APPLIED GLACIOLOGY—THE UTILIZATION OF ICE AND SNOW IN ARCTIC OPERATIONS

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Abstract. In addition to field observations and quantitative analyses of natural phenomena, an opportunity exists for the application of glaciological knowledge. Major problems preventing the widespread use of ice and snow as structural materials are related to processing methods, properties of ice and snow, and deterioration during the melt season. These difficulties have been considered and an experimental program carried out to determine the feasibility of developing practical methods for using ice and snow as engineering materials. Results show that the development of improved processing methods for both ice and snow, the development of ice alloys with improved properties, and the extension of the use season provide real opportunities for applied glaciology.

Résumé. La glaciologie, qui s'occupe d'observations pratiques et de l'analyse quantitative de comportement des masses de glace de formation naturelle, est également susceptible de fournir des occasions multiples dans le domaine du génie civil. D'une façon générale, la fusion saisonnière à laquelle sont sujettes la neige et la glace, ainsi que le problème du traitement qui doit précéder toute utilisation, rendent malaisé l'emploi de ces matériaux dans les constructions. On a etudié ces problèmes, et on a suivi un programme de recherches rédigé dans le but d'élaborer des méthodes pratiques pour rendre la glace et la neige utilisables par les ingénieurs. D'après les rèsultats, on peut affirmer qu'il existe de véritables possibilités pour la glaciologie appliquée: dans le domaine de l'amélioration des traitements que l'on fait subir à ces matières premières; dans la fabrication d'alliages de glace à propriétés mécaniques supérieures; et dans la modification des matériaux à base de neige ou de glace pour prolonger la période de l'année pendant laquelle ils restent utilisables.

Zusammenfassung. Neben Beobachtungen im Feld und quantitativen Analysen natürlicher Phänomene existiert eine Gelegenheit für die Anwendung glaciologischer Kenntnis. Hauptprobleme, die den weitverbreiteten Gebrauch von Eis und Schnee als Baustoff hindern, beruhen auf Verfahrungsmethoden, Eigenschaften von Eis und Schnee und Verschlechterung während der Schmelzsaison. Diese Schwierigkeiten wurden erwogen, und ein Versuchsprogramm wurde durchgeführt, um zu bestimmen, ob die Möglichkeit, praktische Methoden zur Benutzung von Eis und Schnee als Baustoffe zu entwickeln, besteht. Resultate zeigen, dass die Entwicklung verbesserter Verfahrungsmethoden für Eis sowohl wie für Schnee, die Entwicklung von Eislegierungen mit verbesserten Eigenschaften und die Verlängerung der Gebrauchssaison eine wirkliche Gelegenheit für angewandte Glaciologie ergeben.

Introduction

As recently pointed out by Mr. G. Seligman,[1] glaciology is entering into a new phase. In the past, and perhaps at present, the most extensive area of glaciological and Arctic research has been observation, exploration and mapping. In recent years, however, physicists have become more active in the field and a new quantitative glaciology has come into being. This quantitative treatment has largely been restricted to explaining and systematizing observations of natural phenomena. It is the purpose of the present paper to consider the opportunity and feasibility of applying this quantitative understanding to the development of a new field of "applied glaciology" or "glaciological engineering".

A major difficulty with Arctic operations is the complicated logistic approach required; any solution of this problem of logistics would have enormous potential consequences.

In addition to logistics, the general importance of snow and ice phenomena to Arctic operations is obvious. Under the worst conditions it can hamper operations or make them impossible by destroying mobility of personnel and equipment, by hampering the use of facilities, or by causing damage to supplies and equipment. An important aspect of Arctic expeditions has been in keeping these difficulties from stopping activities altogether. However, ice and snow are also potentially of considerable utility in Arctic operations as materials of construction. We regard it as axiomatic that the use of regions in which ice and snow are found in abundance can only be developed when the local environment, including these materials, is positively used rather than passively fought. The utmost utilization of ice and snow as materials of construction is indicated because they are potentially inexpensive and

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readily available. Accepting the fact that extension of our terrestrial frontiers depends on being able to conquer difficult environments, it becomes apparent that we must give careful consideration to the opportunity for applying glaciological knowledge to the development of ice-covered regions.

Ice and snow have been used as construction materials by indigenous peoples for a long time. Applications have included snow houses, ice logging roads and ice bridges, ice storage areas in logging operations, and many others. In all these applications the requirements related to material properties are not stringent and applications have been limited to the use of natural unimproved material. Extensive progress has been made in developing methods of excavation of tunnels and rooms in glacier ice and snow, but the opportunities and usefulness for this kind of construction are obviously limited. Various methods of utilizing compacted snow have been successful for uses where requirements are not stringent. Results have been less satisfactory where uniformly high strength levels are required.

