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Overview of ice roads in Canada: Design, usage and climate change adaptation

Technical Report
OCRE-TR-2015-011

Paul D. Barrette

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October 18, 2015

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[*Frontispiece:* Photograph taken by the author on the Tibbitt-to-Conwoyto operation, in March 2008.]

Executive Summary

From a civil engineering perspective, floating ice covers in cold regions is a readily accessible and cost effective material for transportation infrastructure, notably ice roads, which can be used in areas that would otherwise not be accessible. Because ice roads are floating, they entail risks that other road infrastructures do not have to contend with, namely, that of a breakthrough. In order to better understand what is involved in a safe and cost effective operation of ice roads and other ice-based infrastructure, the physical nature of ice covers (ice type, thickness, temperature, cracking, etc.) and the mechanical properties of that material (elastic modulus, creep behavior) need to be properly assessed. The empirically-derived Gold's formula provides a first order assessment of bearing strength. The actual usage and the nature of the traffic are also important factors. Ice roads are managed by government bodies or by local communities, or they can be private operations. There are a large number of ice roads in the country – an attempt is currently being made by OCRE to centralize that information and make it available to all stakeholders.

A significant number of guidelines (best practices, design codes, handbooks and manuals) currently exist for the construction, maintenance and usage of these structures. They are typically published by provincial jurisdictions, the private sector and some research organizations. They are also found in the scientific literature. These guidelines include various amount of information of different types, notably some background on the nature of the ice cover, how it should be used for transportation purposes and how to determine the maximum load it can safely sustain. For the latter, Gold's formula is almost always alluded to, and is used in slightly different ways. Significant differences are noted in the guidelines' recommendations regarding the strength of white ice relative to clear ice, resulting in a large discrepancy in recommended maximum loads.

A global temperature rise associated with climate has been documented over the last number of decades and affects ice covers in different ways, depending on geographical location. The general consequences are a reduction in the total number of freezing degree days and the delayed onset of freeze-up and earlier onset of melting. Means to adapt to this phenomenon includes adaptation strategies at the operational level, as well as macroscopic and microscopic ice cover reinforcement. Several additional avenues should also be explored. This includes consultation with ice road operators in order to find out about the technical issues, recurrent problems, remediation measures, so forth, and the consolidation of that information so as to make it available to all stakeholders. Another avenue is to clarify the role of white ice on the bearing capacity of an ice sheet. Means of investigating new technologies and reinforcement methods should also be revisited. The availability of cheaper, environment-friendly and more effective material would allow strengthening segments of an ice road that represent a weak link.

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1. Introduction

Ice roads are used in the North by local communities and the private sector to move both people and goods into areas that would otherwise not be accessible in the winter. Further, as activities in the North are expected to intensify, and in the context of a warming climate, a decrease in the average number of 'freezing degree-days' means that ice road builders will have to do more with less, i.e. increased activity with a reduced operational lifespan, without compromising the safety of the operations. Various means of counteracting this phenomenon may be envisaged. One is through an improved understanding of ice bearing capacity. Another is to re-visit means of reinforcing ice covers.

From a civil engineering perspective, floating ice covers in cold regions may be seen as an abundant, readily accessible and cost effective material for transportation infrastructures, notably ice roads. However, because ice roads are floating, they entail risks that other road infrastructures do not have to contend with, namely, that of a breakthrough. A large amount of information currently exists for the construction, maintenance and usage of these structures. They are published by federal, provincial and territorial jurisdictions, the private sector, research institutes and journals, standards' associations and community-based organizations. They take the form of handbooks, manuals, reports, journal papers, best practices and design codes. Information is also found in the scientific literature. These guidelines generally offer a brief description on the nature of the ice cover, how it should be used for transportation purposes and how to determine the maximum load it can safely sustain. They differ in some respects – e.g. the factors for determining maximum loads, the difference between clear ice and white ice, and between freshwater ice and sea ice.

The purpose of the present report is:

1. To provide background information on the nature of ice covers and ice bearing capacity notions, including the physics of deformation.
2. To present a brief overview of some guidelines on ice roads available to ice road builders and users in Canada and elsewhere (the most recent editions were used), and to see how these guidelines address maximum ice loading.
3. To discuss prospective avenues to adapt to the effects of climate change on the operational lifespan of ice road operations.

This report should not, itself, be used as a guideline. Rather, it is meant to provide introductory material that can help better appreciate the basis of the existing guidelines.

In this report, a distinction is made between the terms 'winter road', 'ice road' and 'ice bridge'. A winter road is a road that runs over frozen land, including frozen lakes and rivers. An ice road is a winter road that runs mostly on frozen lakes and rivers. The term 'ice bridge' designates a short segment of a winter road that crosses a frozen water body, typically a river.

2. Bearing capacity of floating ice covers

In order to better understand what is involved in a safe and cost effective operation of ice roads and other ice-based infrastructure, one should consider the factors that come into play in assessing ice bearing capacity. In this section, a brief overview is provided on the origin and nature of an ice cover. The general approach used for determining the bearing capacity of an ice cover will then be summarized. This will be followed by an overview of the physics of ice deformation and how it can provide insights into bearing capacity issues. The material presented in this section is only a basis – more information is available elsewhere (e.g. Ashton, 1986; CRREL, 2006; Iliescu and Baker, 2007; Michel, 1978; Petrich and Eicken, 2012; Proskin et al., 2011; Sinha, 1980; Squire et al., 1996), as well as in the guidelines reviewed in this report. Other sources are included in sections to which they are relevant.

2.1 Natural ice covers

Floating ice covers are found on lakes, rivers and sea expanses. They can be quite uniform or they can vary in thickness and internal structure. This will depend on many factors, notably initial freeze-up, growth history and internal deformation (e.g. thermal cracking, pressure ridges). These are, in turn, a function of air temperature, precipitation, winds, currents, wave regimes, water level changes, the size of the water body, amongst other factors. Since these factors vary throughout the winter, an ice cover will keep evolving, at least to some extent, until spring break-up. In short, ice covers are complex and unpredictable.

Following is a general discussion, simplified for the purpose of this report, on natural ice covers.

2.1.1 Ice growth

An ice cover commonly begins as a thin layer of snow that falls on a calm water surface (Figure 1). These crystals then grow downward into columnar-shape crystals, sometimes called congelation ice. Any type of water dynamics, such as wind, wave and currents, will complicate this scenario, leading to ice layering.

The bottom surface of the ice always is at or near melting temperature. The ice’s upper surface is close to the air temperature and may undergo the same temperature fluctuations as the air. A cold air temperature will promote fast ice growth. A snow cover on the ice surface will act as an insulator, and the ice will not grow as fast. The nearby presence of a spring may reduce the ice thickness in a lake. There may be no sign of it at the ice surface. This can also happen near a dam, above a shoal and wherever currents are expected to be strong in rivers and estuaries.

As the average daily air temperature increases at the end of the winter, the ice will start to thaw, at which point it may become greyish in color. A snow layer on top of the ice cover at that time of the year will provide some protection against the increasingly more intense solar radiations, thereby reducing ice degradation.

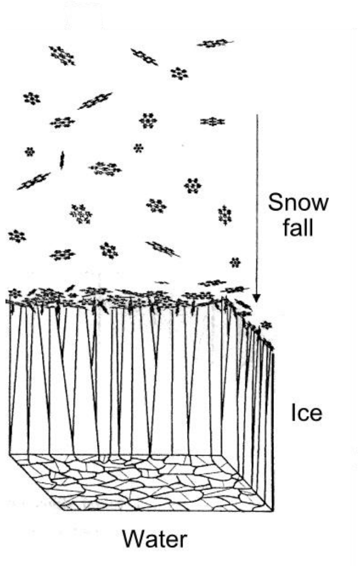

Figure 1: A common scenario for the initiation and growth of an ice cover. Note the crystal outline along the underside, as shown in Figure 5.

At times, ‘wet cracks’ can occur – cracks that cross the full thickness of the ice cover, allowing the water to move upward along the crack and flood part of the ice surface. Many different scenarios can happen – they will have an effect on the ice type and internal layering.

2.1.2 Ice types

Frozen water comes in various forms. When it precipitates from the atmosphere, it is made from ice but is known as ‘snow’. At the surface of a water expanse (e.g. lake, river), it can have different crystal structures.

2.1.2.1 Columnar ice

This ice type, shown in Figure 1, is one of the most common in floating ice covers. Each grain’s crystal axis is in the horizontal plane, and the grains are columnar in shape as they extend vertically downward.

2.1.2.2 Lake ice

Lake ice only forms on calm water surfaces (no wind, currents or snow) and can have very large grains, with vertically oriented crystal axes.

2.1.2.3 Frazil ice

Frazil ice is made from fine platelets or spicules that typically occur in dynamic water conditions, e.g. fast flowing rivers.

2.1.2.4 Agglomerate ice

Depending on the circumstances (weather, ice and water dynamics), an ice cover can comprise several layers. River dynamics may also be conducive to the formation of other ice types, such as frazil ice, which may also form distinct layers inside the ice cover.

2.1.3 Clear ice versus white ice

Frozen water is commonly divided into two types of ice: clear ice and white ice (Figure 2).

2.1.3.1 Clear ice

This ice is also called ‘black ice’ because, being transparent, it allows us to see what is inside the ice – for instance, cracks – right down through to the water column below it, which is usually dark. An example is shown in Figure 3. Columnar-grained ice is typically clear because it is free of air entrapment (bubbles). Naturally occurring water always contains dissolved air, but unlike for white ice, this air does not get incorporated into the ice during growth. Instead, it is being expelled at the ice-water interface.

Figure 2: White ice on top of clear ice in a large block, collected from the Rideau Canal skateway, in Ottawa.

Figure 3: Looking down at a thick clear ice cover, with fracture surfaces nicely displayed. Boot and tire threads for scale.

2.1.3.2 White ice

White ice is sometimes called ‘snow ice’, because it often originates from a layer of snow on the ice cover. This snow eventually gets flooded by water that finds its way to the ice surface, e.g. through cracks. In that case, even if the snow is entirely saturated (all the pores get filled with water), the dissolved air cannot escape. This leads to the formation of air entrapment, which is why the ice is white. Because of the air content, the density of white ice is slightly lower than that of clear ice. At times, water may partially drain out of the snow, leading to a material with a substantially lower density. When that happens, the ice is mechanically much weaker.

Flooding ice with water pumps, a procedure commonly used to increase ice thickness, will also lead to the formation of white ice – air entrapment occurs because the air dissolved in the water could not escape. Unlike snow ice, white ice resulting from this procedure, if properly produced, is reported as being relatively strong. Either way, white ice is more porous and less dense than clear ice.

2.1.3.3 A well-known example

One way to visualize the difference between clear and white ice is by considering a standard household ice cube (Figure 4). Ice growth starts from the sides and proceeds toward the center. The dissolved air is initially pushed away from the ice-water interface. At some point, it accumulates in tiny air bubbles during the cube's final grow stage. In that figure, a zone of clear ice can be seen surrounding the white, bubble-rich core.

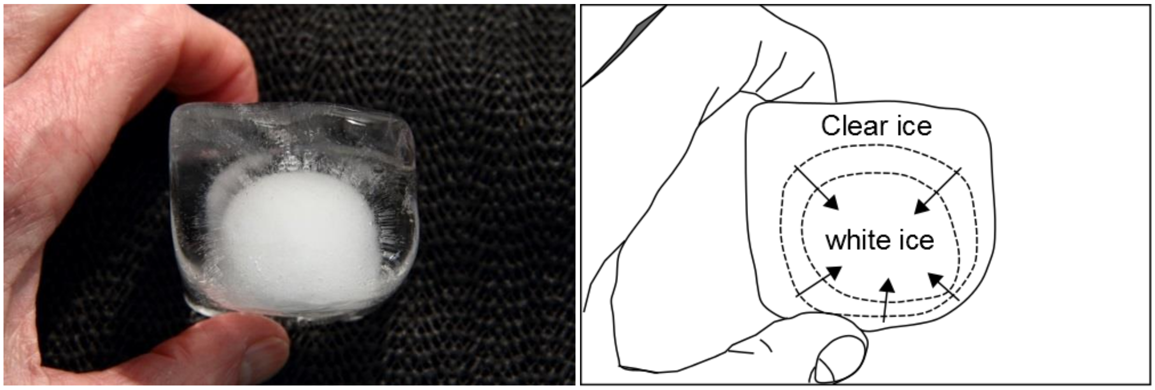

Figure 4: Left) Standard household ice cube, showing clear ice surrounding white ice; Right) Diagram showing the growth direction of the ice - the cube's center was the last part to freeze.

2.1.4 Freshwater ice and saline ice

When an ice cover forms at the surface of a lake or of a river, it is made of freshwater ice. If it forms at the surface of a sea expanse, it is made of saline (or sea) ice. These two ice types have quite distinct physical and mechanical properties (Sinha, 1977; Weeks, 2010, Chap. 7). In addition to air entrapment, saline ice contains a large amount of brine pockets, defining what is referred to as a 'sub-grain structure' (Figure 5). Brine content is a function of ice salinity and temperature. The higher the brine content, the lower the ice strength. The present report is mainly concerned with freshwater ice.

2.2 Empirical approach to ice bearing capacity

When an ice cover is pushed downward as is the case when it supports a load – e.g. a vehicle - it sinks under the load (Figure 6). As it does so, and assuming it is freely floating, it displaces a volume of water whose weight is equivalent to the amount of loading. This is known as Archimedes' principle.

