

# Making Ice Stronger: From the Design of an Aircraft Carrier in WWII to Applications in a Changing Climate

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## ABSTRACT

It was codenamed "Habbakuk" – a very unusual, top secret, 20th century pursuit of the Allies during World War II. The proposal was to build a strategic floating anti-submarine base, an aircraft carrier, out of ice - UK Prime Minister Churchill endorsed it enthusiastically. It was quickly discovered, however, that the ice would have to be reinforced to have a hope of performing satisfactorily. Large scale tests were initiated in Canada at several western universities, in Montréal, and at the National Research Council of Canada laboratories. The results showed that the strength and creep properties of ice could be substantially improved with various types of reinforcement. Fast-forward to the 21st century and a world grappling with the effects of a changing climate. Current engineering challenges in cold regions include extending the life and capacity of ice roads and stabilizing infrastructure built on thawing foundations of ice-rich soils. Contemporary studies in the fields of ice engineering and geotechnique are discussed, which build upon a historical understanding of reinforced ice behaviour and new data to inform the design, operation and adaption of Canada's critical infrastructure in a warming world.

## RÉSUMÉ

On l'avait baptisé "Habbakuk" : un projet hors du commun, ultra-secret, une entreprise stratégique poursuivie par les Alliés durant la Deuxième Guerre mondiale. Il s'agissait de construire une plate-forme flottante en glace à l'épreuve des sous-marins, qu'on utiliserait comme porte-avions. Ce projet comptait sur le soutien enthousiaste du président du Royaume-Uni, Winston Churchill. Toutefois, on allait rapidement se rendre compte qu'il fallait renforcer la glace pour qu'elle puisse jouer le rôle qu'on s'attendait d'elle. Des essais à grande échelle ont été effectués au Canada dans plusieurs universités canadiennes, à Montréal, de même que dans les laboratoires du Conseil National de la Recherche. Les résultats ont démontré que le renforcement de la glace avec certains matériaux augmentait sa résistance mécanique et améliorait son comportement en fluage. Aujourd'hui, où les changements climatiques font les manchettes, on songe à utiliser le même principe pour allonger la durée de vie utile des chemins de glace et en augmenter la capacité portante. Cette méthode pourrait également servir à stabiliser certaines infrastructures reposant sur une fondation de sol riche en glace, qui a tendance à fondre. Des études récentes en ingénierie de la glace et en géotechnique, discutées dans cet article, ont tiré parti de ces connaissances historiques sur les propriétés mécaniques de la glace renforcée, et génèrent actuellement de nouvelles données servant à la conception, à l'utilisation et à l'adaptation d'importantes infrastructures au Canada aux prises avec le réchauffement climatique.

## 1 INTRODUCTION

One of the critical theaters of World War II that directly relates to St. John's was the North Atlantic, where conflict arose between the convoys supplying Great Britain and U-boats attacking them. In 1942, shipping losses were at their height and all avenues of providing more protection to the convoys were being considered. In that desperate time, aircraft were very effective in detecting and attacking submarines, but their range was limited. One of the ideas that surfaced to address this was to build landing fields of ice, thereby greatly extending the range and effectiveness of aircraft sorties. The idea originated with Geoffrey Pyke, an eccentric genius with connections that got him a position as a scientific adviser to Lord Louis Mountbatten, Chief, Combined Operations (CCO), in Great Britain. Combined Operations played an important role in the planning and preparation for offensive missions carried out jointly by the three armed services. It also had responsibilities to assist in the development of equipment and special craft required for these operations. This is where Pyke and his idea of a "ship of ice" or "bergship" gained currency. Pyke introduced