Difficulties in Using Snow and Ice as Engineering Materials

The limitations of ice and snow as structural materials are related first to the engineering properties of these materials, which are rather poor, second to the present state of development of processing techniques, and third to deterioration during the melt season, which limits the useful life. Necessary processing techniques depend to a large extent on the properties which can be achieved, since these properties determine the amount of material that must be handled, the size of structures that can be built and their utility. Similarly, the useful life of the structure determines to a considerable extent the amount of expense and elaborateness which is justified for its preparation. At the present time it is generally true that the level of properties, processing methods and useful life are all below minimum requirements.

With regard to properties, even the best samples of ice and snow are poor as engineering materials. The most satisfactory natural material is pure lake ice, which has an average tensile strength of about 12 kg./cm.^{2} and a compressive strength of about 45 kg./cm.^{2}. Substantial variations are observed between different samples so that the useful strengths are lower than these average values. This is much weaker than any comparable construction material suitable for widespread applications. Concrete, for example, has a tensile strength too low for normal use without reinforcement—about 20-30 kg./cm.^{2}—and a useful compressive strength of about 200 kg./cm.^{2}. In addition to its low breaking strength, ice readily deforms with time under stresses as low as 1 kg./cm.^{2}, so that it is unsuitable for permanent or semi-permanent loads. Other natural products have even worse properties. Sea ice has a strength lower than lake ice by an indeterminate amount depending upon its salinity and temperature. An average tensile strength may be 8-10 kg./cm.^{2}. Compacted snow has a strength lower than that of lake ice due to the substantial porosity present. The strength and deformation properties of snow depend on the fractional porosity and the pore structure.

Alloys based on ice have not been extensively studied. The only serious consideration given to developing improved properties was the development of ice-sawdust mixtures, "pykrete" as described by Perutz.[2] Material with about 15 per cent of sawdust added has a tensile strength of about 50 kg./cm.^{2} and a compressive strength of about 75 kg./cm.^{2}. In addition, it has a much more uniform strength than pure ice and provides a real opportunity for building structures from ice with improved characteristics.

The low strength values observed for natural ice and snow mean that massive structures are necessary in order to achieve useful results. For example, as a landing platform for modern aircraft, thicknesses up to 50 in. (1·3 m.) of fresh ice and up to 74 in. (1·8 m.) of sea ice are recommended in some cases as being necessary for "safe" operations.[3] Thicker layers of compacted snow would be required to achieve equivalent results. These large masses of material could conceivably be built up in many ways. One method would be to utilize natural formations. This is now done with both lake and sea ice and with glacier ice. Manipulation of natural snow and ice by civil engineering processes such as snow removal techniques, excavation techniques and construction of tunnels has been carried out extensively and successfully, particularly by the U.S. Army Snow, Ice, and Permafrost Research Establishment. However, the use of natural formations has the disadvantage that the operating season is short, controls are difficult and supplies are frequently not available where needed. Landing operations for aircraft on Arctic sea ice, for example, are generally limited to the three-month period from 1 March to 1 June.[4] Dependence on these natural formations corresponds roughly to the cave-dwelling, stone-age epic in more temperate climates.

Artificial flooding and freezing has been successfully employed with fresh water in the construction of logging roads, ice bridges and so on. However, fresh water is frequently not available; artificial solidification of sea-water has been attempted on a few occasions but the results have not been very successful. Difficulties arise as a result of the fact that when sea water solidifies, a residual brine is formed with a freezing point below $-36°$ C., although only two per cent of liquid remains at $-22°$ C.[5] There have apparently been few serious efforts to cope with the problem of devising methods for reducing the residual brine content and obtaining sound ice quickly.

Another processing method that has been attempted is snow compaction to form a dense, strong product—the equivalent of hot-pressing or sintering of powdered ceramic compacts which form dense products on heating. Extensive engineering tests have been made; a snow runway has been constructed in Greenland and a 150-acre (60 hectare) parking lot for the winter Olympics at Squaw Valley in the United States is being built.[6, 7] These efforts have not been successful in making a runway suitable for heavy aircraft, but are excellent for applications where only small strengths are required. Compaction of snow on an available solid base has been carried out successfully, but in this case the properties of the compacted snow are not critical.[8]

Finally, the utility of ice and snow structures is limited by the prevalence of at least a short melt season in most Arctic localities. This makes the useful life short and little effort has been devoted towards the possibility of controlling this by insulation, surface treatment or refrigeration techniques.