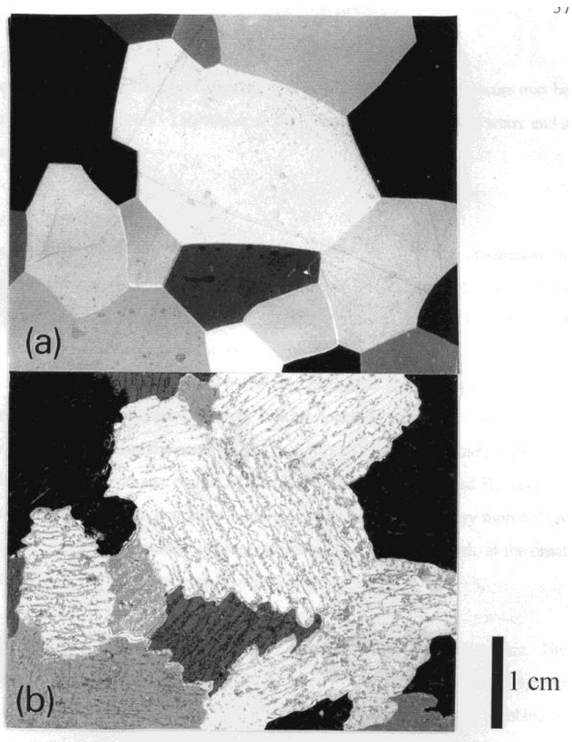

Figure 5: Ice crystal at the underside of an ice cover grown from (a) freshwater and (b) saline water - note tiny brine pockets and sub-grain structure (from Barrette et al., 1993).

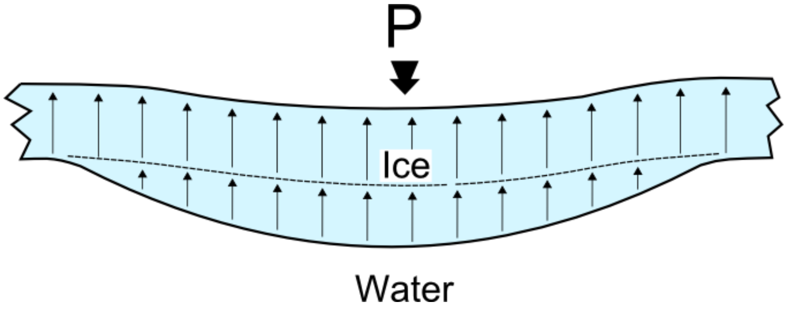

Figure 6: Resistance to sinking of a floating ice cover under load, from the ice buoyancy, is increased by the resistance to flexure (after CRREL, 2006).

If a vehicle is at one location for a short amount of time, the deformation will be mostly recoverable. This is referred to as short-term static loading. The longer the vehicle remains at that location, the higher the amount of permanent (non-elastic) deformation. A vehicle in motion will induce a more complicated loading scenario and associated ice response. This is sometimes referred to as ‘dynamic loading’. This report did not address the dynamic behavior of ice covers under moving loads, which is linked to recommended vehicle speed limits. There is a significant amount of research done on this subject (e.g. Squire et al., 1996) – it is relatively complex and still poorly understood. A review of this behavior is currently underway, and will be published elsewhere.

The amount of load that can be sustained by a floating ice sheet has been addressed in a few ways by a large number of investigators.

2.2.1 Gold's formula

In the 1950s, Lorne Gold, a scientist with the National Research Council in Ottawa, was looking for a way to help ice road users determine how much weight an ice cover of a given thickness can safely sustain. Analytical methods already existed at the time (and are still being used by engineers and scientists). However, they were relatively complex and thus not practical for ice road users who did not have the technical background to understand them. These methods also made assumptions (*e.g.* uniform ice, no cracking) that were not representative of real ice.

Gold collected information from the Pulp and Paper industry on breakthroughs that had occurred, including data on ice thickness and weight, of the vehicles and horses that caused the ice to fail (Gold, 1960; 1971). From this information, he borrowed a formula from Russian researchers (see short summary in Kerr, 1996) and used it in conjunction with the breakthrough data to come up with a method that, to this day, is used as a guideline for ice roads, platforms and landing strips. This formula has the following form

$$P = Ah^2 \qquad \text{Eq. 1}$$

Where

P: Design load
A: Empirical parameter with pressure units
h: Ice thickness

The parameter A is related with the ice flexural stress. As discussed later, the value assigned to it varies widely. The thickness h is assumed to be representative of the ice road as a whole (or a section thereof) with due consideration to prospective variations.

With this formula, a plot can be produced, as shown in Figure 7, that can be used as guidance to determining what a safe load could be for a given ice thickness. The 'A' values used by Gold in this plot are 3.5, 18 and 70 kg/cm^2, retained for the following reasons:

- The first one was the lower bound value for reported breakthroughs, i.e. none (or few) occurred below this line.
- The second value is the upper bound value for successful use of ice covers, i.e. these cases all plot below that line.
- The third value is for a line above which no breakthroughs were observed.

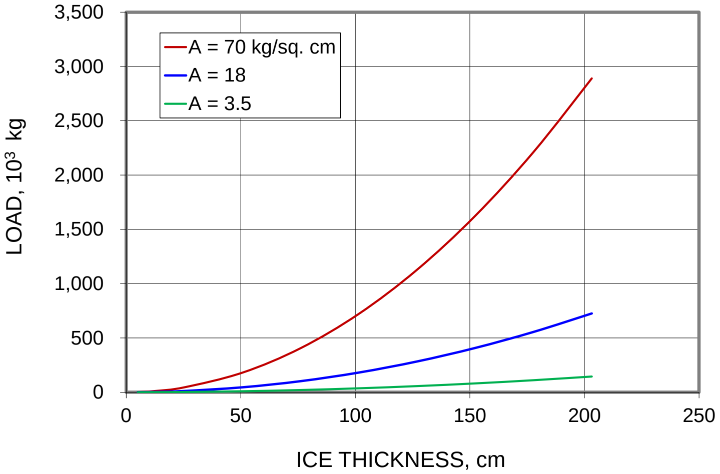

Figure 7: Load as a function of ice thickness for the three different A values used by Gold (1971).

Although simplified, these considerations capture some of the fundamentals of ice road design. Masterson (2009), for instance, alludes to 500-550 kPa as a typical allowable stress, which a corresponding safety factor of 3.0.

It should be borne in mind that Gold's formulation is based on 'empirical' evidence: it relies on observations of real events, not solely on theoretical concepts. It is a curve-fitting exercise – a best-fit line describes the relationship between two parameters, namely ice thickness and loads. This line may be seen as an 'envelope'. Above it, the probability of a breakthrough caused by a number of factors (localized thin ice, presence of a crack, high vehicle speed, etc.) is deemed unacceptable by the guideline.

2.2.2 Load duration

Gold's formula is not meant to be used for loads that remain at one location for a certain time period. The reason is that, after a certain amount of time, failure of an ice cover that safely supports a given non static load could occur. That is because, with time, the stresses induce non-elastic deformation in the form of micro-cracks (e.g Sinha, 1989b), which develop into large cracks and, ultimately, breakthrough.

In general, the heavier the load, the less time it should be allowed to remain on the ice. As to what the length of that time period is, different guidelines have different recommendations. Some, for instance, specify that Gold's formula should only be used for moving loads (CSAO, 2009; Government of Manitoba, 2014). Others specify a two hour limit (CSST, 1996; IHSA, 2014), which is also what Gold (1971, p. 179) prescribed.

If a load has to remain on the ice, some guidelines advise to monitor the freeboard by drilling a hole through the ice. When the water level reaches the ice surface (i.e. the freeboard reduces to zero), the load has to be removed. This practice is supported by the analyses of Frederking and Gold (1976) and has been validated by many sources (e.g. CSST, 1996; IHSA, 2014; Masterson, 2009). BMT Fleet Technology (2011) recommends to use a time-dependent reduction factor if the load duration is to exceed 15 minutes – the longer the duration, the lower the allowable load.

2.3 Analytical approach

Let us now expand a bit on the mechanical basis for bearing capacity determination, using formulations that simplify the relationship between forces and displacements. (If required, the reader can refer to Table 1 for an explanation of the symbols used in this report.) They assume the ice behaves as an elastic medium resting on an elastic foundation. To do this, we will assume that a point load is exerted on a floating ice sheet, and that is of short duration (in the order of seconds). The load is assumed to be away from the ice cover boundary. Resistance to that load will come from both the water buoyancy and the ice's flexural rigidity (Figure 6). The latter can be expressed as follows (CRREL, 2006; Masterson, 2009):

$$\sigma_{max} = 0.275(1+\nu)\frac{P}{h^2}log_{10}\left(\frac{Eh^3}{kb^4}\right) \qquad \text{Eq. 2}$$

where σ_{max} is the maximum tensile stress at the bottom of the sheet, ν is the Poisson ratio for the ice, h is the ice thickness, E is the elastic modulus of the ice and k is the water response (=9.81 kN/m^3 for water). Also,

$$b = \sqrt{1.6c^2 + h^2} - 0.675h \qquad \text{Eq. 3}$$

where c is the radius of the loaded area when that radius is < 1.724h. If the radius is equal or larger than 1.724h, $b = c$. For instance, a vehicle with several axles will exert load on a wider area than a pick-up truck.

These are the equations used to determine P for a given ice thickness and loading radius, and by assigning a maximum tensile stress to σ_{max}. Hence,

$$P = \frac{\sigma_{\max}\ h^2}{0.275(1+\nu)log_{10}\left(\frac{Eh^3}{kb^4}\right)} \qquad \text{Eq. 4}$$

Note the similarity between that equation and Gold's (whereby the load depends on the square of the ice thickness):

$$P = f(h^2) \qquad \text{Eq. 5}$$

Figure 8 is based on the foregoing methodology – it indicates the maximum weight that would be allowed onto the ice as a function of ice thickness. A load that exceeds the ice maximal tensile strength leads to the 'first crack', which is what governs design.

Table 1: Explanation for the symbols used in some of the equations in this report.

Symbol	**Explanation**
A_T	Inverse of the relaxation time at temperature T
b	Constant = $1/n$
c_1	Constant corresponding to the unit grain size d_1
d	Grain size
d_1	Unit grain size
ϵ	Viscous (dislocation creep) strain rate for unit stress σ_1
E_T	Young's modulus at temperature T
E_t	'Effective' elastic modulus
n	Stress exponent for dislocation motion induced viscous flow
N	Damage expressed as the number of accumulated cracks
s	Stress exponent for delayed elasticity (~1)
T	Temperature (K)
t	Time
ε	Total strain
ε_d	Delayed elastic strain
ε_e	Elastic strain
ε_v	Viscous strain
σ	Applied stress
σ_1	Unit stress

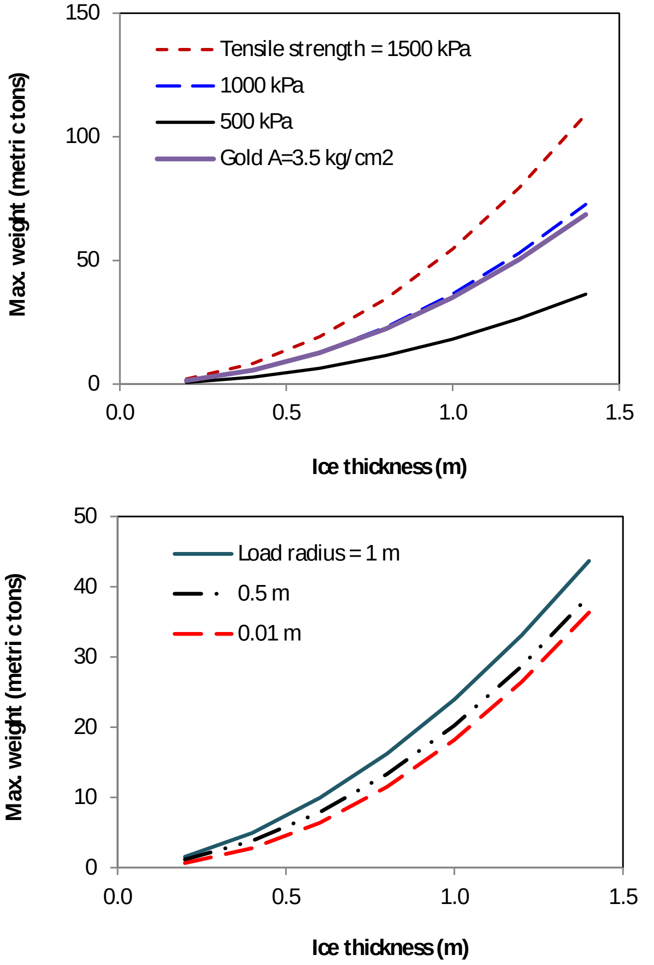

Figure 8: Top: The maximum load on an ice sheet as a function of ice thickness and what is assumed to be the maximal tensile strength (Gold's formulation from Figure 7 is included). Bottom: The maximum load on an ice sheet as a function of ice thickness and loading radius.

