A DESCRIPTION OF THE ICEBERG AIRCRAFT CARRIER AND THE BEARING OF THE MECHANICAL PROPERTIES OF FROZEN WOOD PULP UPON SOME PROBLEMS OF GLACIER FLOW

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INTRODUCTION

In the autumn of 1942, when the German army had advanced almost to the gates of Alexandria and the U-boat war had reached one of its most critical phases, it was evident that some of the Allies' difficulties were due to their lack of air power in the distant battlefields. There was not only a scarcity of aircraft, but such machines as they possessed had a limited range and could not be brought into operation where they were most needed. It had been a common experience that the carrier-based aircraft of the Allies were inferior in armament and speed to the land-based planes of the enemy. It was feared, therefore, that in an invasion of a distant shore the allied armies would be handicapped by lack of air support until they had actually succeeded in establishing their own airfields there.

It was only natural, therefore, that a proposal for the apparently cheap construction of gigantic aircraft carriers, capable of operating land-based aircraft thousands of miles from their base, was seriously considered. In October 1942 Mr. Geoffrey Pyke, the originator of the plan, submitted a memorandum to the Chief of Combined Operations in which he proposed that an iceberg, either natural or artificial, should be hollowed out to shelter aircraft and levelled to provide an adequate runway. It must have a mobility of at least a few knots and be guaranteed against melting, if not indefinitely at least until it had fulfilled its strategic purpose. Mr. Pyke pointed out that all strategic materials such as metals, wood and concrete were already being used to the full for the war effort and that ice, requiring for its manufacture only 1 per cent. of the energy needed for an equivalent weight of steel, would be ideal as a basic material for the construction of large carriers. Ice, he considered, possessed many advantages; it was difficult to break up with explosives, as shown by the tenacious resistance of icebergs to shellfire, and it melted very slowly when insulated. Moreover, the greatest attraction of a floating air-base made of ice was the fact that it could not be sunk.

In December 1942 Mr. Churchill issued a directive that research on the project should be pressed forward at the highest priority, but expressed the opinion that it would be essential "to let Nature do the job" of making the bergship, as otherwise the technical difficulties would prove insuperable. He also suggested that ice floes might be towed into the Atlantic from the Arctic Seas and used as airfields until they were broken up by melting.

It soon became apparent, however, that neither natural icebergs nor ice floes were suitable as air-bases, the former because their surface above the water was too small and the latter because they were too thin to withstand the waves of the Atlantic. The Russian North Pole Expedition under Papanin, for instance, had shown that the thickness of the pack ice even at the North Pole was less than $3\frac{1}{2}$ m. Moreover the experts of the Fleet Air Arm considered a freeboard of at least 15 m. essential for the continuous operation of aircraft from the deck of a carrier. The minimum length of runway required for bombers at that time was 600 m., and 60 m. was considered the most desirable width. Thus the engineers and physicists were given the task of building a raft or vessel of these gigantic dimensions, made basically of ice and satisfying a number of essential requirements. The vessel must be sufficiently seaworthy to withstand the waves of the Atlantic and Pacific oceans; it must be self-propelled; it must have a speed at least sufficient to prevent its drifting in the wind; and it must be difficult to sink.

In order to design this bergship, as it was to be called, the naval engineers needed accurate information on the mechanical strength of ice. A search of the literature revealed a mass of conflicting data which were of little assistance. It soon became clear that most of the physical constants which were needed would have to be determined afresh. A variety of mechanical strength tests were made both in this country and in Canada, but the results were very disappointing. The average modulus of rupture of ice beams in bending, for instance, was found to be about 22·5 kg./cm.^{2}, but individual beams sometimes failed at stresses as low as 4·9 kg./cm.^{2}. Pine wood, for instance, has a modulus of rupture of about 800 kg./cm.^{2}. As a structural material ice was found to be too unreliable and its resistance to explosives quite unpredictable. Owing to its brittleness it was dangerous to regard any reasonable stresses as safe for constructional purposes.