the idea to Max Perutz, a Cambridge Professor, and later Nobel laureate in chemistry. Perutz identified the shortcomings of ice in such an application, but suggested reinforcing ice with wood-pulp to increase its strength and to slow its melting. Perutz also did some testing to optimize its properties and named the material "pykrete". Pyke was enthusiastic and wrote a 35,000 word document promoting the idea of an ice ship built from pykrete and submitted it to Mountbatten in October 1942. The idea was evaluated within Combined Operations, and in December 1942 Mountbatten took this idea to Churchill. Churchill was enthusiastic and took the idea to the War Cabinet in mid-December 1942. To pursue the concept, a Directing Committee of high level military and civilian experts was established. The feasibility of building such a large ship of ice had to be defined quickly. A significant part of the work to do this had to be carried out on a large scale and in cold weather. Accordingly, the Canadian Government was approached to initiate the large scale tests in the winter, January to March 1943. Some of the technical outcomes of this work will be described in this paper.

In addition to that early work on Habbakuk, contemporary research has proven that a host of other materials are capable of improving the engineering characteristics of ice. These approaches are explored later in this paper in the context of climate change related northern transportation challenges and research being conducted by the National Research Council of Canada.

## 2 HABBAKUK ICE REINFORCEMENT FINDINGS

### 2.1 The Call to Canada

The project had already identified that the mechanical properties of ice as a structural material would have to be understood to undertake the design of such a vessel. Small scale testing of ice for its strength and deformation properties and means of enhancing the properties had by now been undertaken in the UK and the US in the autumn of 1942. This work identified that adding wood pulp would result in significant improvements in strength properties. This material was named "pykrete" in recognition of its originator. It was realized that for ice or reinforced ice to be effective as a structural material, its strength and deformation behaviour would have to be determined at a scale that would give confidence in using the measured properties in design. Attention turned to Canada as a site where such testing could be carried out and the Canadian government responded favourably to the request.

### 2.2 Large Scale Testing

#### 2.2.1 Challenges

The National Research Council was approached by the Canadian Government at the beginning of 1943 to undertake the large scale testing required and to provide results by April 1943. Given the scale of the tests, it was clear they would have to be done outside during the winter. It was quickly realized the scope and timing of the required tests were beyond the capability of NRC alone. Three western universities, Manitoba, Saskatchewan and Alberta, were engaged to carry out this testing. The results from this work are presented here as much for historical purposes as for the technical content. The work at these universities focused on the production of reinforced ice and its properties. Coverage here is limited to primarily flexural properties. Later sections of this paper will relate results of contemporary work on ice reinforcement which supersede this work done during World War II. What is most remarkable is what was accomplished by our geotechnical forebearers in a very short period of time under wartime constraints. There wasn't time to order specialized test equipment, even if it had been available, so improvisation was the order of the day. Remember this was before the day of digital data acquisition; manual reading of dial gauges for deflections and load balances for force were standard practice. It is also interesting to note that the whole project was "Top Secret", so carrying out this testing outdoors must have presented its own challenges! Aspects of the work at each of the three western universities will be highlighted here.

#### 2.2.2 University of Manitoba

The work at the University of Manitoba was carried out in the Department of Civil Engineering. It was conducted in an outdoor facility in February and March, 1943, with the testing being cut short because of an early thaw. The testing focused on the bond strength between various dimensioned steel and wood reinforcing bars and ice. The results are summarized from Gold (1993). The steel reinforcement included 2 in. pipe,  $\frac{3}{8}$ ,  $\frac{1}{2}$  and  $\frac{3}{4}$  in. bars, and 1/10 in. wire. The wood reinforcing included 2 by 4's, 1-9/16 by  $\frac{3}{8}$  in. laths and 1 by 1 in. fir, excuse the inch dimensions! The reinforcing materials were frozen into 25 cm cubes of ice or a snow and ice mixture. Little information is available on the conditions of freezing and testing but some results are provided to give an indication of the results.