It should be noted that the elastic behavior is, in theory, fully recoverable upon unloading, and the elastic modulus for ice is in the order of 9-10 GPa. This modulus reflects the time-independent resistance to lattice distortion – it increases slightly as a function of temperature (Sinha, 1989a). This being said, analytical treatments use what is referred to as 'effective' moduli, which may be about half that value, when attempting to model elastically a visco-elastic material. The next section provides some insight into this question.

2.4 Physics of ice loading and deformation

In addition to the empirical and analytical approaches, there is a third, complementary approach to studying the behavior of the ice under load: the physics of deformation. From the 1970's to the 1990's, N.K. Sinha from NRC worked alongside L. Gold and looked into the physics of ice deformation. He developed a model that has a strong physical basis. It has been guided by microstructural observations as well as the results of laboratory testing and field trials. That model answers a number of questions that Gold's formula cannot address. Notably, why and how load duration affects the ice cover, whether or not we predict the amount of deflection with time, why the elastic response is a function of load duration (and other parameters), and how load history influences deflection. Sinha's findings allow one to predict, to a large extent, how long a given load can remain on the ice before it has to be removed.

The purpose of this section is to present some fundamentals on the mechanical behavior of ice under load, as documented by Sinha's research (Sinha, 1988a; Sinha, 2010). They shed light on what is actually taking place inside the ice when it is loaded. As such, they can help improve analytical treatments.

2.4.1 Behavior of ice under stress

What happens inside an ice cover when it is loaded? Why does it fail, and how? What are the fundamental mechanisms taking place at the crystal and microscopic scale that control ice strength? To address these questions, investigators study the deformational behavior of ice and the physical processes responsible for that behavior with small specimens. These are tested under controlled conditions in a laboratory, inside a refrigerated chamber.

2.4.2 Loading modes

Investigations on the physics of deformation thus begin at the scale of a specimen. Vertical loading of an ice cover in the context of ice roads involves three main loading modes: tension, compression and flexure (Figure 9). This figure is a simplification of what happens in a real ice cover, as seen earlier (e.g. Figure 6). Note that flexure combines compressive and tensional loading – it is more directly applicable to bearing capacity scenarios but it is also more complex. Testing in tension presents challenges with ice, which is a particularly brittle material, because specimens are prone to fracture under this loading mode. Also, end platens able to hold on to the specimen are a design challenge. For these reasons, testing in compression is the preferred mode.

The physical processes taking place inside the ice in all cases are essentially the same in the three modes. At this point, a key concept needs to be addressed: homologous temperature.

2.4.2.1 Homologous temperature – An important concept

Temperature is a measure of the atomic structure's kinetic energy: the higher the temperature, the higher that energy. A high temperature promotes the activation of physical processes involving broken interatomic bonds, diffusion, generation and motion of atomic crystal defects, amongst others.

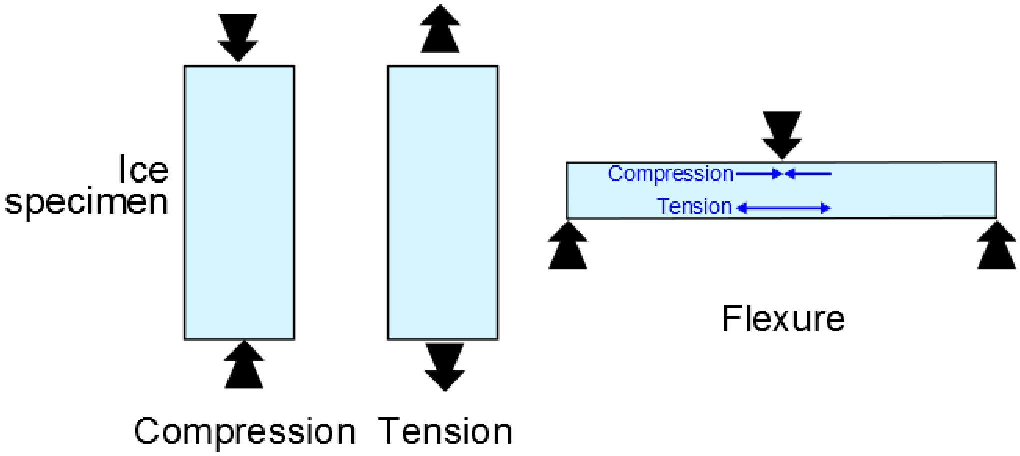

Figure 9: Three loading modes relevant to ice bearing capacity: compression, tension and flexure – note that flexure is a combination of both compression and tension.

The *homologous temperature* of a given material is equal to the material's actual temperature divided by its melting point, both measured on the Kelvin (K) temperature scale. The higher the homologous temperature, the closer the material is to its melting point. One may visualize an iron rod a blacksmith heats up to a high homologous temperatures so as to be able to hammer it into shape (Figure 10, left). In that material, as in ice, an increase in temperature promotes the generation and mobility of crystal defects in the material. This behavior is referred to as plasticity, or permanent deformation. The term viscosity is a synonym, and is often preferred in the metallurgical literature. Most importantly, as will be seen later, a high homologous temperature promotes deformation mechanisms that promote material failure, thereby reducing the strength of the material, namely grain boundary sliding.

A better example could be the collapse of the World Trade Center in 2001 (Figure 10, right), because it illustrate a case of failure under constant loading, as is the case for long term loading of an ice cover. Steel failure is seen as a major contributing factor to this disaster because of an increase in homologous temperature (Eagar and Musso, 2001). Under standard service conditions, steel is at about room temperature (20 deg. C or 293 K). Assuming a melting temperature of 1500 deg. C (or 1773 K), the homologous temperature of this material during its service life is around 0.16 (=293/1500). However, because of the fire, one of the steel components in the buildings' structure reached temperatures estimated at 650 deg. C (923 K)(Eagar and Musso, 2001). This is equivalent to a homologous temperature 0.62, with a corresponding 50% strength reduction. These components – angle clips that supported each floor level – failed, causing the affected floors to fall, inducing a domino effect. For more information on the failure of metals at high homologous temperatures and constant loading, see Sinha and Sinha (2011).

Consider now the homologous temperature of an ice block at, say, -10 deg. C (or 263 K). Its melting temperature is 273 K, such that the homologous temperature is 0.96. Naturally occurring ice may therefore be referred to as a very high temperature material. This, of course, is counter-intuitive. We perceive ice as a cold material, but that is because we see it from a human perspective. As far as the material is concerned, it is extremely hot. If that were not the case, ice roads would be able to support higher loads.

Figure 10: Two examples of materials at a high homologous temperature: Left) A red hot iron rod being hammered into shape.[1]; Right) Some critical steel components in the WTC twin towers' structure in New York, whose failure ultimately caused domino-style floor collapse.[2]

2.4.2.2 The brittleness of ice

In both steel and ice, a high homologous temperature activates intra- and inter-crystalline processes that contribute to weakening the material. But ice is also known to be a brittle material. As stated in Sinha (1988a, p. 201), "At high homologous temperatures, the lattice diffusion coefficient in ice is significantly lower than in most metals. Consequently, ice maintains brittle characteristics even at temperatures very close to its melting point." It will thus have a propensity to break, say, when hit with a hammer. Its brittleness stems from a diffusivity that is two or three orders of magnitude lower than that of most other materials (as discussed in Sinha, 1988a; Sinha, 1988b). The mobility of crystal defects in its molecular structure is low and, as a consequence, re-organization of its structure is slow. What this means is that even though the ice is very close to its melting point, intra-granular plasticity will be low. This makes the contribution of inter-granular mechanisms, namely grain boundary sliding, more significant. As we will see later, this mechanism is responsible for micro-cracking activity and, ultimately, ice failure.

2.4.2.1 Laboratory testing

We now go back to laboratory testing as a means of investigating the consequence of these two factors (a very high homologous temperature and a high brittleness). Laboratory testing allows for good control on material and test parameters: high-precision specimen

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[1] Source: http://commons.wikimedia.org/wiki/File:Blacksmith_at_work02.jpg

[2] Source: http://commons.wikimedia.org/wiki/File:UA_Flight_175_hits_WTC_south_tower_9-11_edit.jpeg

machining, optimized control of ambient temperature and deformation, adequate instrumentation and monitoring devices.

During a given test, the load exerted on the specimen divided by the specimen's surface area is the stress. The deformation divided by the gage length is the strain, which is often given as a percentage. The total amount of deformation in these tests usually does not exceed 1-2%, at which point specimen distortion becomes too high and stress distribution inside the specimen is no longer uniform. Also, a change in specimen cross-section becomes significant, with a concurrent change in applied stress.

2.4.3 Strength tests

The strength of the ice can be defined as the highest load/stress the specimen can support without failure. This is a function of test conditions (*e.g.* deformation rate and temperature, notably) and ice properties (*e.g.* structure, grain size, salinity). Deformation rate is the amount of strain per second – for instance, 1% strain in 10 seconds is $10^{-3}s^{-1}$. Strength tests, also called constant deformation or strain rate tests, are typically done at strain rates between $10^{-2}s^{-1}$ to $10^{-5}s^{-1}$. Strength tests provide useful information on what stresses can be sustained by the material without failing.

In a given test, specimen strength is obtained by ensuring the stress imposed on the specimen to achieve the desired strain rate is constant. This is done by attaching a deformation-measuring device to the central section of the specimen, whose response is then used as feedback to control the deformation in a closed loop fashion (Sinha, 1989c).

The stress is then plotted against deformation, as in Figure 11. This figure shows the general trends expected from tests done at three different strain rates (everything else being constant – ice type, temperature, etc.). The following two observations can be derived from this plot:

1. The slope of the initial, linear or quasi-linear, segment of these traces is the effective elastic modulus. The word 'effective' means that this slope is not equal to the true (Young's) modulus. Instead, it depends on the strain rate. The faster the strain rate, the higher the effective modulus.
2. A fast strain rate will promote brittle failure, otherwise the deformation will be on-going after a maximum stress level has been achieved.

The loading conditions during a strength test are applicable to many situations in ice engineering. For instance, an ice sheet carried by water currents can exert a load on a bridge pier that approximates a constant deformation rate.

One significant drawback with strength tests is that they only provide limited information on the effect of loading time, an important parameter for ice road engineering. As will be seen next, when the time factor is addressed adequately, insights can be gained on the deformation processes taking place within the ice.

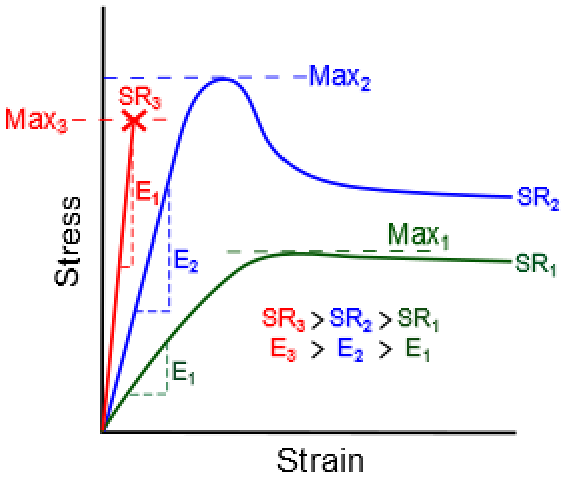

Figure 11: Schematics summarizing the results of three strength tests (1, 2 and 3) plotted on a stress-strain diagram. E: Effective elastic modulus, SR: Strain rate, Max: Maximum stress achieved. Test 3 failed in a brittle fashion.

2.4.4 Constant stress (or 'creep') tests

Creep tests provide information on the behavior of a loaded ice cover, including its strength. Because they take into account time effects, these tests can also help one understand what happens to an ice cover when, for example, a vehicle is parked on it for an extended period of time. To study this loading scenario, ice specimens are tested as described above, but in this case, the specimen is submitted to a constant load (or stress)[3] instead of a constant deformation rate. In other words, the specimen is allowed to deform at its own natural rate. The investigator records the specimen's strain as a function of time.

Figure 12 is a typical outcome showing the full creep response: an initial, elastic response followed by progressive decrease in strain rate down to a minimum, followed by a phase of accelerated creep and ice failure. These three stages have traditionally been referred to as 'primary', 'secondary' and 'tertiary'. Here again, the response is a function of test conditions and ice properties. As with the strength response (Figure 11), the plot shown in Figure 12 is very well known amongst the ice engineering community. The minimum strain rate is usually the parameter of interest, as is the maximum stress for strength test. In fact, a correspondence has been made between these two tests (Figure 13)(Mellor and Cole, 1982; 1983; Sinha et al., 1995).

2.4.5 Components of deformation

Creep tests can be made even more informative than what is shown in Figure 12, by focusing on the initial part of the creep response, most relevant to engineering applications. During that time, the specimen is unloaded. This load-unload procedure affords additional

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[3] When the total amount of specimen deformation is small, changes in the specimen loading area can be neglected, and the applied stress is assumed to be constant.

insights that can be used to investigate the fundamental mechanisms taking place within the crystal structure during deformation.

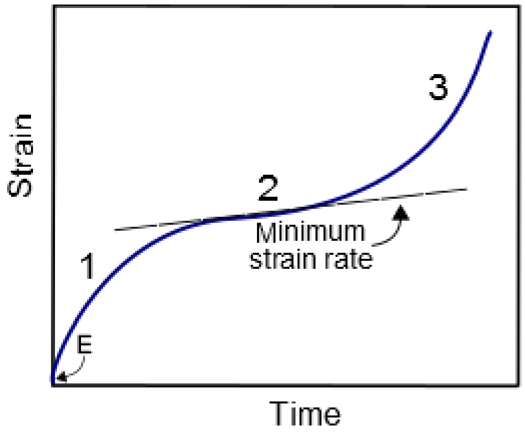

Figure 12: A typical 'creep' curve plotted on a strain-time diagram: the long term deformation trace of a specimen submitted to a constant stress. 1, 2 and 3 refer to the 'primary', 'secondary' and 'tertiary' stages, respectively.