In February 1943 the project did not look very hopeful, but the outlook was suddenly transformed by the discovery that the inclusion of a small percentage of wood pulp improved the mechanical properties of ice in a spectacular manner. The discovery was made by Mark and Hohenstein, working at the Brooklyn Polytechnic. In view of the similarity to concrete and in honour of the originator of the bergship project, the frozen wood pulp was given the code name of pykrete (Pyke's concrete).

Pykrete

Wood pulp consists of mechanically ground spruce or pine wood and is the raw material used for the manufacture of newsprint. A mixture of 10–15 per cent. wood pulp with water is a spongy mush, while a 5-per cent. suspension has a consistency rather like porridge. If any such mixture is frozen the mechanical properties are vastly superior to those of ice. Lumps of the material do not disintegrate on being hit with a hammer and the impact of small arms' projectiles does not crack them. Preliminary results with the new material were so hopeful that a small research unit was immediately established in one of the refrigerating rooms of a London meat store and given the task of producing large blocks of pykrete. Ultimate strength tests performed by the Engineering Division of the National Physical Laboratory, and explosives tests carried out by the Road Research Laboratory of the Department of Scientific and Industrial Research, yielded very satisfactory results. All this work was under the general direction of the Department of Scientific Research (Admiralty). Shortly afterwards research on a larger scale was begun in Canada under the auspices of the National Research Council and was directed by Professor G. M. Williams. The results given below are quoted from a number of reports submitted by the teams working in this country and in Canada.

Table I gives a series of values for the modulus of rupture in flexure of beams of different pulp content. These measurements were made by supporting a beam of pykrete at each end and applying a load at the centre. In practice the beam is bent by the movement of a piston forced down by a hydraulic pump at a constant rate of, say, 2·5 cm. per minute; the maximum load which precedes rupture is recorded on a dial.

It will be seen that the strength increases rapidly up to a pulp content of 4 per cent., after which the increase is comparatively small.

Table II shows a comparison of tensile and compressive strengths of pykrete containing 14 per cent. Scotch pine wood pulp, with the corresponding value for pure ice.

More important even than the increase in the mean values which these tables represent was the comparatively small scattering of the individual test results in pykrete, as opposed to ice. Beams of pure ice, for instance, might break at any stress between 5 and 35 kg./cm.^{2}, while ice containing wood pulp gave results which were reproducible to within about $\pm$25 per cent. Thus the main effect of the pulp fibres embedded in the ice was the elimination of brittleness. Pykrete, in fact, was ductile and could even be machined on a lathe. In its resistance to projectiles and explosives it was weight for weight as good as concrete. While an ice block 60 cm. square and 28 cm. thick was severely cracked by the impact of a revolver bullet, a similar block of pykrete suffered only insignificant damage, consisting of a crater about 2·5 cm. in diameter and 1·2 cm. deep.

TABLE I

MODULUS OF RUPTURE OF BEAMS IN FLEXURE AT −17° C.
(MEAN VALUES)

Pulp Content (Percentage)	*Modulus of Rupture in kg./cm.²*
0	22·5
1	22·8
2	32·0
4	50·0
6	51·0
7	61·5
8	53·7
14	66·7

TABLE II

MECHANICAL STRENGTH OF PYKRETE AND ICE at −15° C.
(MEAN VALUES in kg./cm.²)

	Pykrete	*Ice*
Ultimate strength in compression	77·3	43·6
Ultimate strength in tension	49·2	11·6

Table III gives measurements of the penetration of a ·303 rifle bullet and demonstrates the resistance of pykrete as compared with some other materials.

TABLE III

PENETRATION OF ·303 (7·69 mm.) RIFLE BULLET

Material	*Penetration, cm.*
Soft wood	63·5
Pure ice (−7° C.)	35·6
14 per cent. pykrete (−7° C.)	16·5
Brickwork	15·2
Concrete	7·0

From the results of small-scale underwater explosives tests it was calculated that a torpedo hit would produce a crater 60 cm. deep and about 4·5 m. in diameter. Nevertheless, it was considered that a minimum wall thickness of 9·0 m. would be required for the bergship to be safe against the blast effects of underwater attack.