In general, then, utilization of ice and snow in its natural state has been well developed and engineering methods have been successful. However, construction and fabrication techniques for using snow at a site selected by the engineer have not, as yet, been developed, nor has it been shown that this kind of ice and snow engineering is feasible; thus ice and snow engineering is still in its "stone age". Analysis of the feasibility and limitations of applied glaciology or glaciological engineering is the first requirement towards extending our control over the Arctic regions.

Ice Properties and Ice Alloys

The major property requirement for developing ice as a more useful structural material is obtaining improved strength and improved resistance to creep deformation. Ice samples are variable in strength and deform under stresses as small as 1 kg./cm.^{2}. The rate of deformation becomes large, even over periods of a day, at stresses of the order of 5 kg./cm.^{2}. There have been a number of investigations reported on the strength of pure ice and analyses of its deformation and fracture characteristics. The result of these investigations is that the properties of ice are unsatisfactory for engineering purposes unless large volumes of material are employed.

This conclusion was reached in considering the use of ice for the construction of an aircraft carrier.[2] As a result, improved mechanical properties were developed by use of a sawdust-ice mixture. We have found that substantially higher strengths can be developed by incorporation of a small fraction of Fiberglass as a reinforcing agent. For use in the Arctic, Fiberglass has an advantage over materials such as steel in that radiant energy absorption is less extensive and no liquid film is formed at the interface as occurs for metals. Experimental data were obtained for the transverse strength (modulus of rupture) of samples of fresh ice alone and with various amounts of Fiberglass additions. These results are collected in Table I and compared with similar results for ice-sawdust mixtures. In addition to the samples

TABLE I. STRENGTH OF FRESH ICE WITH SAWDUST AND WITH FIBERGLASS ADDITIONS

	Modulus of Rupture, kg./cm.²	
% Addition	*Sawdust (−17° C.)²*	*Fiberglass (−20° C.)*
0	22·5	24·1
0·8	22·7	24·0
2·5	35	65·4
9·0	60	161
14·0	66·7	—

reported there, measurements were carried out of salt ice frozen in ¼ in. (0·6 cm.) layers and tested by a tensile ring test using a 3 in. (7·6 cm.) outside diameter ring with a ½ in. (1·3 cm.) central hole as recommended by Butkovich.[9] Here it was found that the salt ice had a strength of 21·5 kg./cm.², while a sample in which 15 per cent Fiberglass mat was frozen had an average value of 193 kg./cm.² for a maximum load, as illustrated in Table II.

TABLE II. STRENGTH VALUES FOUND FOR VARIOUS ICE SAMPLES PREPARED IN THE LABORATORY AND TESTED AT −20° C.*

Method of Preparation	*Measured Density (gm./cc.)*	*Average Ring Tensile Strength [9] (3″ O.D., ½″ I.D. sample)† lb./in.²*	*kg./cm.²*	
Fresh Ice	0·915	430	(30·2)	(range 281- 542, 5 samples)
Flooded Sea Ice, 3″ (7·6 cm.) Layers	0·925	320‡	(22·5)	(range 241- 309, 5 samples)
Flooded Sea Ice, 3″ Layers	0·906	315§	(22·1)	(range 241- 351, 8 samples)
Flooded Sea Ice, ¾″ (1·9 cm.) Layers	0·932	372‡	(26·2)	(range 301- 402, 5 samples)
Flooded Sea Ice, ¾″ Layers	—	294§	(20·6)	(range 256- 351, 8 samples)
Rolled Sea Ice, ⅛″ (0·03 cm.) Layers	0·926	505‡	(35·5)	(range 452- 522, 5 samples)
Rolled Sea Ice, ⅛″ Layers	0·927	487‡	(34·2)	(range 321- 597, 6 samples)
Rolled Sea Ice, ⅛″ Layers	0·919	295§	(20·7)	(range 251- 361, 5 samples)
Rolled Sea Ice, ⅛″ Layers, 15% Fiberglass	0·95	1,757‡	(123·5)	(range 1,506-1,908, 4 samples)
Rolled Sea Ice, ⅛″ Layers, 15% Fiberglass	0·95	2,558§	(179·8)	(range 2,560-2,912, 4 samples)

* These measurements were carried out by A. Funai.
† Values obtained with ½″ (1·3 cm.) I.D. sample were higher than those with a ⅞″ (2·2 cm.) I.D. sample by a factor of 1·45.
‡ Maximum stress exerted parallel to surface.
§ Maximum stress exerted normal to surface.