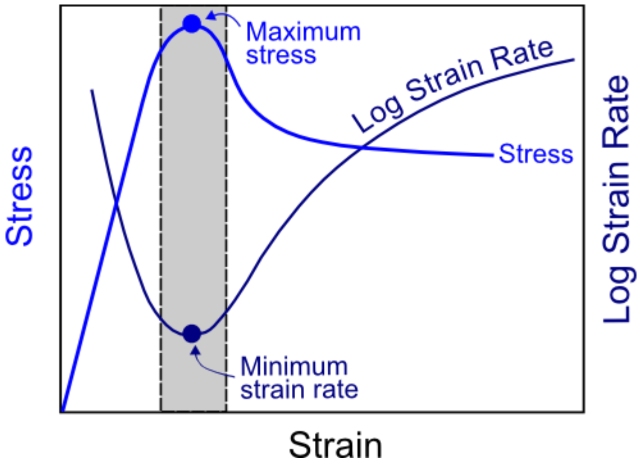

Figure 13: Correspondence between the maximum stress of a strength test and the minimum strain rate (plotted on a log scale).

Consider what happens to an ice specimen submitted to a constant load, and is unloaded at some point during the test (Figure 14). The deformational behavior, as indicated in that plot, points to three distinct components: elastic, delayed elastic and viscous. The elastic component E is instantaneously recoverable upon unloading. The delayed elastic (or anelastic) component (D) is also recoverable but requires time. The viscous (or plastic) component (V) is permanent.

In Figure 15, each of these three components is plotted on its own, which helps visualize the effect of different deformation mechanisms.

2.4.5.1 The elastic component

If we assume no micro-cracking takes place, the elastic component remains stable throughout the loading phase. This component represents the elastic distortion of the crystal lattice structure. Young's modulus is often alluded to as a measure of that deformation. It is 9-10 GPa for freshwater ice, but varies with temperature and grain structure (Sinha, 1989a). If specimen loading is fast enough, the resulting elastic response is comparable to that obtained with high-frequency sonic methods (Sinha, 1978b).

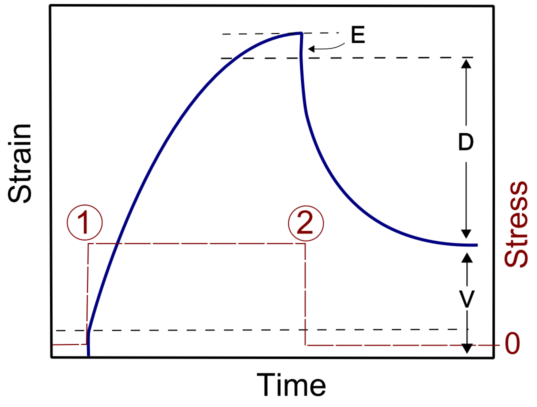

Figure 14: The specimen is loaded at point 1 and unloaded at point 2.
E: Effective elastic modulus, D: Delayed elasticity, V: Viscous deformation. Not to scale.

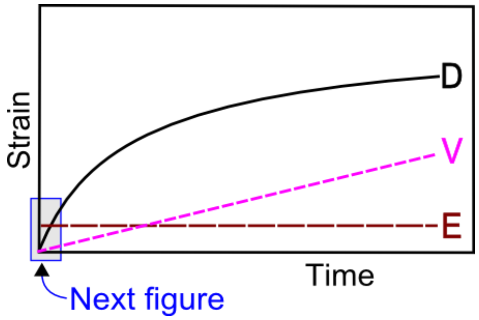

Figure 15: Simplified drawing showing the contribution of strain by each component indicated in Figure 14.
E: True elastic modulus, D: Delayed elasticity, V: Viscous deformation. Not to scale.

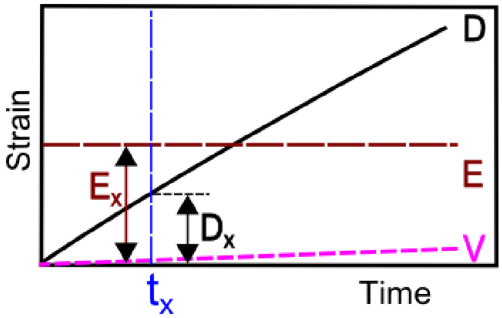

Figure 16: Close up shown in Figure 15, showing the contribution of both true elastic response and delayed elastic response, while the viscous response is negligible.

2.4.5.2 The viscous component

The viscous component increases immediately upon load application. For short-term scenarios, it is typically very small (for the purpose of illustration, it is made larger in Figure 14 and Figure 15). This component is the expression of intra-granular deformation mechanisms (generation, motion and rearrangement of crystal defects), which are responsible, for instance, for glacier flow – the slow downward, gravity-driven motion of ice masses in mountains and ice shelves. Viscous deformation under fast loading conditions is normally negligible.

2.4.5.3 The delayed elastic component

The delayed elastic component does the opposite of the viscous component: it increases rapidly initially and then levels off. This component represents inter-granular sliding, also known as grain boundary sliding (GBS)(Figure 17)(Sinha, 1979). During this process, crystal defects are mobilized inside the grain boundary zone. But once the load is removed, the elastic energy stored within the crystals reverses the sliding direction. This form of elasticity is ‘delayed’ because crystal defects rearrangement requires time.

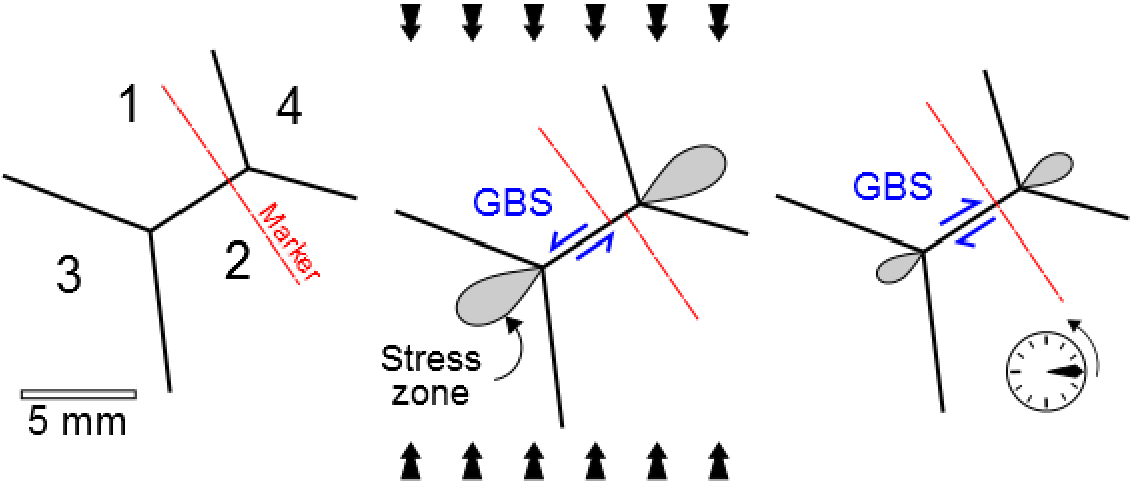

Figure 17: A simplistic depiction of grain boundary sliding (GBS). Left) An initial, hypothetical grain configuration, with a marker horizon crossing the boundary between grains 1 and 2 (approximate scale). Centre: Loading induces GBS, which generates stress zones inside grains 3 and 4 that counteract sliding. Left: When the load is removed, the stress zones dissipate with time and grain boundary displacement is completely recovered.

Since grain boundary sliding becomes effective immediately upon loading and unloading, it contributes to the elastic – i.e. recoverable – response. Along with the lattice distortion represented by the true elastic (Young’s) modulus, the ice stores an additional amount of recoverable strain, which amounts to an ‘effective’ elastic modulus (Sinha, 1978b). Because of the resulting time dependency of the overall elastic response, the analysis of many engineering scenarios involves an effective modulus, which is much lower than the true modulus. Figure 16 indicates why: the recoverable strain at any time during loading is the sum of the true elastic strain plus the delayed elastic component. This is the case for the bearing capacity of an ice cover, as pointed out earlier.

2.4.6 Constitutive equations

So far, a short qualitative description of each of the major strain components was provided. Following is a cursory outlook at how each of these components can be obtained, according to the Sinha model.

The total amount of strain recorded by ice under load is the summation of the elastic component, the delayed elastic component and the viscous component (see Table 1 for explanations of symbols):

$$\varepsilon = \varepsilon_e + \varepsilon_d + \varepsilon_v \qquad \text{Eq. 6}$$

where

$$\varepsilon_e = \frac{\sigma}{E_T} \qquad \text{Eq. 7}$$

$$\varepsilon_d = \frac{c_1 d_1}{d}\left(\frac{\sigma}{E_T}\right)^s [1 - exp(-(A_T t)^b)] \qquad \text{Eq. 8}$$

$$\varepsilon_v = \epsilon \left(\frac{\sigma}{\sigma_1}\right)^n t \qquad \text{Eq. 9}$$

Note the correspondence with Figure 15. The elastic strain is time-independent; the delayed elastic strain follows an inverse exponential form; the viscous strain increases linearly with time.

2.4.6.1 Effective elasticity

When a load is applied onto an ice cover and removed within a relatively short amount of time (say, one minute), a given ice cover sinks and moves back up again. We can assume that, within that time frame, the viscous component is negligible. Assuming $s = 1$, the total amount of strain is therefore

$$\varepsilon = \frac{\sigma}{E_T}\left\{1 + \frac{c_1 d_1}{d}[1 - exp(-(A_T t)^b)]\right\} \qquad \text{Eq. 10}$$

In a different scenario, where loading is instantaneous (*i.e.* $t \sim 0$)(typically achieved via ultrasonic methods), there would only be an elastic component (ε_e), and Eq. 10 would reduce to Eq. 7. But since, in our scenario, there is a delayed elastic component, the effective elastic response has to take that into account. Keeping in mind that the total strain ε contains both elastic and delayed elastic components, we may define an ‘effective elastic modulus’ (E_t) as follows

$$E_t = \frac{\sigma}{\varepsilon} \qquad \text{Eq. 11}$$

By combining the two previous equations, we have

$$E_t = \frac{E_T}{1+\frac{c_1 d_1}{d}[1-exp(-(A_T t)^b)]} = E_t(t, T, d) \qquad \text{Eq. 12}$$

From here, we can address the frequency response of the effective elastic modulus. Consider an ‘average’ strain rate (the total strain divided by a given time interval):

$$\epsilon_{av} = \left(\frac{\varepsilon}{t}\right)_{av} = \frac{\sigma}{E_0 t}\left\{1 + \frac{c_1 d_1}{d}[1 - exp(-(A_T t)^b)]\right\} + \epsilon\left(\frac{\sigma}{\sigma_1}\right)^n t \qquad \text{Eq. 13}$$

Using the two previous equations, it is possible to determine the variation of effective elastic modulus as a function of strain rate for short load durations, so as not to induce a significant amount of viscous strain (Gold and Sinha, 1980; Sinha, 1978a). The dependency of the effective modulus on frequency of load application is shown in Figure 18. In this plot, frequency is assumed to be equal to $(2t)^{-1}$, where t is the total time of loading (i.e. equivalent to a full load-unload cycle). The relationship in that figure also varies as a function of other parameters (e.g. ice type, temperature). It is here provided for illustrative purposes. It can be seen that, from loading times of 0.0001 seconds and above, the effective modulus decreases progressively from a value of 9.3 GN/m^2, the true elastic modulus, to about 5.0 GN/m^2 for 100 seconds.

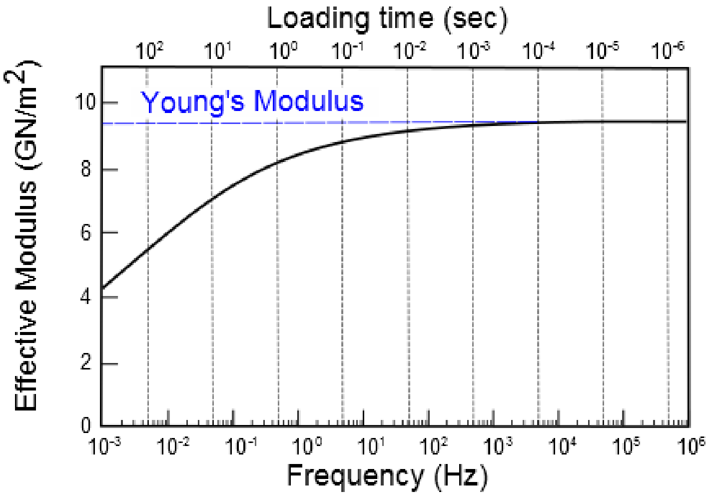

Figure 18: Frequency dependence of the effective modulus for polycrystalline ice at -10C (modified after Gold and Sinha, 1980)

The last equation and Figure 18 illustrate the principle behind the use of an effective modulus, based on a simplified crystal structure. Given the complexity in internal structure of an ice cover, it can conceivably achieve much lower effective moduli, depending on the loading scenario.