For rapidly applied loading to the steel reinforcing bars bond strength in ice ranged from 470 to 2050 kPa with 20 of the 27 tests in the smaller range 470 to 1250 kPa. Thirty-nine tests with wood reinforcing gave bond strengths in the range of 360 to 650 kPa for a group of 17 tests and 860 to 1350 kPa for the other group. There is insufficient background material to explain the scatter of the results. Time dependent tests of bond strength in snow-ice were also carried out with time to failure documented. Time to failure for  $\frac{3}{8}$  in. steel bar was 2 days at 700 kPa and 13 days at 200 kPa applied stress. For test on  $\frac{3}{4}$  in. squared fir at applied stress levels of 500, 550 and 700 kPa failure times were about 12 days. Simple compression tests on 10 cm cubes at -2°C yielded compressive strength of 1500 to 2500 kPa for ice samples and 2000 to 4500 kPa for ice and snow mixtures.

#### 2.2.3 University of Saskatchewan

At the University of Saskatchewan, the work was carried out within the Faculty of Engineering in the Department of Civil Engineering. The original report on the work has been published as Appendix 2 of Gold's book (Gold, 1993). It is interesting to note that in this report ice is referred to as "Habbakuk", perhaps their manner in writing about the "Top Secret" work without revealing what the material was. Specimen preparation and testing for strength and deformation was originally done outdoors but was moved to a cold storage plant to get better consistency of results. Ice for the testing was prepared by first breaking ice into 2 to 5 cm sized fragments, packing it into moulds and then flooding with water and allowing it to freeze. This was done in 5 or 10 cm lifts.

Bond strength of 1 inch oak dowel and  $\frac{3}{8}$  in. steel rod in a 10% by weight pulp mixture was about 700 kPa, with slow failure for oak and abrupt failure for steel. Further bond tests with refrozen crushed ice yielded high bond strength for both wood and steel, in the range of 1500 to 3000 kPa. Time dependence of bond strength was determined under a constant stress of 100 kPa. Oak dowel  $\frac{1}{2}$  in. showed no slip after 7  $\frac{1}{2}$  days. With  $\frac{3}{8}$  in. steel average failure time was under 4 days. Surprisingly, crushed ice had a higher bond strength to wood and steel than the wood pulp mixture. Comparison to the Manitoba tests are not possible because of different test conditions.

At the University of Saskatchewan, quite extensive testing of beams with and without reinforcing were conducted. The beam dimensions were 10 cm wide, 25 cm deep and 150 cm long. Loading was at the mid-point or quarter-points. The results from one test series are reproduced in Table 1. The beam materials were refrozen ice fragments and 10% pulp (referred to elsewhere as pykrete). Some of the beams were plain, but a number of them had reinforcing bars near the top and bottom, as well as diagonal bracing, as noted in the table. The results of Series 1, ice with no additives, is typical of beams that size (Timco and O'Brien, 1994). Beams of a frozen mix containing 10% pulp, Series 10, experienced an almost 5 fold increase in flexural strength. Adding a single fir reinforcing strip, Series 2, increased flexural strength by a factor of 3. Adding additional reinforcing strips and diagonal reinforcement resulted in up to a factor of 10 increase in the flexural strength. Time dependent deflection was determined from applying a 300 kg weight to the centre of the beam span (1300kPa) for 15 days. Series 3 and 4 beams experienced about 10 mm deflection in this time period, Series 5 and 6 about 2 mm of deflection.

Table 1 Flexural strength of ice beams at -4°C.

Series	No. of Tests	Material	Reinforcement			Average Strength (kPa)
			Top	Bottom	Diagonal	
1	6	crushed ice	None	None	None	840
2	8	crushed ice	None	one ¼ fir	None	2800
3	6	crushed ice	None	one ¼ fir	lath*	4400
4	3	crushed ice	None	two ¼ fir one ½ fir	lath**	8100
5	3	crushed ice	one ¼ fir	one ¼ fir	lath**	7800
6	3	crushed ice	three ¼ fir	two ¼ fir one ½ fir	lath**	6800
10	2	10% pulp	None	None	None	4600
11	2	10% pulp	None	two ¼ fir one ¼ steel	lath**	9400
12	2	crushed ice	None	one ¼ fir	lath**	6900
13	2	crushed ice	None	two ¼ fir one ¼ steel	lath**	7900

Dimensions of reinforcements, inches; shape, fir square and steel round.

lath\* 11 cm o.c. alternate sides

lath\*\* 11 cm o.c. both sides

Note that the average strengths given in Table 1 were calculated assuming the beam was a homogenous material ( $\sigma_f = My/I$ ).