These results were most encouraging, but soon a new difficulty emerged. It was noticed that the ultimate strength of pykrete in compression was dependent on the rate of loading, *i.e.* if a piston, driven by a hydraulic pump, was lowered on to a cylinder of pykrete at a constant velocity, the load at which fracture occurred became greater the slower the movement of the piston. Ultimately, at a very slow rate of compression, fracture never occurred at all, but the cylinder of pykrete underwent plastic deformation until it had assumed the shape of a flat disk. Behaviour of this type is a characteristic property of materials which are liable to undergo slow, permanent deformation under the sustained action of small stresses, a phenomenon technically known as creep. If pykrete was subject to creep, the possibility had to be faced that a bergship built of this material would slowly sag under its own weight. It was essential, therefore, to test the creep properties of pykrete as a function of all the possible variables, such as load, time, temperature and pulp content. For this purpose batteries of creep-test machines were installed in cold rooms at different temperatures. Their principle of construction is illustrated in Fig. 1.

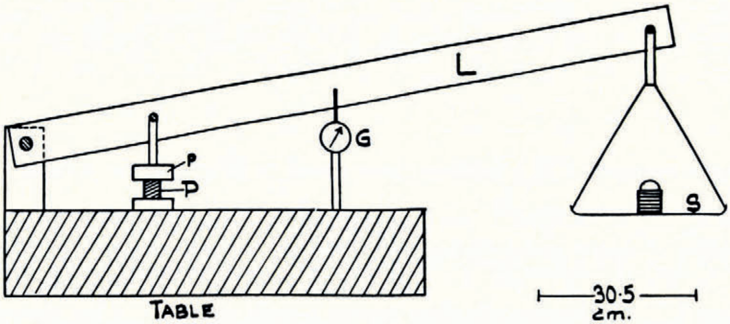

Fig. 1. Creep-Test Machine for Ice

By means of the piston p the lever L exerts a pressure on the pykrete block P. Weights are applied in the scale pan S and the movement of the lever can be read on the dial of the gauge G. When an experiment is started the dial is read every few hours. Later, readings are continued daily until the rate of compression assumes a constant value. The type of curve obtained in such an experiment is illustrated in Fig. 2 (p. 99) where total compression in inches is plotted against the time for a series of different loads. The curves do not represent actual experimental results, but merely serve to illustrate the type of behaviour observed. The figures on the curves give the load in kg./cm.^{2}

The figure shows that with loads of the order of 7–14 kg./cm.^{2} a rapid initial compression (which is partly elastic) is followed by a gradual slowing down, until, after a few weeks, the rate of compression becomes constant. At higher loads the experiments usually had to be discontinued before this happened on account of the large deformation of the specimen.

A very similar set of curves is obtained if the load is kept constant and the creep is determined at different temperatures, with the creep rate rising rapidly as the melting point of ice is approached. The results of the creep experiments also varied according to the grade of wood pulp used. With Scotch pine at a pressure of 7 kg./cm.^{2}, creep settled down to a constant rate corresponding to the reduction in height of a column of pykrete by 1 per cent. per annum. Using Canadian spruce, on the other hand, creep at this load actually became negligibly small after a few weeks. This result was very important, because 7 kg./cm.^{2} was the maximum stress which the bergship was expected to exert within its walls under the action of its own weight. On the basis of the creep curves, it was possible to predict that in a bergship made of 4 per cent. Canadian spruce pulp, plastic deformation of the ship would cease after an initial period of sagging lasting several weeks. The curves also showed that $-15°$ C. was the highest permissible working temperature if deformation of the ship through creep was to be avoided.

By the summer of 1943 the mechanical properties of pykrete had been sufficiently well established, at least in small-scale tests, to proceed with the design of the ship. The ultimate strengths of pykrete in tension, compression and shear were sufficiently great to allow the naval engineers a substantial safety margin, even on the hypothesis that the ship might encounter the largest waves known to have been observed in the Pacific. (Data on this subject are somewhat unreliable, but the existence of waves 21 m. high and over 300 m. long seems to have been definitely established.)