2.4.7 Micro-cracking

By definition, a crack is a free surface that forms inside the material. Because the rate of diffusion in ice is low, as mentioned earlier, intragranular plasticity (i.e. crystal deformation) contributes little to the total amount of deformation. Sinha (1988b, p. 201) points out that, “because of the low diffusivity, the intragranular creep mechanisms in ice contribute relatively less (at the same temperature) to overall deformation than do those in most metals. This makes the contribution of the intergranular mechanisms, such as grain-boundary sliding, more pronounced in ice.”

The generation of cracks accelerates deformation. It has been shown (Sinha, 1988a; b) that Eq. 9 becomes

$$\varepsilon_v = \epsilon\left(\frac{\sigma}{\sigma_1}\right)^n \int_0^t \left[1 + \left\{\pi^2/\left(12\sqrt{3}\right)\right\} N d^2 n^{0.5}\right] dt \qquad \text{Eq. 14}$$

At low strain rates ($<10^{-7}s^{-1}$) or a low applied load/stress ($<10^{-4}E_T$), which are conditions that are applicable to glacier flow, micro-cracking does not typically occur. For higher strain rate or stress levels, applicable to bearing capacity scenarios, this mechanism becomes active (Figure 19), and can ultimately cause the failure of an ice cover.

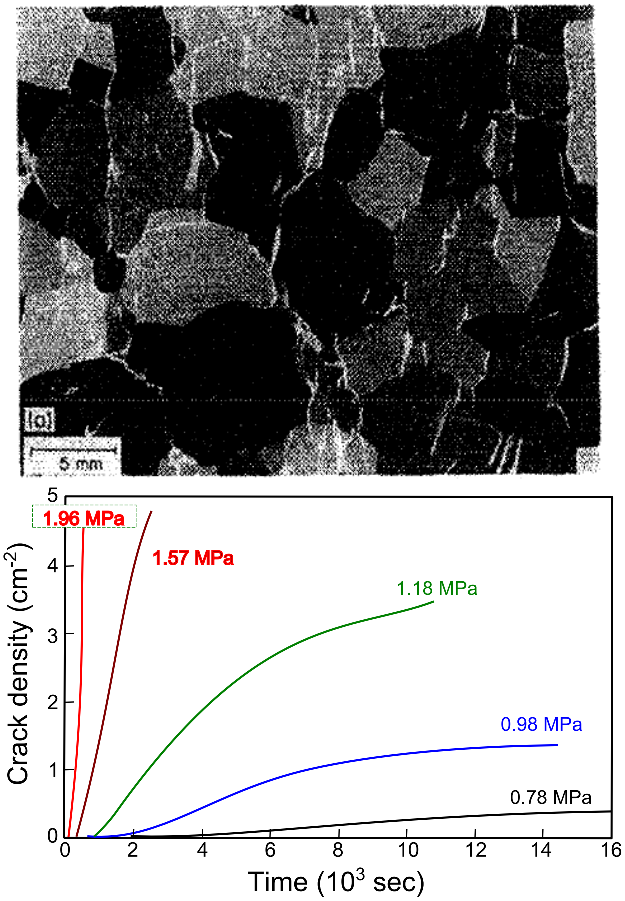

Figure 19: Above) Polycrystalline ice with micro-cracks (Sinha, 1988b). Below) Number of micro-cracks per unit area observed in ice specimens deformed at -10C submitted to five different stresses (Gold, 1972)

2.4.8 Summary

The following may be derived from the foregoing description on the physical processes taking place in ice under stress.

- In its natural state, ice is a high temperature material, which means its molecular structure is prone to disruption, i.e. unless load application is extremely short, it will not behave solely in an elastic manner.

- Instead, additional mechanisms will take place in the ice cover, whether we are dealing with a fast moving vehicle, short-term load, long-term loading,
- One is the viscous component, a permanent deformation, which always occurs but is negligible under rapid loading/unloading events, and only becomes significant under very long loading times (days, weeks).
- Another component is linked with delayed elasticity, a crystal boundary shear mechanism that accounts for a recoverable strain, but which is delayed in time.
- Because the latter mechanism contributes to the recoverable deformation, it induces an apparent, or ‘effective’, modulus, which can be considerably lower than the genuine Young’s modulus.
- Ice is also a brittle material, i.e. diffusion processes are slow, such that after a certain amount of crystal boundary shear, free surfaces develop along these boundaries. With time, these micro-cracks form a network of increasing density, and connect into a continuous free surface (a fracture) that ultimately causes ice failure.[4]

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[4] The development of these micro-cracks, which result from sliding along grain-boundaries in material at high homologous temperatures, should be distinguished from the notion of fracture toughness, an important material parameter, but that is independent of temperature.

3. Ice roads in Canada

Ice roads in Canada may be divided into three categories, based on how they are managed. These are: 1) government-run operations, 2) private operations, 3) local community operations.

3.1 *Government operations*

These operations are managed by the relevant provincial or territorial government. For instance, in the NWT, there are three major ice roads:

- The Tłı̨chǫ Winter Road System from NWT Highway # 3 to Gamètì with a spur winter road to Wekweètì.
- The Mackenzie Valley Winter Road system, from Wrigley (northern terminus of NWT Highway #1) to Fort Good Hope, with spur winter roads to Colville Lake and Deline.
- The Inuvik-Tuktoyaktuk road on the McKenzie River, which will be replaced by an all-weather road schedule to open in 2017/2018.

3.2 *Private operations*

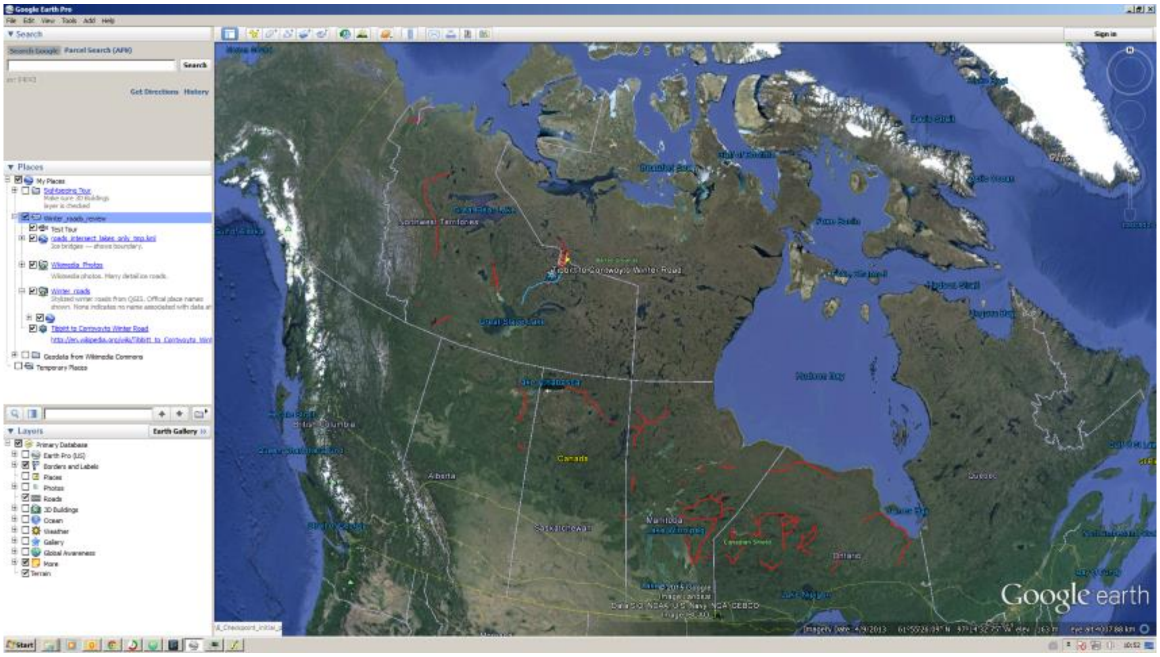
The best known private operation is the Tibbit-to-Conwoyto ice road in the NWT. This is a 600 km long ice road that has been used for about 30 years to service the mining industry. Diesel fuel constitutes the largest cargo – others include cement, tires, prill (for explosive manufacturing) and construction material.

3.3 *Community operations*

There are a significant number of ice roads that are managed by local communities. They can be run by the town or by a community member. Examples are three ice bridges on the Ottawa River (between Ottawa and Montreal), connecting Lefaivre and Fassett, Pointe-Fortune and St-André-d’Argenteuil, and Hudson and Oka. Information on these roads is more difficult to obtain. Some of these operators maintain a webpage, others do not.

3.4 *Ice road distribution*

An attempt is being made to compile the ice road distribution across Canada. A tool has been devised that will allow this information, as well as other data associated with each operation, to be stored and displayed (Figure 20). This endeavor is on-going – a full picture on ice road distribution in Canada is expected to emerge over the next few years. The challenge is that, while information on the larger operations is readily accessible, that is not the case for many others. Stakeholder consultation and word of mouth should help generate additional information.



Make sure 3D Buildings layer is checked

Ice bridges — shows boundary.

Wikimedia photos. Many detail ice roads.

Stylized winter roads from QGIS. Offical place names shown. None indicates no name associated with data ar

Figure 20: *Output from a prototype tool that is being devised to store and display information on ice roads.*

4. Examples of guidelines on using floating ice for transportation

Following are examples of existing guidelines, mostly from Canada but also from elsewhere. They are in chronological order and a short description of each one is presented. Most allude to Gold's formulation, implicitly or explicitly, for the determination of the bearing capacity of an ice cover. The latest editions, known to the author as of this writing, have been consulted.

4.1 Federal, territorial and provincial guidelines

4.1.1 CSST (1996)

The *Commission de la Santé et de la Sécurité au Travail* (a Quebec Health and Safety organization) published guidelines for industry workers and the recreational usage of ice covers. They do not apply to operations involving heavy loads or to those on saline (sea) ice. The guidelines begin by describing a hypothetical scenario on the growth of an ice cover, involving various ice types. It warns of unusual current patterns responsible for ice thickness variation. Sections through the ice cover are required to monitor thickness and ice type over the planned working area. Ice bearing capacity is a function of ice type, thickness and expected loads. A relationship similar to that of Gold is used for that purpose, taking into account spacing between loads. Load duration, cracks, extreme variations in air temperatures and vehicle speed (i.e. dynamic loading) have to be taken into consideration. Signing, maintenance (snow removal) and safe driving and emergency procedures are also discussed briefly.

4.1.2 Treasury Board of Canada (2002)

This document, referred to as a 'safety guide', is no longer referred to by the Treasury Board, but it remains useful for the purpose of this report, as it also documents the historical trends in published recommendations. The guideline focusses on freshwater ice and can only be used for loads up to 22.5 metric tons. Its purpose is to: "(a) specify rules of good safety practice for all Public Service employees engaged in operations on ice covers; (b) provide information on the thickness of ice required to support moving and stationary loads; (c) specify methods for determining ice thickness and quality; and (d) outline approved methods for the preparation and maintenance of ice bridges." It contains general information on ice formation, ice 'color', ice thickness, the bearing capacity determination for static and moving loads, effects of cracks and some considerations about spring thaws. It also contains information about the construction of ice bridges, which it defines as "a natural untouched ice cover, a built-up, or a combined reinforced and built-up crossing route". This includes flooding, maintenance and precautions to be considered during operation. Information for snowmobile drivers is included.

4.1.3 Government of Saskatchewan (2010)

Saskatchewan's Ministry of Highways and Infrastructure produced a handbook on winter roads meant for winter road contractors, "intended for use on winter road alignments built in the same general vicinity each year". Information is provided on ice formation, snow clearing and flooding procedures. Types of ice and thickness determination and equipment for rivers and lakes are also discussed. Bearing capacity is assessed on the basis of Gold's formula, taking into account extreme temperature changes, presence of cracks (and ways to deal with the larger ones), road usage and loading modes (moving, multiple, long term). Recommendations on equipment are made: outriggers, floatation device, careful use of crawler tractors and other vehicles. A full section on signing is presented, along with environmental considerations (e.g. spill management), winter road safety (training, protective equipment, communications), safety guidelines for ice road workers and ice road users, accident response, survival information and general road management.

4.1.4 Government of Manitoba (2012)

The Government of Manitoba published a “Contractor’s manual for the construction and maintenance of Manitoba infrastructure and transportation winter roads”. This is the 8th edition. Means of ensuring safe usage include proper thickness assessment, considerations of factors such as currents, angle with the shoreline, appropriate clearing width and procedures, load duration, vehicle speed and flooding operations. Recommendations are also provided on how to test the ice for thickness, ice types, reporting, using Gold’s formula, types of cracks, effects of air temperature changes, pressure ridges and how to ‘bridge’ large cracks. Comments about equipment for working on ice roads refer to the use of outriggers and floatation devices, and point out to a number of safety procedures: means of escape from a vehicle, maximum speeds, careful use of tire chains, hydraulic buckets and flex track equipment.