The fracture behavior of the samples containing Fiberglass reinforcement was quite different from those of pure ice, which failed with a typical brittle fracture. With the Fiberglass additives, cracks formed in the ice as the stress was increased, giving a partial stress release at a constant strain without fracturing the sample. Added application of stress gave rise to increased deformation and increased cracking of the ice phase, but still without complete fracture of the sample. That is, the maximum stress recorded could be withstood for a considerable length of time and varied with the loading rate. In practical applications this feature would add some margin of safety and provide an advance warning of impending failure.

The advantages of Fiberglass additions are that they provide maximum reinforcement, giving strength values almost ten times as high as those of pure ice. Sawdust as an additive is less effective as a strengthening agent, but frequently may be more readily available and is certainly less expensive. (However, where much of the cost is transportation, the cost differential between Fiberglass and sawdust may not be large.) In any event it is clear that for a particular application there is an opportunity to use pure ice with rather poor properties, sawdust-reinforced ice with improved properties, or Fiberglass-reinforced ice with quite good properties, depending on the requirements of each particular situation.

As is the case for sawdust additions,[2] Fiberglass additions give a substantial increase in resistance to creep deformation. Results for a constant stress bend test using a $1 \times \frac{1}{2}$ in. ($2 \cdot 5 \times 1 \cdot 3$ cm.) cross-section sample over a 5 in. ($12 \cdot 7$ cm.) span are illustrated in Fig. 1. At stresses of about 20 kg./cm.^{2}, deformation of pure ice occurs rapidly. Fracture occurs after a time period of a few hours. (The fracture stress of ice in these and other experiments was observed to be time dependent, showing a stress-rupture behavior similar to the high-temperature behavior of metals.) The addition of 0·8 per cent Fiberglass did not much change the deformation characteristics, but prevented fracture occurring for longer times. Addition of 9 per cent

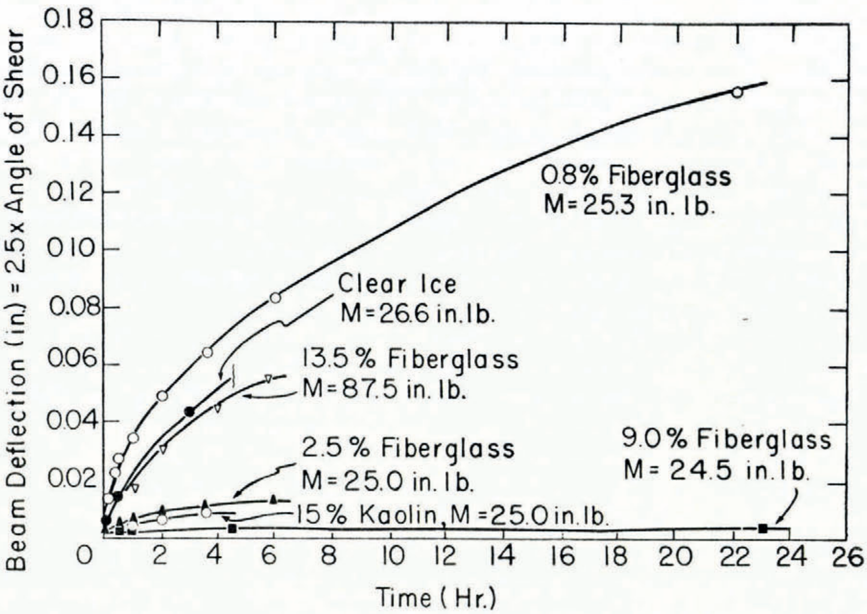

Fig. 1. Deformation of various samples in bend tests with bending moment M as indicated on curves. Slope of curves is a measure of apparent viscosity (1 in. lb. = 1·15 gm. cm.; 1 in. = 2·54 cm.)

Fiberglass decreased the creep deformation by almost two orders of magnitude and allowed a three or four fold increase in stress to be employed with resultant deformation and fracture time better than those of pure ice. In addition to Fiberglass, it was found that dispersions of clay also increased the creep resistance of ice but without giving increased short-time strength. Presumably clay and similar fine-powdered materials solidified as a dispersed phase in ice provide a separate method for altering ice properties.

While only cursory experimental measurements have been completed, it is plain that it is feasible to improve substantially the strength and creep resistance characteristics of both salt ice and fresh ice. Increases in strength allow either the bearing of heavier loads or alternatively the use of thinner sections with more economical processing methods.

Attempts have also been made to add chopped Fiberglass strands to snow prior to compaction as a strengthening agent. These attempts have so far been unsuccessful. Apparently the different deformation characteristics during compaction lead to residual stresses that make the material containing the Fiberglass strand weaker than material compacted without it.