Plans for Design and Construction of the Bergship

With a runway of 600×60 m., a freeboard of 15 m. and an all-round wall thickness of 9 m., it was found that the bergship would have to have a draught of 45 m. and a displacement of 2,200,000 tons.* To build a ship twenty-six times heavier than the *Queen Elizabeth* from a material which

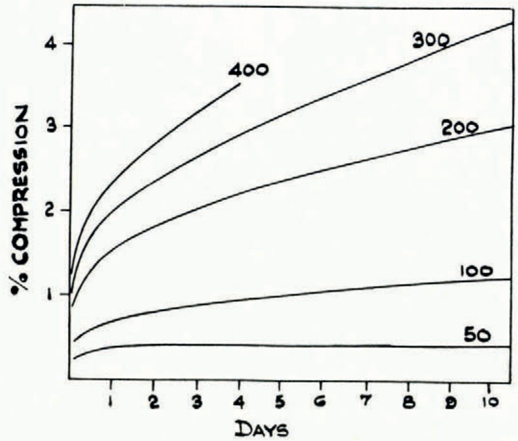

Fig. 2

had never been used before was a formidable proposition. Indeed, many experienced engineers regarded the difficulties as almost insuperable from the outset, particularly since our directives required that at least a prototype of this monster should be built within the short span of one winter, and that an entire fleet of bergships should be ready in time for the projected invasion of Japan. In retrospect this may seem the obvious verdict, but it must be remembered that the bergship plan was only one of several apparently impossible engineering feats conceived during the war (*e.g.* the atomic bomb) and that the question was not so much one of absolute feasibility but rather of whether the ultimate strategic advantages to be gained by the bergships were in proportion to the expenditure of man-power and materials involved in their construction. In fact, I think that had not the course of the war and the state of our armaments changed, the bergship could have been constructed. Considerable progress was in fact made on the design, and many ingenious plans were developed for the construction of the ship.

For the sake of simplicity of construction it was decided to give the ship the shape of a hollow square beam, with bevelled edges to reduce the drag under water (see Fig. 3*b*, p. 100). The outside walls were to be surrounded by a waterproof insulating skin and the pykrete was to be kept at a

* The English ton is slightly heavier than the metric *tonne*, 1016·05 as against 1000 kg.

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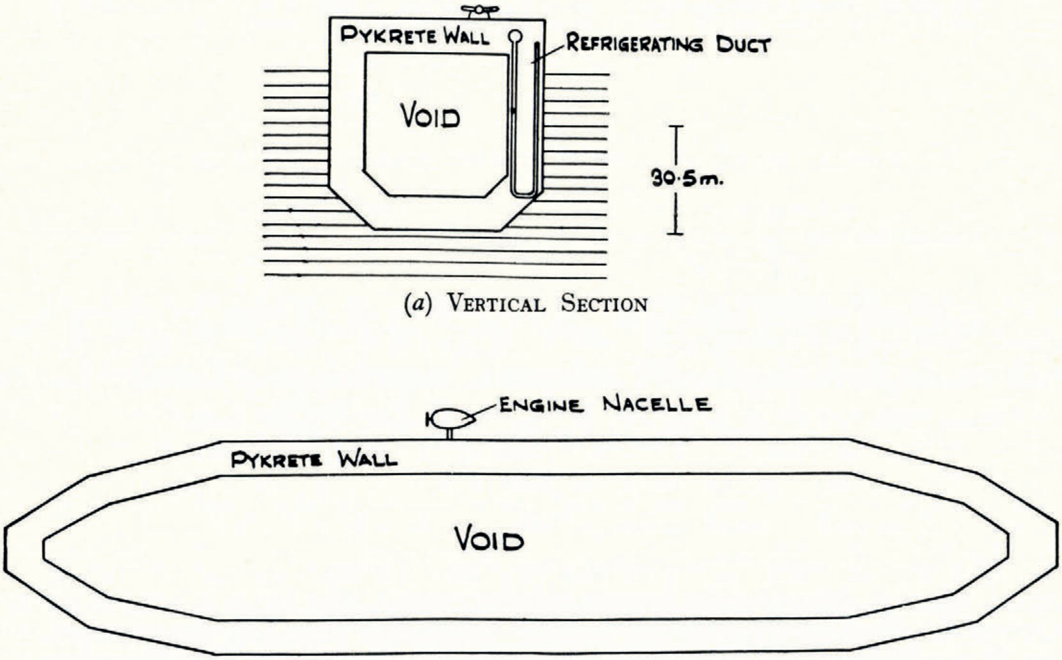
constant temperature of $-15°$ C. with the help of artificial refrigeration. U-shaped ducts of the type shown in Fig. 3*a* were to be built into the walls. These ducts were to be placed about 1·2 m. away from the outer surface of the pykrete and cooled with compressed air at $-30°$ C. Sixteen refrigerating plants, each with its own circulating system, were to supply cold air.