#### 2.2.4 University of Alberta

The work at the University of Alberta was led by the Civil Engineering Department, and was carried out at the university campus in Edmonton and also in Jasper, see Appendix 3 of Gold (1993). All the work was at the mercy of ambient weather conditions. A number of small scale (9 x 9 x 90 cm) beam tests under three point loading were conducted on the campus to explore the influence of reinforcement on the strength of frozen water, and frozen

snow or ice chips saturated with water. Results of reinforcement similar to those in the Saskatchewan tests were obtained. Presoaking the wood reinforcement was identified as yielding a very significant benefit. One variation in beam composition was the inclusion of hay with normal tension reinforcement near the lower edge of the beam. It resulted in a strength increase beyond that of normal tension reinforcement. This increase was attributed to the hay impeding the growth of cracks. The report also made careful note of cracking in the beams as a diagnostic of the failure process. Two large scale compression test on columns 22 cm square and 175 cm long were conducted at Jasper. The ice was clear columnar ice from a lake. The ice temperature was near the freezing point. Load was increased by moving a weight along a beam, another example of improvisation. The number of cracks increased until the column failed by "crumbling" at a stress of 2700 kPa. Another test with similar ice and column dimensions again resulted in extensive cracking and excessive deformation which limited the stress to 2200 kPa.

For the Alberta work what was most significant were the large scale beam tests carried out at Lake Louise. For more detail see Appendix 4 of Gold (1993). These tests were conducted by the Canadian Department of Mines and Resources. Beam size ranged from 15 x 30 cm by 3.5 m long to 0.6 x 1.2 by 12.2 m long, so they were quite substantial in size. A large work crew was needed to perform the beam fabrication and testing, all while maintaining secrecy. Beams were made by freezing a mixture of snow or ice chips and water in lifts, or freezing together ice blocks cut from the lake. Steel or wood or a combination of both were frozen into the lower part of the beam where maximum tensile stress was generated. Back calculation from stresses at failure gave bond strength between wood and clear ice as 350 kPa, snow-ice 300 kPa and ice-chip ice 275 kPa. Beams 0.6 x 1.2 x 10 m failed at centre loads from 340 kN to 770 kN depending on the type, amount and placement of reinforcement. Temperature of the beams was from -1 to -6°C. The overall conclusion was that sufficient information on the performance of reinforced ice beams had been gained that structural elements could be designed.

#### 2.2.5 Summary of Large Scale Testing Results

The testing in Western Canada identified that the structural behaviour of ice could be substantially enhanced by reinforcement. Macro-reinforcement, where wood or steel were strategically placed in the beam, produced significant improvements at a quantity 2 to 3 % by weight, but would require much labour in placement. Micro-reinforcement with pykrete, at 10% by weight, achieved significant performance improvements, but also had drawbacks in getting a uniform dispersion in the wood pulp in the beam.

This brief review has covered some the principal results relating the bending strength of reinforced ice within the Habbakuk project. There were also comprehensive tests on the compressive, tensile and shear strength of various compositions of ice and additives at the three western universities and the National Research Council. Another avenue of investigation not described here but also very important, and a fascinating read, was on the development

of methods for producing the vast quantities of ice which would be required in the construction of a “bergship” as documented in Gold (1993) and Gold (2004).

