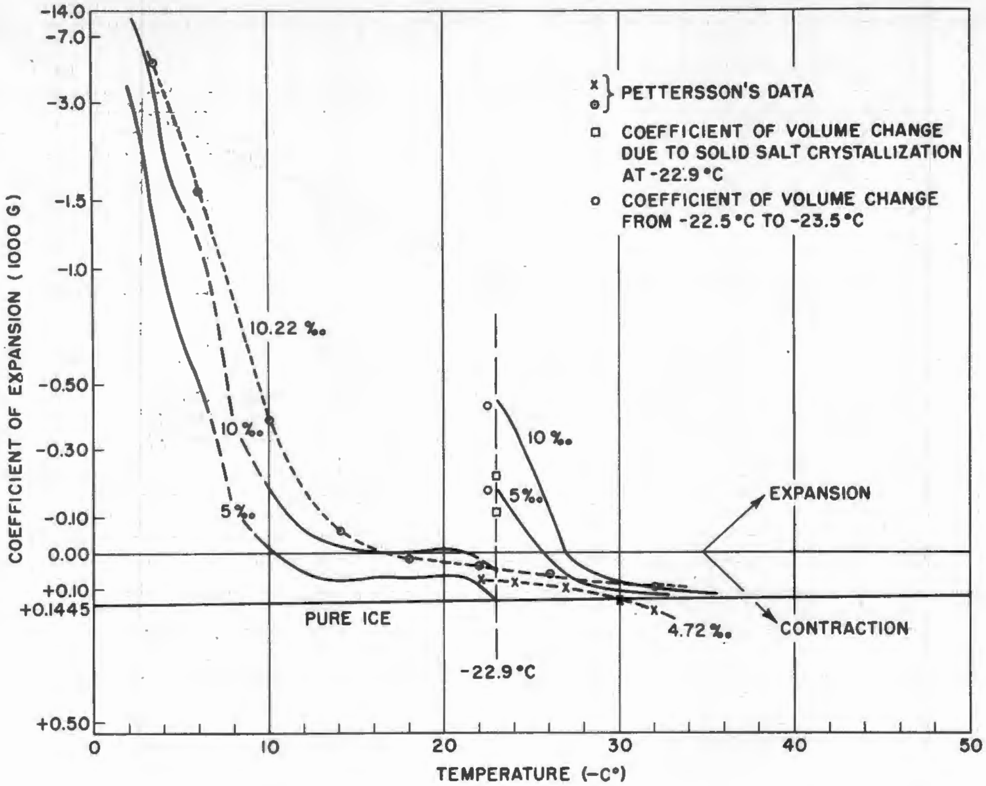

Fig. 3. Coefficient of thermal volume expansion of air free sea ice.

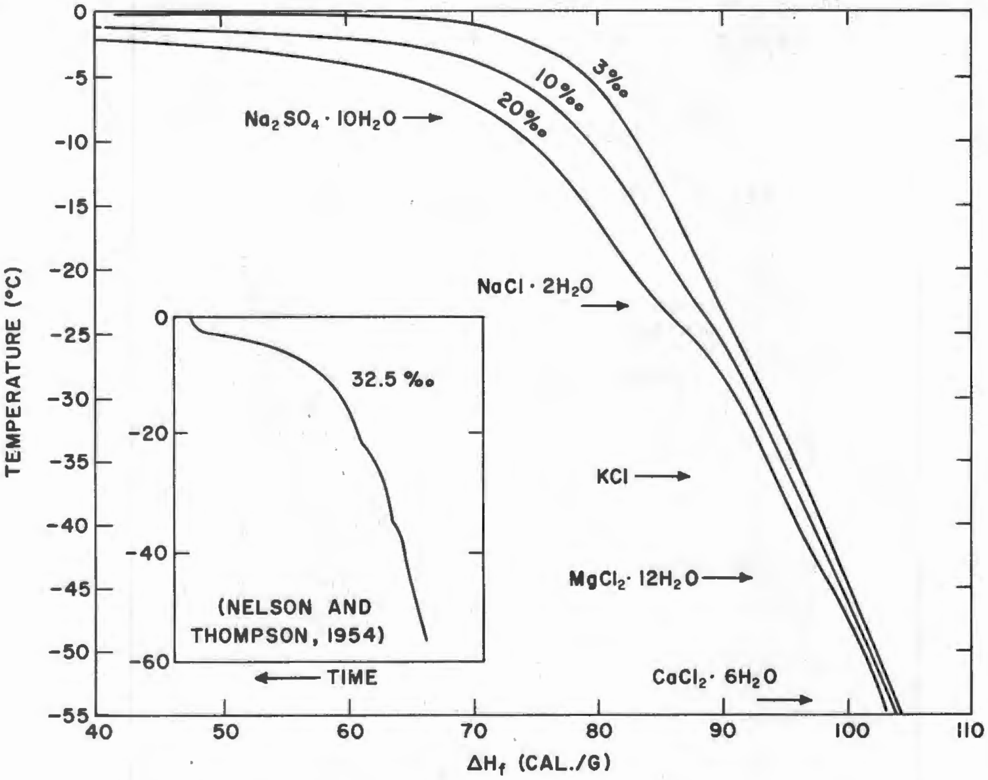

Fig. 4. Heat required to melt one gram of sea ice completely.