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The difficulty lies mainly in devising a satisfactory mechanism for incorporating a reinforcement during compaction without setting up internal stresses.

Sea-water Solidification

When fresh water is available as a usable raw material, as in rivers and lakes during the early part of the winter, there is no real problem in obtaining or processing material to obtain a suitable product. Pumping techniques and methods for rapidly building up ice strength under these conditions are well developed.[10, 11, 12] However, a source of fresh water is but seldom available. A possible process would be to melt ice or snow to form water; however, as those familiar with melting a little snow are aware, the high latent heat of melting (80 cal./gm.) makes this an uneconomic process that would require extensive fuel supplies.

In the process of freezing sea-water, which is readily available in many polar regions, there are two principal objectives. One is to obtain a high rate of solidification (as measured by the weight of ice formed per hour) in order to be able rapidly to form a solid structure which may have to be several feet thick. This can advance the date of availability from some time in spring to early after initial freeze-up. The second objective is to form structurally useful ice and to eliminate residual brine. The fractional separation of solids from the liquid phase has been extensively studied [13] with the results illustrated in Fig. 2.[14] As shown there, about 20 per cent of the original material remains as concentrated brine at −12° C.; at −20° C. about 15 per cent of the original liquid still remains as concentrated brine. A major problem in developing a useful solid material is to eliminate this concentrated brine, which has a low freezing point and makes for poor ice properties except at very low temperatures.

In natural ice formation, heat must flow from the liquid-solid interface through the ice to the cold ice-air surface, which acts as a heat sink where the heat generated by solidification is eliminated. As the ice layer increases in thickness, the heat flow path becomes longer and freezing becomes very slow. In order to obtain a rapid rate of solidification, particularly for thick structures, this heat flow path through the ice must be "short circuited". This can be done by pumping the sea-water from beneath the ice and bringing it directly into contact with the cold ambient air (and top ice) temperature. The simplest procedure for doing this has been flooding layers of sea-water in dikes on top of a natural ice surface. The technique that has been mostly used in the past is one of forming 3 to 6-in. (7·6-15·2 cm.) layers and allowing a few days for each layer to solidify. Analysis of the heat flow under these conditions indicates that shorter cycles of solidifying thinner layers lead to an increasingly rapid rate of ice build-up. In theory, and probably in practice, the method of obtaining the most rapid build-up is completely to remove the latent heat in the cold air by a technique of spray solidification similar to the spray drying used for removing solvents in many industrial processes. In this process fine droplets of material passing through the cold air would be cooled and mostly solidified before coming into contact with the ice; large surface areas are exposed and resulting cooling rates rapid. While a certain amount of experimental work has been done in this direction, not enough has been carried out as yet to be definite. An analysis of the thermal restrictions on the rate of ice formation is now in preparation.[15]

A technique that offers the opportunity for both rapid solidification and also some desalination is to utilize sequential freezing and brine separation. Using the cold layer of base ice as a regenerative heat sink, experiments were carried out at Point Barrow, Alaska, in which the top surface of the ice was typically below −20° F. (−29° C.) with a local temperature gradient of less than 2° F. per inch (1° C. per 2·3 cm.) near the surface. A considerable excess of sea-water at its freezing temperature was brought into contact with the cold exposed ice surface for a controlled period of time, after which solidification took place and the supernatant, more concentrated brine was quickly removed by means of a rubber "squeegee", heavy rollers or natural drainage. The solid ice was then allowed to cool by exposure to the air in preparation for the next cycle. A typical cycle was to have four minutes of water on the ice, 16 minutes of cooling; using a "squeegee" to remove the supernatant liquid produced $\frac{1}{8}$ in. (0·3 cm.) per cycle having a salinity of 1·2 per cent from sea-water of 3·5 per cent initial salinity with the ambient air temperature at −30° F. (−34·4° C.). Using a 4 in. (10 cm.) diameter roller to compact the ice and simultaneously remove the water gave a solidification rate some 60 per cent higher under the same conditions. Continuous free flooding and drainage of excess water over the ice surfaces results in rapid growth rates but higher salinities and lower strengths than were obtained with the "squeegeed" or rolled ice. The strength and soundness of the ice formed are superior to those of natural sea ice.