The bergship was to be propelled by over twenty 1100-B.H.P. electric motors housed in pressure hulls and distributed for safety. It was decided that 7 knots * was the absolute minimum speed necessary to keep the ship from drifting in the wind; for this turbo-electric generators totalling 32,000 B.H.P. would be necessary.

Steering presented a particularly difficult problem to the naval engineers. The proposal to alter course by changing the relative speed of the propellers was discarded by the experts in favour of a fin and rudder. This would have added several hundred tons of weight, and the problem was never satisfactorily settled.



(*a*) VERTICAL SECTION

(*b*) HORIZONTAL SECTION

Fig. 3

Another serious difficulty was presented by the void, 884 m. × 43 m. × 43 m., in the centre of the ship. If it were left empty the walls would be liable to bend inwards by creep and if a crack occurred, due, say, to frequent torpedo hits, there was danger of flooding. Some sort of reinforcement could probably have been designed.

There were still further difficulties which contributed to the project being abandoned. These were partly connected with problems of construction. It was soon realized that no accessible place on earth was cold enough to "let Nature do the job" of freezing the pykrete. The locality eventually

* 1 knot = 1853 m. per hour.

selected for building the prototype was Corner Brook in Newfoundland, where an average daily temperature of -5° C. could be expected for 100 days and where protected waters of sufficient depth could be found.

The manufacture of the pykrete itself was, of course, one of the most formidable problems. 1,700,000 tons were required for one ship. This would have needed a plant covering some 100 acres (40 hectares). The amount of piping and refrigerating apparatus alone would have been a heavy drain on North American production and engineering industries.

These difficulties were in part responsible for abandoning the project early in 1944. There were other reasons, not connected with the technical difficulties themselves, which played their part. Since 1942 the range of aircraft had increased so much that it had become possible to provide air cover over most of the Atlantic with land-based planes. The island-hopping campaign of the American forces in the Pacific had been successful beyond expectation and had made an eventual invasion of Japan appear feasible without large floating air-bases. Finally, the length of runway needed for the newer types of aircraft had increased far beyond the estimates of the previous year, and by 1944 a flight-deck 600 m. long had become insufficient for the heavy types of machine for which the bergship had originally been intended.

From the point of view of the war effort the research and planning spent on the bergship project proved to have been wasted. Yet, looking back, it is easy to understand how this daring venture came to fascinate men's minds and was welcomed as a possible solution for one of the most difficult military problems facing the Allies.

The secrecy of the project was so great that most of the workers engaged on pykrete research had no idea of its purpose. Nevertheless, the volume of first-rate data produced within a period of six months in this country and in Canada under the pressure of war far exceeded the total volume of reliable work that had been done before on the mechanical properties of ice itself.

Some of the results of the pykrete research shed an interesting light on the properties of ice and on the mechanism of glacier flow, and these are considered below.

Creep and the Mechanism of Glacier Flow

Creep, under the influence of continuously applied stress, is a property which pykrete has in common with all metals and many other crystalline materials under suitable conditions. The deformation of materials under constant stress is generally characterized by the following sequence of events. Application of the load produces an instantaneous deformation; this is followed by creep at a rate which diminishes at first and tends to assume a constant value with time. This type of behaviour has been explained theoretically as being due to the superposition of two distinct phenomena: (*a*) transient creep (Andrade's β component), which is mainly responsible for the initial rapid creep rate and tends towards a vanishingly small rate with time, and (*b*) quasi-viscous flow, whose rate remains constant throughout the experiment.[1, 2] Transient creep, by its very nature, is not likely to be of any importance in connection with glacier flow and need not be discussed here. Quasi-viscous flow, on the other hand, must be one of its dominant features. Its rate increases with temperature and with stress, though it is not a linear function of the latter (hence the name quasi-viscous, as opposed to viscous or Newtonian flow, where the deformation is a linear function of the applied force).