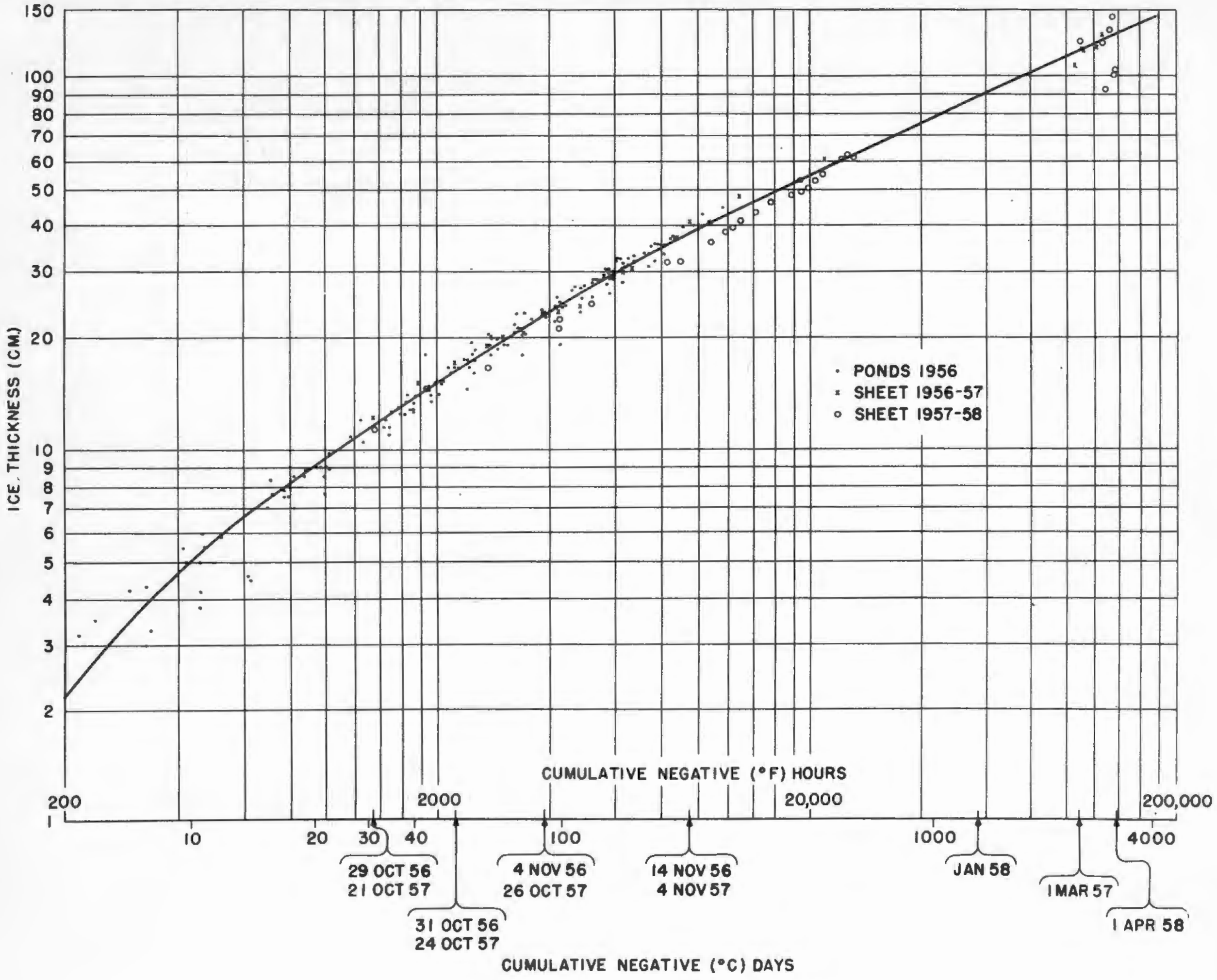

Fig. 5. Growth curve of sea ice.

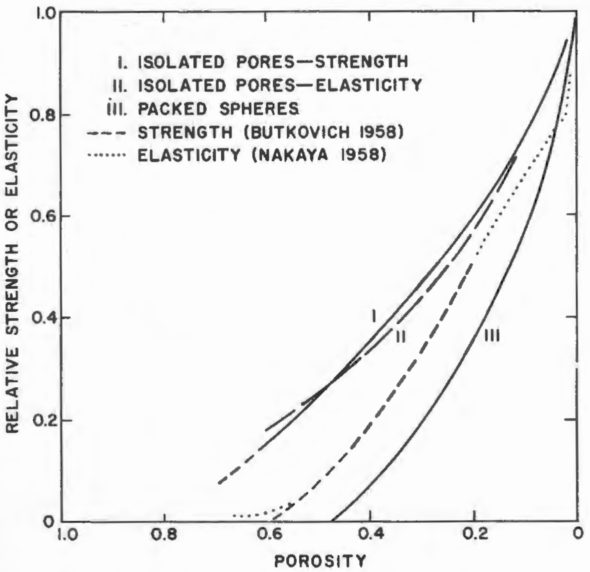

Fig. 6. Experimental and calculated values for strength and elasticity of firn.