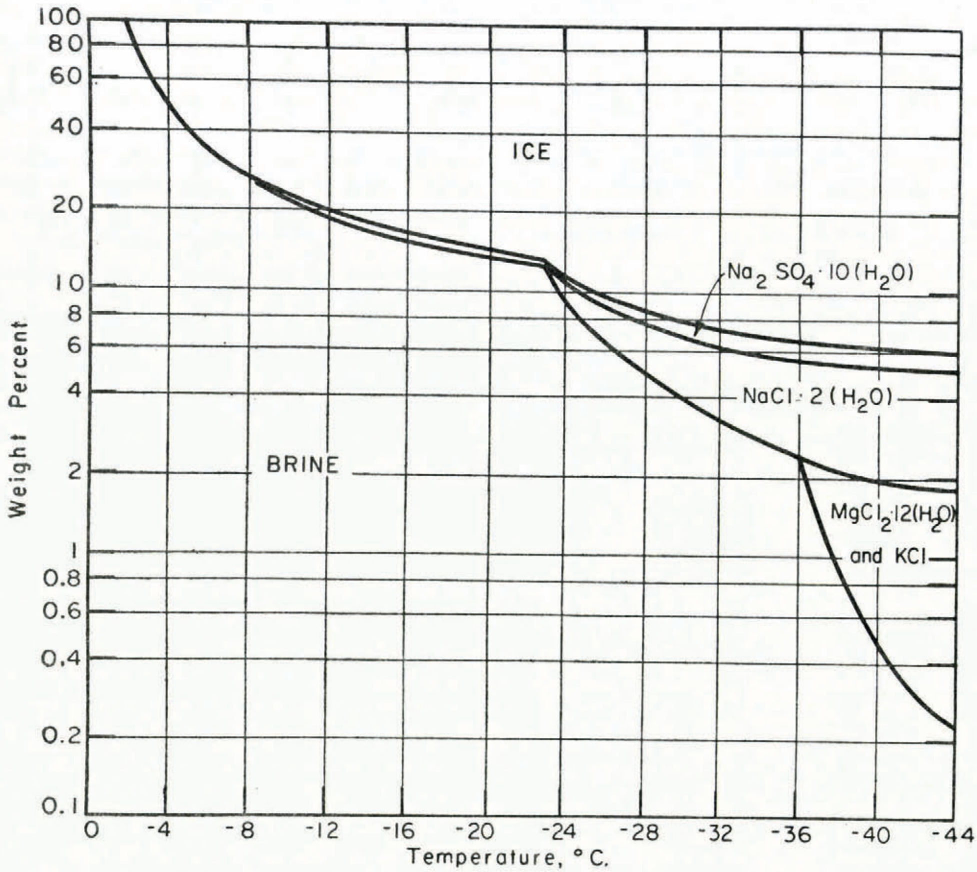

Fig. 2. Phase diagram in the solidification of sea-water. After D. Anderson [14] from data of K. H. Nelson and T. G. Thompson [13]

Growth rates greater than $\frac{3}{4}$ in. (1·9 cm.) per hour can be obtained by a thin layer flooding without desalination (for example, by using $\frac{1}{4}$ in. (0·6 cm.) flooded layers added at twenty minute intervals). The fine grain structure and absence of gross segregation of brine in the structure give good low temperature properties in spite of the high salinity. For some applications where only low temperature use is expected but rapid build-up is necessary, this technique may be useful.

One of the difficulties in using an ice base for a heat sink or platform for solidification during processing of large amounts of material is that the temperature of the ice gradually

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increases. Ice temperatures were observed by the U.S. Navy Civil Engineering Laboratory researchers in experiments at Point Barrow during solidification of 3 in. (7·6 cm.) layers formed by flooding. By the time a 40 in. (1 m.) layer of new ice had been built up, the temperature of the entire sheet was within a few degrees of the melting point, the average temperature being above 20° F. (−7° C.).[16] This results in ice which, as formed, has rather poor properties and which would require a long time for the temperature to decrease to a point where ice properties are more satisfactory.

These considerations lead to the conclusion that it would be better to separate the construction aspects from the material preparation. That is, that the desalination of sea-water to form ice having useful structural properties should be carried out separately from where a structure is being built on top of the ice surface. This would allow better conditions of ice-brine separation and at the same time eliminate warming of the ice. Preliminary experiments of freezing a layer of water about 9 in. (23 cm.) thick on top of an ice surface show that the first ice formed at the ice-air contact has a relatively low salinity which gradually increases as the layer thickness and boundaries between grains contain a larger amount of salt. Salinity versus depth for a sample of freshly formed ice is illustrated in Fig. 3. New ice a few inches thick still has brine films between long columnar grains and consequently can be easily broken, handled and transferred. It seems entirely feasible partially to solidify sea-water in a flooded area and then use the initial two or three inches having a relatively low salt content (lower than might be thought from Fig. 3, because in that case the ice was completely frozen whereas natural ice removed after partial solidification would have an opportunity for some brine to drain out). The ice could subsequently be compacted on a cold ice surface where solidification becomes complete. Laboratory tests indicate that this process is a feasible one; by separating a large part of the heat transfer and brine separation to auxiliary areas, deposition rates for building up ice structures can be increased to any level for which manpower is available. That is, the thermal restrictions and salinity restrictions can both be eliminated by suitable processing methods.