4.1.5 Government of Alberta (2013)

The Government of Alberta’s published an extensive ‘Best practice’ document whose purpose is to cover “the basic steps for planning, design, construction, operation and closure of an over-ice project”. It is for short-term loading scenarios and does not apply to saline ice and very large loads. It provides a background on ice type, cracking/rupture modes and their origin, load duration, and factors (climate, terrain,etc.) influencing route selection. It then discusses procedures for ice design, including Gold’s formula (to be used in combination with hazard control), ice thickness determination, effects of extreme temperature changes, how to deal with stationary loads, recommended lane dimensions and dynamic effects (from a moving vehicle). Ice monitoring and maintenance controls and the development of an ice safety plans are other aspects that are covered in that document.

4.1.6 IHSA (2014)

In January 2010, the Infrastructure Health & Safety Association (IHSA) amalgamated with the Construction Safety Association of Ontario (CSAO), the Electrical & Utilities Association (E&USA) and the Transportation Health & Safety Association (THSAO). Its purpose is to work with employers and workers in Ontario to prevent occupational injury and illnesses (source: www.ihsa.ca). They published “The best practices for Building and Working Safely on Ice Covers in Ontario”. This document is essentially the same as the 2013 edition of Alberta’s own safe practice (described above).

4.1.7 Government of the NWT (2015)

These guidelines begin with a short description of the various ice types, with recommendations as to what to consider when determining the effective thickness of the ice cover. Various construction and operation levels are outlined (routine, enhanced, acute). Temporary loads, stationary loads and moving loads on a natural ice cover are discussed.

An extensive section on hazard control describes the factors that adversely affect the integrity of the ice cover (e.g. cracks, snowbanks, high winds, water level changes), load and ice thickness monitoring (manual and GPR), hole spacing and data recording. Gold's formula is adapted to specific circumstances for the (pre-)construction or operation phases. 'A' values (4, 5 or 6) vary as a function of ice road (bridge, on lake, along a river) and for each safety level, taking into account all control measures (e.g. frequency of thickness measurements and method, loading control, enforcement). Information on ice cover management is provided (speed limits and spacing, inspections, traffic enforcement, signing, temporary road closure, public information, training, monitoring and reporting). Recommendations on means of extending the safe operation at the end of the season are also presented.

4.2 Design codes and standards

Design codes and standards provide information about important features of product, service or system (SCC, 2014). In most cases, compliance is voluntary; in others, it is mandatory and monitored by regulatory bodies. Some are objective-based, others are prescriptive. These documents are continuously being improved upon, with new editions appearing from time to time; others may be withdrawn. They are overseen by various national or international committees, and can be quite different even though they address similar issues. The following are examples of two such documents which contain guidelines on ice roads.

4.2.1 API RP 2N (2007)

The API RP 2N version (2nd edition) reviewed in this report, published in 1995 and reaffirmed in 2007, is a recommended practice. Its purpose is to provide the latest knowledge for planning, designing and constructing arctic systems. It is targeted at sea ice, which is not discussed in this report, but it is of interest for information purposes. Unlike in the other guidelines, the bearing capacity for static loads is determined analytically – no reference is made of a Gold-like formulation. This may be because offshore operations typically involve very high loads, best dealt with analytically, on a case-by-case scenario. Other information is provided on how to deal with moving vehicles and long term loads, snow removal, road signs and cracking. These are mostly consistent with other guidelines. Tidal effects are alluded to and using freshwater ice as a crack fill material is recommended. Mat ice bridges across a crack and emergency equipment are also included.

4.2.2 CSA-ISO 19906 (2011)

This is the standard's first edition, and an adoption without modification of the document produced by the International Standards Organisation known as ISO 19906. The standard provides recommendations for offshore structures in cold regions. As with all ISO standards, it is divided into a normative section (what the user should or must do) and a longer informative section (what the user should know, i.e. background knowledge). The normative part mentions that 'expert guidance' should be used in determining design thickness, construction technique and operating procedures. Two guiding principles must be followed: "the ice shall not fail in flexure" and "the freeboard shall remain positive". Strength testing procedures, driving speed, weight determination procedures (equipment and vehicles), ice inspection for cracks and flooding instructions are also provided.

4.3 Other guidelines

Following are other sources of information that provide some measure of guidance in the construction, maintenance and usage of ice roads.

4.3.1 CRREL (2006)

U.S. Army's Cold Regions Research and Engineering Laboratory (CRREL) produced an 'Ice Engineering' manual that has a chapter on the bearing capacity of floating ice sheets. It begins by suggesting means of measuring ice thickness, then it examines the bearing capacity of floating ice sheets analytically and empirically. In the latter case, a Gold-like formula is used. Information on moving loads and long-term loads is also provided.

4.3.2 Luleå University of Technology (Fransson, 2009)

The Luleå University of Technology, in Sweden, published an 'Ice Handbook' which includes a section on ice bearing capacity that is of intereset. At the outset, a discussion is provided on the cracking activity under loads and how to go about determining the ice thickness. Bearing capacity is assessed analytically. Calculation of first crack load and a semi-empirical formula to determine the breakthrough load are shown.

4.3.3 Rideau Canal Skateway (BMT Fleet Technology, 2011)

These guidelines apply to the Rideau Canal Skateway in Ottawa. It is not an ice road, strictly speaking, but it is designed to support motor vehicles. The report provides guidance for two vehicle classes: a two-axle vehicle and one pulling a trailer. Information on vehicle separation distance, ice thickness definition/measurements and effects of temperature is included. They make recommendations about how to handle static loading of vehicle, and also during special events held on the ice – a 'show' with a large audience, where the surface area occupied by the crowd is factored in.

4.3.4 Transportation Association of Canada (Proskin et al., 2011)

The Transportation Association of Canada published a succinct overview of the winter road classification, including an instructive perspective on the differences between various types of over-land and over-ice roads. Ice roads planning, routing and usage are discussed, as well as ice types and cracks in the ice cover. It alludes to Gold's formulation as a means of determining safe ice loading, while specifying the 'A' value depends on the hazard control procedures and level of risks. Short discussions are presented on analytical determination of ice thickness, ice road width, ice deflections resulting from long-term loading and hydrodynamic effects of a moving load. This document comprises chapters on ice road constructions (e.g. methods, quality assurance and control, thickness measurements), on road user safety (hazard assessment/control, incident response plan) and on environmental protection (water quality, terrain degradation, spill prevention). It includes a comparison between various recommendations made by six of the most accessible federal, provincial and territorial guides to winter roads.

4.3.5 Canadian Red Cross (2015)

The Canadian Red Cross provides a small amount of information on its website about 'ice safety' (last consulted in April 2015). This includes ice color and recommendation for determining adequate thickness for pedestrians and snowmobiles, as well as instructions as to what to do when someone breaks through the ice. By having this information displayed on its website, it is readily available to its entire readership. Environment Canada refers to that site for information regarding ice safety.

4.4 Scientific literature

There are a large number of documents published in the scientific literature that address the bearing capacity of floating ice. These are published in specialized journals and in a various conference proceedings. The article by Gold (1971) mentioned earlier is often the starting point of later studies, many of which tend to be more technical, as they often contain analytical treatments. Frederking and Gold (1976) and Kerr (1996) are examples. Kuryk (2003) provides some recommendations about planning and construction of ice bridges in Manitoba. The reader might also be interested in the review by Masterson (2009), which is well illustrated and provides technical background on mechanical principles and methodology for ice road design.

5. Discussion

Three main points will be discussed: 1) Features and issues dealing with ice bearing capacity, on an overall basis and on a case-by-case scenario; 2) the effects of climate change on the ice road infrastructure; and 3) means of addressing these effects.

5.1 Ice bearing capacity

5.1.1 Short-term and long-term loading

The limit between what is referred to as short-term and long-term loading durations, typically set at 2 hours, is used for practical purposes. It is a way of making ice road users aware that, in addition to the weight of a vehicle, time is also an important safety factor. Hence, even if an ice cover is found to be strong enough for a short-term load, it may eventually collapse under that load for extended durations (e.g. a parked vehicle). In these situations, several guidelines recommend to monitor the ice deflection by making a hole in the ice (e.g. with an auger) and ensure the freeboard remains positive (the water level does not reach the ice surface). If the freeboard becomes negative, the vehicle has to be removed from that area.

It is instructive to consider that the three deformation mechanisms alluded to earlier – elastic, delayed elastic and viscous – become operative at the outset of loading. However, with time, the relative amount of viscous (permanent) deformation increases (as illustrated in Figure 15). Also, both the elastic and delayed elastic components are recoverable. The delayed elastic component is time-dependent, and is responsible for the development of micro-cracks. With time, these micro-cracks increase in density, ultimately causing ice failure. It also explains, as discussed earlier, why an 'effective' modulus (as opposed to the true Young's modulus) has to be used for analytical purposes when the analyses are based solely on elasticity principles, as a first approximation. An example is shown in Figure 21. In reality, as discussed above, ice is viscoelastic and these analyses could be adapted to provide a more accurate picture of material behavior.

5.1.2 Is white ice weaker than clear ice?

As stated by Gold (1971, p. 173), white ice has a lower strength than clear ice, and it has been the practice to assume that this ice has an effective thickness of only one-half its actual thickness." He also pointed out that "No studies have been undertaken to verify this assumption".

Different guidelines provide different answers to that question (Table 2 – the sources are identified in Table 3 – they are ordered by publication year). In several cases, it is recommended to reduce the strength of white ice to half that of clear ice. Gold (1971) makes that distinction, but does not appear to use it in his plots. Some guidelines (BMT Fleet Technology, 2011; Treasury Board of Canada, 2002) further distinguish white ice created by flooding operations, as is normally done by the construction crew, from white ice resulting from frozen saturated snow or slush. In the former case, the ice has a density of about 0.9 g/cm^3 and is considered 'dense ice'; the latter should be of lower density and

Table 2: Values assigned to A (h in cm, P in kg) and comments about the strength of clear versus white ice from various sources. 'n/a' is not applicable because Gold's formulation is not alluded to in the corresponding source.

Source	**A (kg/cm^2)**	**Comments**
Gold (1971)	7	White ice stated to be half the strength of clear ice.
CSST (1996)	3.5	White ice has half the strength of clear ice.
Kuryk and Domaratzki (1999)	7	No info on the relative strength of clear and white ice.
MNRO (2002)	No recommendation	White ice has half the strength of clear ice.
Treasury Board of Canada (2002)	1.7 and 3.5	The strength of 'high density' white ice is comparable with that of clear ice. "White opaque ice, or 'snow ice', is normally considered to be half as strong.
CRREL (2006)	10	White ice has half the strength of clear ice.
API RP 2N (2007)	n/a	No info on the relative strength of clear and white ice.
CSAO (2009)	1.7 and 3.5	'A' same as for Treasury Board recommendations. For moving loads only. White ice has half the strength of clear ice.
Masterson (2009)	3.5-5.0 (early season), 6-7 (late)	Blue ice and white ice strength equivalent as long as it exceeds 0.88 g/cm^3 and is well bonded.
Government of Saskatchewan (2010)	6.0	For blue ice. When combined with field observations, an appropriate value for A can be safe. White ice has half the strength of clear ice.
BMT Fleet Technology (2011)	3.5 for 2-axle vehicles, 4.5 for 2 axle pulling a trailer	The strength of white ice produced by 'careful flooding' is equivalent to the strength of clear ice. If the white ice is from saturated snow or slush, its strength is half that of clear ice.
CSA-ISO 19906 (2011)	>3.5, <7.0	These 'A' values are valid for sea ice also, because although it may or may not be as strong as freshwater ice, it is considered more ductile. No difference between strength of white ice and clear ice, especially if the former is at the upper surface, where it works in compression.
(Proskin et al., 2011)	3.5-7	Effective ice thickness includes both "good quality well-bonded white ice and blue ice". White ice produced from natural flooding "can be of lesser quality" and should not be considered.
Government of Alberta (2013)	3.5-7.0	Clear ice and 'constructed' flood ice have the same strength. White ice produced from natural flooding "can be of lesser quality" and should not be considered. Different 'A' values for lake ice and river ice.
Government of Manitoba (2014)	4	Moving loads only, not stationary. No info on the relative strength of clear and white ice.
IHSA (2014)	3.5-6.0	Clear ice and 'constructed' flood ice have the same strength. White opaque ice produced from natural flooding "is considered to be only half a strong" as clear ice.
Canadian Red Cross (2015)	n/a	Clear ice is 'strongest'.
Government of the NWT (2015)	4, 5 or 6	'Natural ice' is considered the basis for full-strength, but only if it is clear. Well-constructed flood ice or spray ice also. 'Natural overflow ice' and poorly constructed ice are excluded from the measurement.

Table 3: Sources in Figure 25.