### 2.3 Montreal Engineering Company Ltd. and the End of Habbakuk

Since the ultimate objective of the project was to be the construction of a ‘bergship’, an engineering company, Montreal Engineering Company, was brought into the project. The vessel envisioned was to be 2000 ft long, have a beam of 300 ft and a draft of 150 ft. Even when reduced to metric units, 600 by 90 by 45 m, it was to be enormous! Montreal Engineering conducted a review of the results of the work at the three western universities and the NRC in Ottawa. The work scope was broader, looking at the mechanical properties of ice and pykrete, their behaviour as structural materials, and their constructability. They identified that long term deformation rather than short term strength was a key requirement. In this regard they conducted further tests of pykrete to optimize the composition with regard to this requirement. This was done in a cold storage plant in Montreal in June, July and August 1943, and provided summer employment for a couple of students. The report on this work is in Appendix 12 of Gold (1993). A concentration of 6% wood pulp was found to be optimal in minimizing long term deformation. Given the size of the vessel, it would have to be built-up from smaller blocks of pykrete which would have to be welded together. Even welding with pykrete resulted in weak ice-rich layers. At the end of August 1943, Montreal Engineering reported to NRC on the feasibility of the project, see Appendix 11 Gold (1993). Their findings were not positive, and identified 14 critical problems. They were mostly technical but the last two were an estimated cost of \$100,000, 000 in 1943 dollars and the absence of a dry-dock to accommodate a vessel of that size. From an engineering perspective the project had ended.

## 3 CONTEMPORARY MUSINGS ON REINFORCED ICE

### 3.1 The Evolution of Pykrete

The intensity of pykrete fascination may have waned somewhat since the days of Habbakuk, but innovative investigators are still expanding the breadth of reinforced ice applications and fine-tuning the composites first explored in the 1940’s. In just this past decade, pykrete has been used to construct an ice arch in Fairbanks, Alaska and a 30 m dome in Juuka, Finland – the largest application of pykrete technology to date (Pronk et al., 2014). These trials suggest that a micro-reinforced ice comprising 10% wood fibers by mass results in optimal reinforced ice properties – the same result that was later reported by Vasiliev et al. (2015). Vasiliev et al. (2015) systematically tested pykrete samples with sawdust and shavings in a mass concentration of 2.5% to 15% and also investigated practical attributes of the material, including pumpability.

A further innovation on the basic pykrete formulation was the addition of newspaper fibers and a gel (sodium

carboxyl methyl cellulose gelatin polyelectrolyte complex – SGPC). This new formulation was dubbed “Ultimate Pykrete” by Li et al. (2015) and exhibits improved properties including higher strength, low weight and short curing time.

### 3.1 Other Reinforcing Materials

Based on the early successes of pykrete and reinforced ice testing, researchers and practitioners have continued to trial numerous reinforcing materials in ice. These approaches and test results are well documented in Barrette (2018), Barrette and Charlebois (2018) and Carreira (2019).

Broadly speaking, the categories of microscopic reinforcement materials that have been documented in the literature are: fibers, aggregates and cryotropic gels (gels formed during freezing). Fiberglass yarns, asbestos and even shredded bark have been evaluated in laboratory investigations and are contrasted with contemporaneous studies that focused on reinforcement by the addition of silts, sands and gravels. Cryotropic gels comprising non-toxic polyvinyl alcohol (PVA) have been combined successfully with soils to form an intriguing composite with lower permeability and increased plasticity – ideal for watertight applications around hydroelectric dams (Vasiliev et al. 2014) (Carreira, 2019).

In addition to naturally abundant materials like timbers, logs and branches, viable macroscopic reinforcement materials also include: steel rods and cables, glass fiber rods, fiberglass yarn and geosynthetics. The geosynthetic category includes geogrids and geofabrics – common tools in modern geotechnical engineering. For ice crossing applications, geogrids have been tested in laboratory-grown, floating freshwater ice covers by Haynes and Martinson (1989). The researchers found that the geogrid had the most significant impact on strength when incorporated into a thin ice sheet (30 mm) – a 300 % bearing capacity increase resulted. Later field trials by Haynes et al. (1992) showed that an unreinforced ice cover showed 40% greater deflection under a static vehicle load when compared to a geogrid-reinforced ice cover. The practicality of deploying and managing the position of the geosynthetic within the ice cover, however, remains a considerable challenge.