Snow Comminution and Compaction

It is well known that the strength properties of snow depend greatly on its density [17] and also that there is a strong dependence on time; that is, age hardening occurs.[6, 17, 18] The increase in density of the snow and the age-hardening processes are similar to the densification occurring during the firing of ceramic products where a powdered material is compacted and then subjected to heat treatment in order that densification and strengthening will take place. As shown by various theoretical calculations,[19, 20] and also by the better strength and compactability of wind-driven snow and snow-miller snow, fine particle size material is one of the main requirements for successful snow compaction. A device that is suitable, at least in principle, for reducing coarse snow and ice to a product having particle sizes in the range of a few microns has been built and tested.[21] In this device a high-speed rotor creates extreme turbulence by means of attached lugs to give impact grinding of fine particles; at the same time these lugs provide a hammer mechanism for breaking coarse lumps of ice. The operating temperature and rotor speed have a considerable effect on the product formed, but particle sizes are in the micron range, so that the resulting particle sizes as indicated in Fig. 4 are two orders of magnitude smaller than those which occur in natural snow.

A few tests of compactability and resultant properties have been carried out with a natural hoar frost and also with material ground to form a substantial fraction of fine powders. Samples were prepared having a 4 in. (10 cm.) outside diameter and a 2 in. (5 cm.) inside diameter by compressing the snow between end plugs fitted into two brass tubes. Compaction was done by hand and results showed some variability depending on just how the samples were made. Natural hoar frost was compressed in this way to a density of 0·55–0·59 g./cm.^{3}, and in the ring tensile test [9] had a measured average strength of about 125 lb./in.^{2} (8·8 kg./

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cm.[2]). In contrast, material formed by grinding ice at a rotor speed of 3,750 r.p.m. compacted to a density of 0·68-0·71 g./cm.[3] and had a measured strength of about 150 lb./in.[2] (10·5 kg./cm.[2]). Both samples were aged for about seven days at 0° F. (−18° C.). Previous results indicated that strength changes with aging occurred mainly within the first few days with natural frost and occurred in a few hours with fine particle comminuted material. These results should be considered as being preliminary in nature.

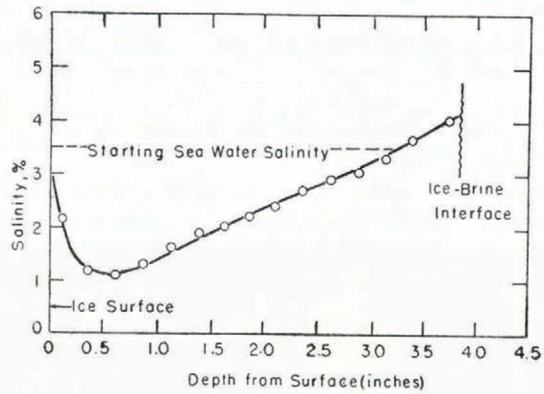

Fig. 3. Salinity versus thickness for freshly formed sea ice frozen 30 hours from a 9 in. (23 cm.) deep pool at −40° F. (−40° C.)

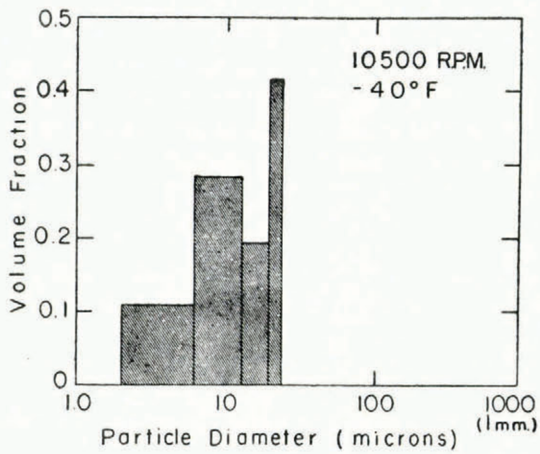

Fig. 4. Product of snow grinder with rotor speed of 10,500 r.p.m. at an ambient temperature of −40° F. (−40° C.)