Source	Target readership	Reference
1	None	Gold (1971)
2	Quebec	CSST (1996)
3	Manitoba	Kuryk and Domaratzki (1999)
4	Canada	Treasury Board of Canada (2002)
5	USA	CRREL (2006)
6	None	Masterson (2009)
7	Saskatchewan	Government of Saskatchewan (2010)
8	Rideau Canal	BMT Fleet Technology (2011)
9	None	CSA-ISO 19906 (2011)
10	Canada	Proskin et al. (2011)
11	Alberta	Government of Alberta (2013)
12	Manitoba	Government of Manitoba (2014)
13	Ontario	IHSA (2014)
14	NWT	GNWT (2015)

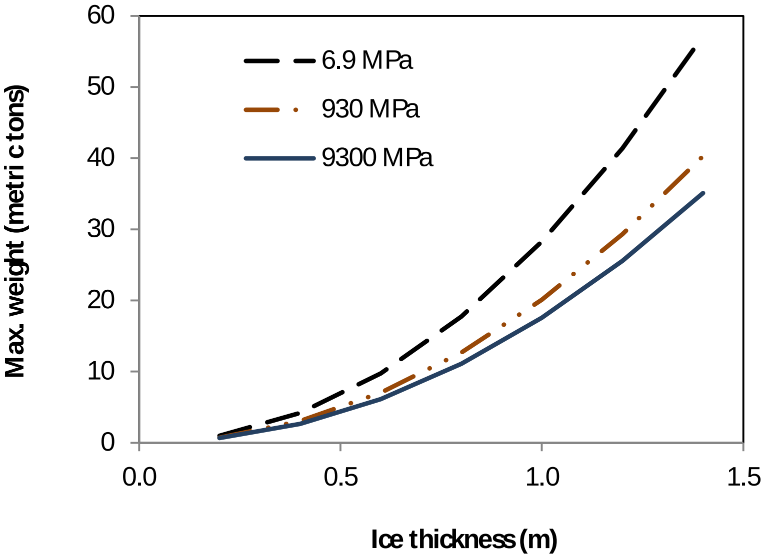


Figure 21: Influence of the effective elastic modulus on the maximum weight to be allowed before first crack.

its strength is assumed to be 50% that of clear ice. Others, such as Kuryk (2003), distinguish between clear and white ice but only by considering the former and ignoring the latter in thickness determination. Information does exist indicating a reduction in ice strength with increased porosity (Murat and Tinawi, 1986), although this is for saline ice. Exactly how that translates into flexural capacity is an issue that has been poorly documented to date.

The results of an experimental program devised to address that question (Barrette, 2011a) provided evidence that ice considered in BMT Fleet Technology (2011) to be 'good quality' white ice was, on average, weaker than clear ice (Figure 22). Strength of white ice was down to about 50% of clear ice close to the melting temperature, thereby justifying the above-mentioned recommendations. This study also showed some indication of an increase in strength with an increasing density (Figure 23). The relevance for the evaluation of bearing capacity, however, should be carefully assessed. Firstly, data scatter in that study was significant. Secondly, in a typical scenario, the white ice only occupies the upper part of the ice column. Flexural behavior will be controlled by the clear ice at the bottom of the ice cover (see the discussion in Masterson, 2009 for instance).

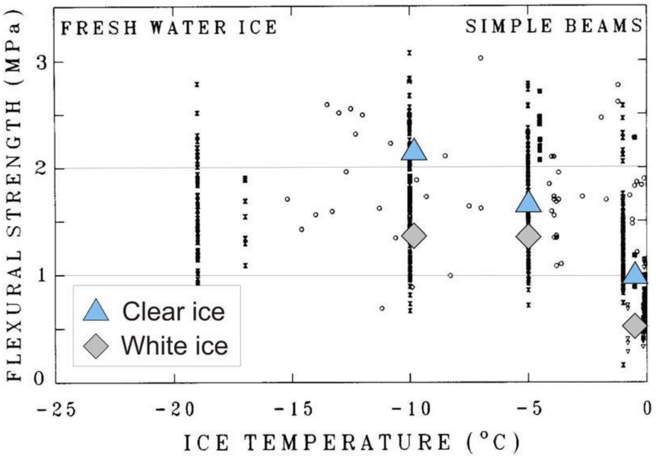


Figure 22: Flexural strength of white ice and clear ice from on the Rideau Canal Skateway in Ottawa (Barrette, 2011a), plotted on a compilation by Timco and O'Brien (1994).

This brings us to consider three factors.

1. There are indications that white ice is weaker than clear ice in compression also (not only in flexure, as indicated in Figure 22). This author extracted data from a number of sources, all of which tested clear ice in uniaxial compression at a temperature of -10C. The results, shown in Figure 24, also include the data by Sinha (1984), which were produced with either clear or white ice from naturally-occurring multiyear ice[5]. What this plot shows is that the white ice is consistently lower in strength under compression.
2. The higher the ratio of white/clear ice, the more buoyant the ice. What role can this play in the amount of flexure at the base of the ice sheet, along a transversal cross-section of the road?
3. What is the influence of layering, as is typically displayed in white ice, in the bearing capacity of an ice cover?

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[5] Multiyear ice is sea ice that has survived more than one summer. It is, therefore, more akin to freshwater ice than to sea ice in terms of mechanical properties.

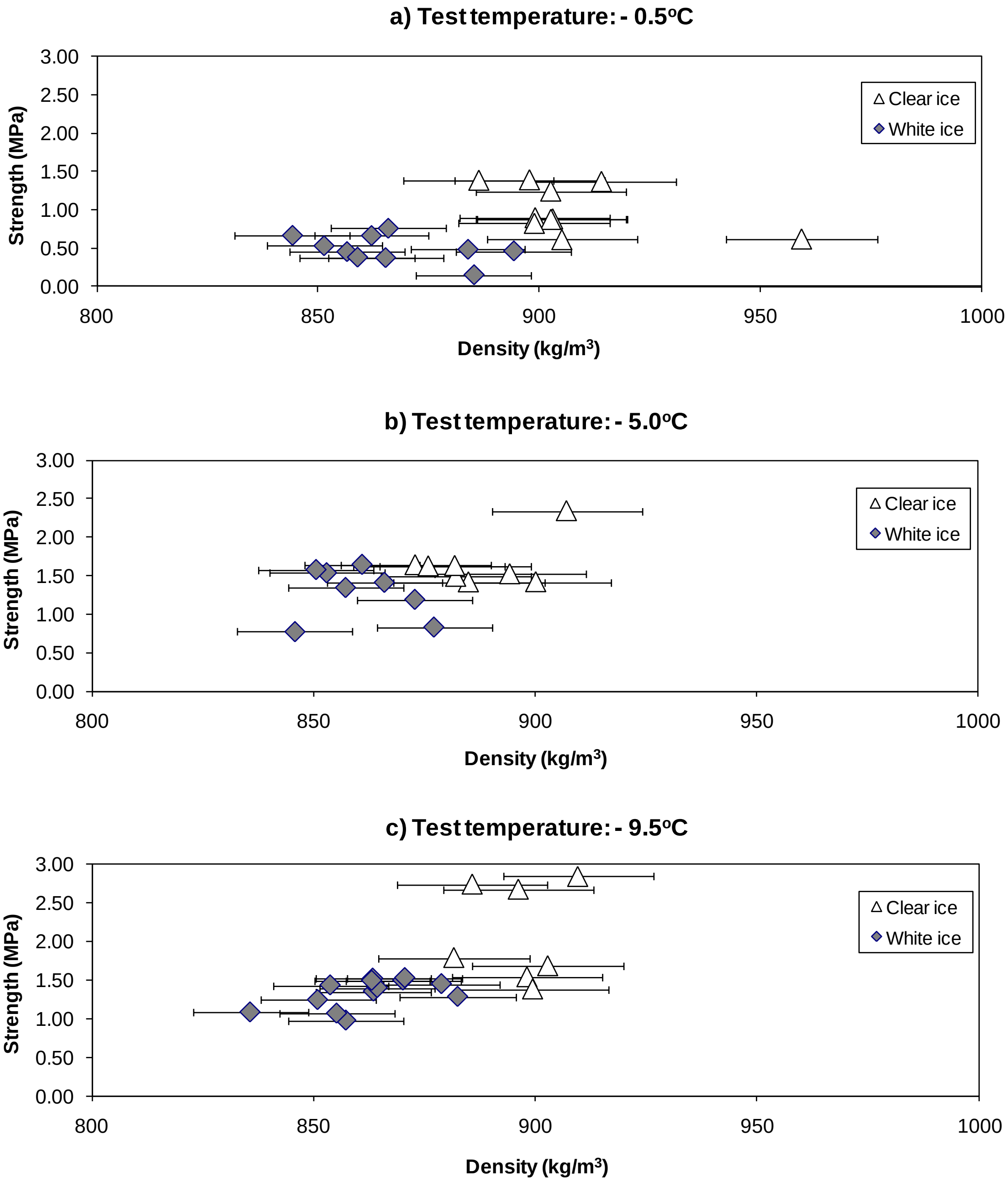

Figure 23: Flexural strength of white ice and clear ice from on the Rideau Canal Skateway in Ottawa (Barrette, 2011a), plotted as a function of density.

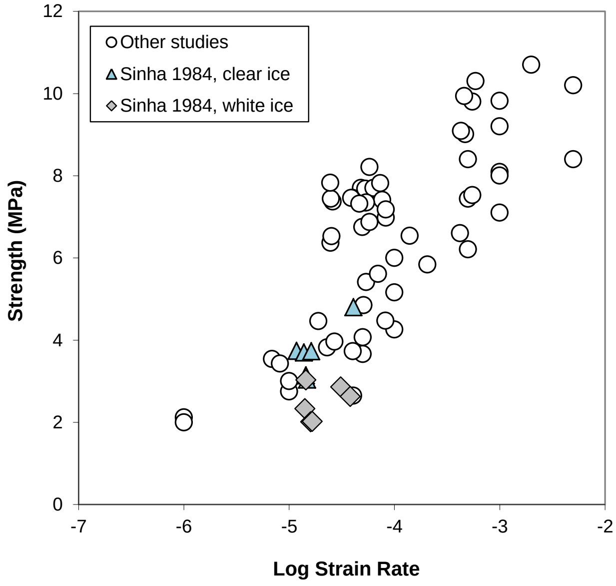

Figure 24: Test results from uniaxial compressive tests on laboratory-made clear ice. These data include those from (Sinha, 1984), produced with natural clear and white ice.

5.1.3 The 'A' parameter

As initially pointed out by Gold (1960; 1971), a value assigned to the parameter 'A' may vary because it depends on a number of factors, e.g. ice road usage, quality of the ice, units used, vehicle speed, temperature changes, cracks, etc. Experience also comes into play. Several guidelines have been using Gold's formulation with similar recommendations. This point is more explicit in some guidelines than in others. For instance, the Government of Alberta (2013)'s guidelines mention that Gold's method "must be combined with ice monitoring, maintenance and administrative hazard controls" (p. 24). Table 2 provides examples of 'A' values as recommended in various sources. In some cases, the table provides a range, leaving it up to the operator to decide which value is the most appropriate within that range.

5.1.4 Comparison between guidelines

A comparison between recommendations made by various guidelines is shown in Figure 25 for two scenarios. The top diagram (a) assumes a total ice thickness of 100 cm, made entirely of clear ice; the bottom diagram (b) is for the same ice thickness, but with 60 cm of clear ice and 40 cm of white ice. The length of the bars is the range, whereby the minimum and the maximum 'A' values provided by the source was taken into account.

The observed variations in recommended values are caused by 1) a different 'A' value, and 2) by whether or not white ice is considered 50% weaker than clear ice. Note that, in Figure 25b, the white ice component is assumed to be from natural flooding, as opposed to from artificial ice thickening procedures. Also, when no recommendation is provided in the guidelines about the relative strength, the white ice is assumed to be equivalent to the clear ice.

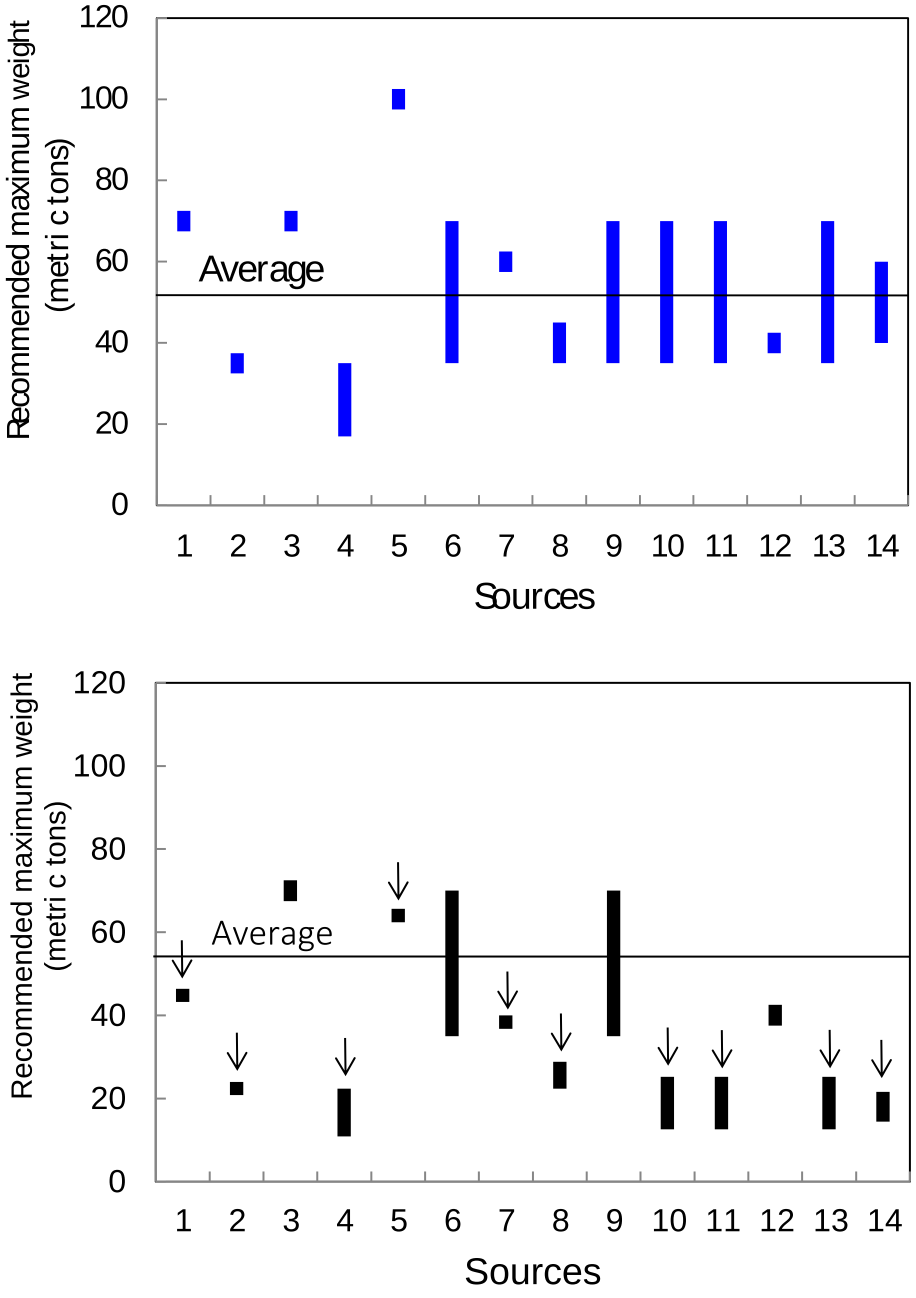

Figure 25: a) Above, recommendations assuming a total ice thickness of 100 cm made entirely of clear ice. b) Below, same thickness as above but with 60 cm made of clear ice and 40 cm made of natural white ice of questionable quality. The arrows in (b) indicate a reduction in recommended values due to the presence of white ice.