### 3.2 Selection Criteria for Reinforcing Materials

Some work has been done to investigate approaches to selecting a candidate reinforcing material depending on the specific application (Charlebois and Barrette 2019). Technical specifications and material characteristics are dependent on the specific use case and consideration of loading mode. Considerations of material availability, cost, constructability, environmental compatibility and stakeholder acceptability are also critical, especially in applications for sensitive environments in Northern Canada.

### 3.3 Making Ice Stronger through Cyclic Loading?

Though requiring the reader to engage in some counter-intuition, researchers have actually shown significant increases in the flexural strength of laboratory ice after subjecting it to periods of cyclic loading (Iliescu et al. 2017). Experiments demonstrated that the flexural strength of plates of freshwater, columnar-grained ice could be increased by a factor of 2 or more after cyclic loading at low frequencies (~0.1 Hz) and stress amplitudes ranging from 1.3 MPa to 2.6 MPa. The researchers ascribe this strengthening phenomenon to grain boundary sliding and reduction in stress concentration. Making ice stronger, perhaps, is not about what you put in it, but what you put on it (and at what frequency).

#### 4 REINFORCED ICE APPLICATIONS FOR NORTHERN TRANSPORTATION

##### 5.1 Winter Roads Safety and Reliability

Climate change has affected northern transportation in many respects, but most certainly in the domain of ground transportation by winter roads – those seasonal roads over permafrost and across frozen lakes and rivers that link communities and serve northern industries (Barrette and Charlebois 2018). A reduction in the reliability and length of operating windows has been reported by operators, creating an opportunity to improve upon natural ice covers by means of reinforcement.

##### 5.2 Ongoing Research and Development

Geosynthetics offer a potential solution to extending the seasonal operating window for winter roads. The National Research Council of Canada has recently partnered with Transport Canada, Crown-Indigenous Relations and Northern Affairs Canada, and the Royal Military College (RMC) of Canada to test and model the behaviour of ice covers reinforced with geogrids (Barrette et al. 2019). The work focuses on assessing the impacts of reinforcement on reducing cracking and failure of ice covers (Figure 1).

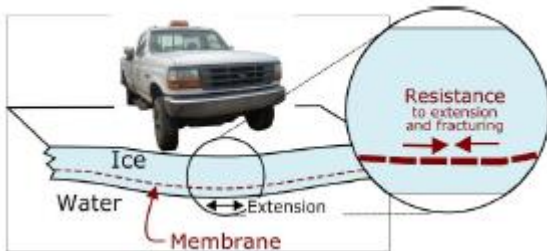


Figure 1 – incorporation of a geosynthetic in an ice cover to resist extension and fracturing under vehicular loading (Source: Barrette et al. 2019).

In that work, non-reinforced and reinforced ice beams were subjected to loading with a 4-point beam test rig. Interestingly, preliminary work with the ice beams in the laboratory suggest that, under those conditions, reinforcement did not necessarily increase the ultimate

yield strength (breakthrough strength) of the ice, but instead acted to prolong the run-up period before failure – thus absorbing the energy of the load over more time and delaying the onset of failure.

The application of contemporary reinforcing materials and decades of knowledge has the potential to greatly improve the resilience of northern infrastructure and to increase transportation safety for northern residents and industries during a period of significant climatic change. It is hoped that this line of research will continue to evolve, as the potential applications for future generations are yet unwritten.

#### 6 CONCLUSIONS

Reinforced ice has captured the imaginations of engineers and researchers for over seventy years. Given the right economic and climatic conditions, its potential applications are far ranging – from a structural element in the hands of naval architects to an innovative construction material for ice road operators and civil engineers. Much work has been done over this period and beneficial properties of reinforced ice in a changing climate have been highlighted in the literature. Specific applications for improving the reliability and safety of Canada’s winter roads networks are being investigated. Through periods of international strife and climatic change, innovators in geotechnical and civil engineering must continue to rise to meet society’s ever-evolving global challenges.

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