One advantage of fine grinding is the greater compactness obtained, giving rise to higher densities and higher strengths as well as more rapid age hardening. Another significant advantage is the greater reproducibility of results using processed snow. Indeed, previous applications of compacted snow [6] have largely had difficulties because of the variability of the resulting product. The best results obtained by most processes have been satisfactory.

Another method of achieving high densities by compaction is the formation of a liquid phase which will allow greater densification to occur under a moderate applied pressure. Attempts to do this by "hot processing" using heaters have been unsuccessful because of the

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excessive energy required. A much more satisfactory method is to incorporate small amounts of an additive into the snow during processing so that it forms a liquid boundary between particles. This was tested with additions of ethyl alcohol and methyl alcohol in amounts up to 2 per cent as a feed material along with snow in the ice comminuting device. The products, when compacted by the same method as the snow already referred to, gave high densities ranging from 0·70 to 0·77 g./cm.^{3}, and a typical value of 0·74. The age-hardening process in this case requires evaporation of the liquid phase which forms the film between particles and gives initially very low strengths. Quantitative measurements of this age-hardening were not carried out, but it was found to be incomplete after a week at 0° F. (−18° C.). This was indicated in the appearance of the samples and also in the wide range of strength results. The best strength values found were for samples containing one per cent ethanol; these gave an average strength of 320 lb./in.^{2} (22·5 kg./cm.^{2}), which is several times greater than that normally achieved for compacted snow and begins to approach values observed for ice samples. The advantages of higher density and higher strength coupled with the longer time required for age-hardening suggest that this type of additive may be desirable for some applications but not for others. It provides an additional processing technique that may be useful in some cases.

Ablation Control

Analysis of the heat transfer between an ice surface and the atmosphere is complex and will not be discussed in detail here. Preliminary analysis of available data for the solar radiation, ice temperatures and air temperatures during the 1953 season on Ice Island T3 at a time when its average position was lat. 86° N. indicates that but a small fraction of the incident radiant energy is consumed by melting ice and snow. The major portion is either re-radiated or goes into raising the temperature of the ice sheet. Consequently, small changes in the reflectance, emissivity and insulation characteristics of the surface can have a large effect on the amount of melted ice. This analysis varies from one place to another, of course, depending on the annual temperature, maximum summer temperature and the thickness of the ice sheet.

Few, if any, surface materials have the combined effectiveness of fresh snow, which is a good thermal insulator, an excellent reflector for solar radiation, and a good emitter for low-temperature radiation. Consequently, a composite surface coating may be more effective, particularly during the melt season. For structural applications any such coating would also require satisfactory mechanical properties. For the construction of a compacted snow parking area at Squaw Valley, a layer of sawdust on the surface provides adequate insulation to prevent daytime melting.[7]

While preliminary calculations and experimental observations suggest that summer melting can be substantially eliminated at sites such as Ice Island T3, much more work needs to be done. Experimental sites have been prepared on the Ellesmere Ice Shelf for more detailed analysis during the 1960 field season.

Summary

At present, we are at a point corresponding to emergence from the Stone Age in the utilization of ice and snow as engineering materials. Natural deposits have been used successfully, employing excavation and cut-and-fill techniques. Fresh water has been used by freezing in place as a method of preparing various structures. Widely available raw materials, such as sea water, snow and old sea ice, have not been successfully employed as structural materials where substantial strengths are required.

Analysis of the problem involved shows that substantial difficulties occur with regard to the properties of ice as a structural material, with regard to processing methods for forming

structures, and in the fact that ablation restricts the useful life of any structures which might be built.

Investigation of alloying systems indicates that substantial strength increases can be obtained by the incorporation of Fiberglass as a reinforcing medium. Somewhat less effective improvements can be made with additions of clay or sawdust.[2] Improved ice properties which are capable of attainment substantially decrease difficulties in processing since they reduce the amount of material that must be handled. Consideration of rates of formation and resultant properties of solidified sea-water indicate that improvements in processing can be made with regard to both desalination and increased rates of solidification. Improved techniques here would make possible the construction of ice structures from a widely available raw material which can be manipulated without difficulty. Similarly, effective snow comminution provides a method for utilizing compacted snow structures having greater uniformity of properties, increased density and better strengths than have commonly been obtained. Additives can improve the densification rate. Further investigation of methods of decreasing the rate of melting of snow structures is necessary. Preliminary analysis indicates that in some Arctic areas the ablation rate can be much decreased.

In general, the development of practical methods for utilizing ice and snow as structural materials appears to be promising. Field trials of their utility and the development of engineering methods offer a new opportunity for development of an applied glaciology that can contribute in an important way to the extension of our terrestrial frontiers.

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