Fundamentally, quasi-viscous flow may be considered to be due to local rearrangements of atoms in the crystal lattice, leading either to deformation of individual crystals or to the transfer of atoms across crystal boundaries. The rearrangement of the atoms is activated by their thermal energy, *i.e.* the applied external force produces deformation by giving a preferential direction to the otherwise random thermal movement of the atoms. A rise in temperature increases the mean thermal energy of the atoms, thereby increasing the number of rearrangements taking place at any given instant. This increased frequency of local rearrangements manifests itself as an acceleration of creep.

The research on pykrete has proved the creep mechanism in ice to be fundamentally the same as in other materials. This is important, because the opinion has often been expressed that the plasticity of ice is somehow connected with its peculiar property of melting under the influence of hydrostatic pressure. Creep of pykrete went on even at $-25°$ C., when the effect of pressure melting and regelation, in the usual sense of the word implying a macroscopic process, must have been negligible. The true "melting and regelation" during creep is probably a mechanism which involves only small groups of water molecules at a time. It does not lead to the melting of any macroscopic quantity of material, although small lattice regions at crystal boundaries may "melt" instantaneously and "refreeze" in a different orientation. Thus the plastic flow of glaciers can henceforth be regarded as one particular instance, on a gigantic scale, of plastic deformation in a polycrystalline material subjected to sustained stresses. This will mean that theories formulated to describe the creep of metals can be applied to glaciers and perhaps also that some generally useful information on the flow properties of polycrystalline materials can be gleaned from detailed observation of glacier flow.

The creep properties of pykrete are also significant in connection with certain views on the mechanism of glacier flow which have recently been advanced by Streiff-Becker [3] and independently by Demorest.[4] These authors came to the conclusion that the hitherto accepted picture of river-like flow fails to account for the behaviour of certain glacier plateaux. Streiff-Becker calculated that more ice disappears annually from the Claridenfirn in the Swiss Alps than can be accounted for by the combined effects of ablation and flow as measured on the glacier surface. He concluded that the balance must be "extruded" from the bottom of the glacier under the pressure of the overlying mass of ice. Demorest applied similar consideration to the Greenland ice cap and asserted that the majority of the great ice streams emerging from it owe their existence to extrusion from the interior rather than to flow from the surface of the ice cap.

A satisfactory test of these theories will not be possible until the yield stress and the creep properties of pure ice have been determined as thoroughly as those of pykrete. In pykrete at $-15°$ C. the minimum load necessary to produce continuous creep was of the order of 7 kg./cm.^{2}, corresponding to a column of ice about 78 m. high. In ice at 0° C. the minimum load is undoubtedly very much lower, so that the minimum depth needed to produce extrusion flow may well be of the order of 45 m., as estimated by Demorest, or even less. It is to be hoped that more exact estimates will shortly be possible as a result of researches now under way.

ACKNOWLEDGEMENTS

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DISCUSSION

The CHAIRMAN (Professor S. E. Hollingworth): You will have listened with great interest to this account of a most venturesome project. The meeting is now open to discussion.

Dr. RICHARD SELIGMAN: I would like to ask if the presence of wood pulp affected the creep rate or the effect of temperature on creep rate?

Dr. M. F. PERUTZ: It is difficult to compare the creep rates of pykrete and pure ice for the following reason: all creep tests of pure ice were carried out on blocks of river ice. This consists of large crystals in preferred orientation, with their optic axes normal to the river surface. Pykrete, on the other hand, contains small crystals in random orientation. The creep rates of river ice are much greater than those of pykrete, as shown by the following figures:

PLASTIC FLOW IN COMPRESSION OF RIVER ICE AT −9·5° C. IN PER CENT. PER ANNUM

Load	3·5 *kg./cm.*²	5·3 *kg./cm.*²
Stress parallel to freezing surface	20	63·5
Stress normal to freezing surface	2·6	5·4
Pykrete	1·0	

The presence of the wood pulp prevents preferred orientation of the ice crystals and also helps to keep the size of the crystals small. The small crystal size may be more effective in preventing creep than the actual presence of the fibres.

The principal effect of the wood pulp on the mechanical properties of ice lies in the prevention of cracking. Cracks usually exist on the surface of materials; an external stress gives rise to a high stress concentration at the bottom of the surface crack. This in turn leads to a deepening of the crack. In this way a crack is propagated through the material until complete fracture results. The cellulose fibres which are embedded between the ice crystals probably prevent the propagation of of the crack by providing a reinforcement on a microscopic scale.

Mr. G. SELIGMAN: You would only get a crack between the crystals and not in the crystal itself?

Dr. PERUTZ: In pure ice, cracks run right through the crystals. In pykrete there is no information on this point.

Dr. SELIGMAN: Does the grain size play a major part?

Dr. PERUTZ: Probably so far as creep is concerned. We possess no experimental data for ice, but in metals quasi-viscous flow is a "structure sensitive" property which depends, among other factors, on the grain size.

Dr. N. E. ODELL: Did you carry out experiments on different-sized fibres or attempt to give them orientation?

Dr. PERUTZ: No. We did not examine the effect of different-sized fibres, nor did we try to orientate them, but we ascertained that certain types of wood produced better results than others. Spruce was found to be better than pine.

Dr. ODELL: Do you think this reinforced ice could be used in some engineering undertakings, especially in cold countries?

Dr. PERUTZ: I think it might be useful for runways in Arctic countries.

The CHAIRMAN: In connection with the figure you gave for tensile strength, is that new, or based on Tammann's work? From the point of view of the action of glaciers, the tensile strength seems of fundamental importance in the plucking action at the headwall and by the bottom layers of a glacier.

Dr. PERUTZ: The figure is an average one based on experiments carried out at the National Physical Laboratory. The determination of tensile strength is complicated because of the brittleness of ice and reproducible results are almost impossible to obtain. There is also the difficulty of producing really pure ice free from air bubbles.

Lt.-Cdr. J. CORTLANDT-SIMPSON: In the case of cirque formation with dust and detritus falling on the glacier, would this increase its strength and ability to eat into the mountain side?

Dr. PERUTZ: I think so. If sufficient quantities of detritus fell on the ice they might increase its strength and its erosive power.

Mr. W. H. WARD: You would have to have a very much larger amount of sand than wood pulp to make any difference to the strength of ice.

Dr. B. B. ROBERTS: It has been the practice in Scandinavia to use snow in battlements as a protection against cannon balls.

Dr. PERUTZ: I believe the Germans used this technique in Russia, too.

Mr. C. B. CROFT HANDLEY: The Russians supplied us with details of "ice concrete" used in field fortifications during the war. The projectile penetration figures compare favourably with ordinary cement concrete.

Dr. PERUTZ: As a protection against explosives pykrete is weight for weight as good as concrete.

The CHAIRMAN then closed the discussion with thanks to Dr. Perutz for his paper and the important data he had brought to light.

SNOW SURVEYING IN INDIA

THE official *India News* of 4 September 1947 publishes a preliminary account of the expeditions organized by the Central Waterways, Irrigation and Navigation Commission with the help of Dr. J. E. Church, the originator of the system of snow surveying. The expeditions were three in number, one each into East and North Sikkim and the third along the East Nepal border. In addition to Church, irrigation and hydro-electrical engineers accompanied by scientific and professional experts of the C.W.I.N.C. took part. The account continues:

> The first expedition which started in April went eastwards from Gangtok, the capital of Sikkim, up to the pass Natha La (13,000 ft). The second went northwards later in April from Gangtok up to Chunthang, the northernmost P.O. in Sikkim, and thence to Thanggu and Jha Ghu, climbing up to about 16,500 ft. where snow was found. The third went along the East Nepal border, *i.e.* mainly over the ridges of the Singalila range, up to Nayathang, 12,600 ft., much of it over pathless and stony slopes.

The organization of a snow survey on the scale necessary to deal with run-off, from even a part of the enormous hinterland of mountains and glaciers which lie above the sub-continent, will be a task of very large proportions indeed. That Church, who is not a young man, has been willing to undertake its inauguration and take part in severe expeditions to great heights is a tribute to his unbounded energy and enthusiasm. Details will no doubt be communicated later.

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