5.1.5 Discussion

The analysis outlined above is addressing this issue from the perspective of prospective guidelines users wishing to gain additional insight as to how to go about determining the bearing capacity of an ice cover. This readership may be puzzled by the lack of agreement between how different guidelines deal with the white ice/clear ice dichotomy, and the consequences on recommended ice thickness. This, evidently, is an important issue:

- If flooded white ice is considered to have the same strength as clear ice, this assumption will increase the effective thickness of the ice cover, which may imply a substantial increase in the ice road's operational lifespan.
- If natural white ice is altogether excluded from the ice thickness measurements, this will have the opposite effect.
- If white ice resulting from flooding operations is weaker than clear ice (which is likely the case, as discussed above), then the assumption it is equivalent to clear ice will cause bearing capacity to be overestimated by an unknown amount.

Another point of interest is the range in 'A' values that is found in the guidelines when using Gold's formula. In the guidelines summarized in the present report, these values vary from 2.5 to 10. In some of the most recent guidelines, the range is from 3.5 to 7.

5.2 Effects of climate change

Climate change (or global warming) refers to the progressive rise in temperature of the Earth's atmosphere that has been documented over the last number of decades (e.g. Figure 26). At the planetary scale, this temperature rise has important repercussions on the complex dynamics of the atmosphere. It affects ice covers in different ways, depending on geographical location (Strandberg et al., 2014). Comiso (2002) mentions a 9% reduction in Arctic perennial sea ice cover every decade, and an increase in ice temperature of more than 1 deg. C per decade. This, in turn, causes the delayed onset of freeze-up and earlier onset of melting. Melling et al. (2005) reports that a 1.5 deg. C warming trend from 1974-2004 caused a thinning trend of the seasonal ice pack, as recorded by moored, upward-looking sub-sea sonar.

An example of a decrease in the freezing index for the Northwest Territories is shown in Figure 27. Surdu et al. (2014) document a reduction in the extent of grounded ice in lakes as well as thinner ice covers. Shorter operational windows have been reported from elsewhere e.g. (Kuryk, 2003). Because of its saw-tooth pattern, the pattern is not predictable. An example that is often brought up is the winter of 2006, the warmest on record, and its consequence on the Tibbit-to-Conwoyto operation (McGregor et al., 2008; Rawlings et al., 2009). A 72 day operating window was brought down to 49 days, which was too short to haul all the required material to the mine sites. Expensive airlifting was carried out (>$100 M). The warming trend is expected to continue for that ice road, and a reduction in the number of freezing degree-days will delay in ice road opening date, while an increase in melting degree-days will lead to earlier closure (RSI, 2014).

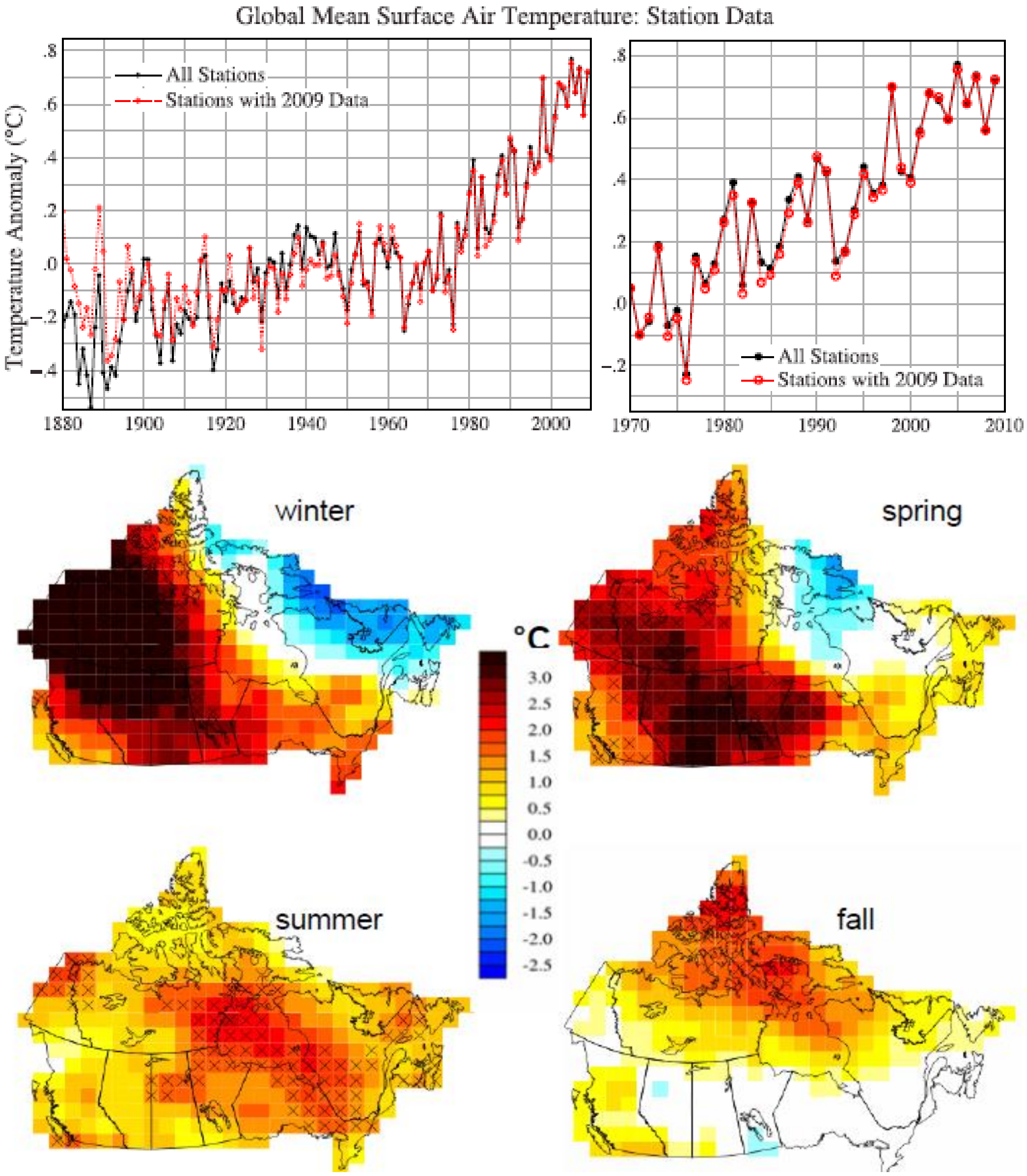

Figure 26: Above) Global mean surface air temperatures (Hansen et al., 2010). Below) Warming of Canada's North (Jackson, 2010).

Ways have been devised to adapt to the impact of climate change on the operation of ice roads and on the reduction of their yearly operational lifespan. Two requirements for extending ice road into the spring have to be considered. Firstly, the integrity of the ice cover must be maintained. Secondly, means of preventing the deterioration of the ice surface must be sought. In this section, we will briefly look at some adaptation strategies at the operational level, and using ice reinforcement.

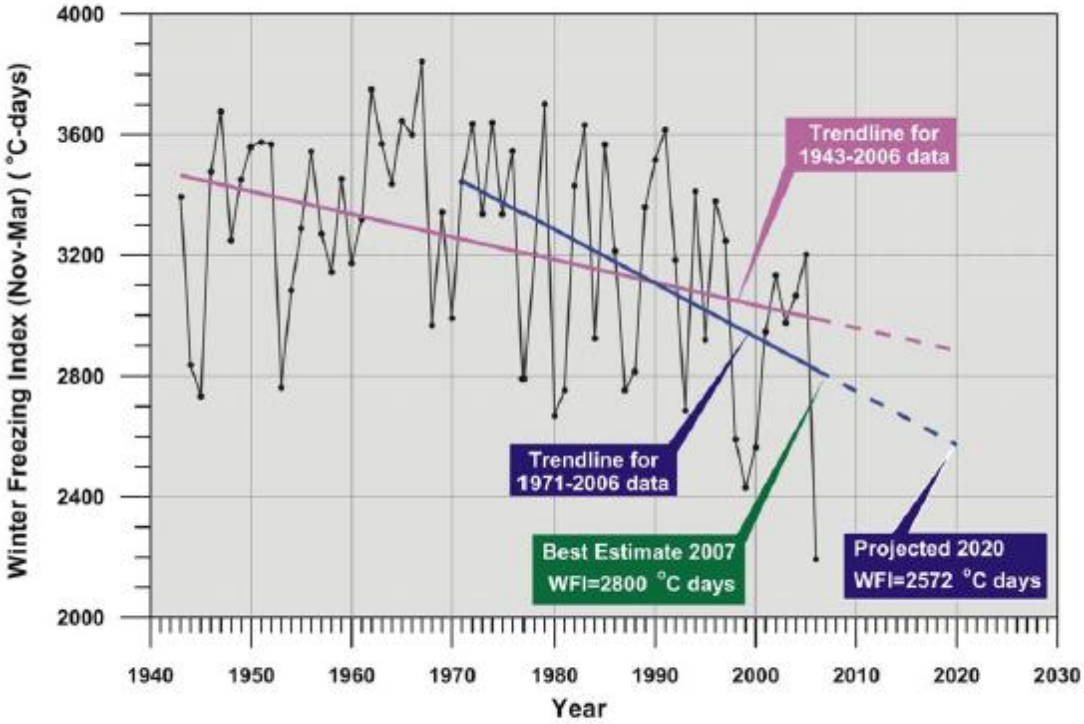

Figure 27: Fluctuation and overall decrease in the number of the freezing index in the Northwest Territories (McGregor et al., 2008).

5.2.1 Operational aspects

Adaptation strategies at the operational level have been reported. They include the following (Barrette, 2011b; McGregor et al., 2008; Michel et al., 1974; Rawlings et al., 2009; Strandberg et al., 2012):

Design, construction and maintenance

- Laying bridges to replace river crossings when these become choke points
- Building and maintaining multiple routes, in case one becomes unusable
- Improving the technology for conducting stress analyses and for estimating ice bearing capacity
- Including improved standard operating procedures on ice that are embedded in contracts
- Improving means of monitoring the ice thickness, notably by optimizing ground penetrating radar technology, temperature and strength
- Limiting the size of windrows, which can cause a crack to form in the center of the road, thereby inducing ice flaking and surface deterioration
- Maintaining a minimum width for the road so as to allow the traffic to make its way around flooded areas
- Relying on spray ice in some locations where this method can be used to help maintain ice thickness

- Using snow on the ice surface to maintain a high albedo[6] – snow banks can be used for that purpose or an artificial material (mats)
- Regular inspection of the ice to report on accumulation of dirt
- Covering the ice with a sufficiently thick layer of saw dust to insulate it against warm air temperatures

Traffic management

- Using the road at night, while the ice is stronger
- Restriction on day time use of roads
- Putting in place driver awareness campaigns
- Allowing one lane to be faster for empty loads
- Improving the overall traffic control

The access to and from the ice cover (ramps) can be a weak link for ice roads. Means of adapting this include:

- Considering north to east facing slopes for these ramps, which are not as exposed to sun
- Maintaining a thick snow layer over the ramp throughout the winter, so that the bare ground does not become exposed
- Preventing exposure of that surface to the sun by covering it with a mat or other materials.

5.2.2 Ice cover reinforcement

As we have seen earlier, the bearing capacity of an ice cover can be increased by artificially increasing its thickness through flooding or spraying operations. Alternatively, it can also be reinforced. In the context of climate change, this approach may be able to maintain, and even extend, the operational lifespan of an ice road. Ice cover reinforcement can be divided into two types: macroscopic and microscopic (Vasiliev et al., 2014).[7]

5.2.2.1 Macroscopic reinforcement

Macroscopic reinforcement is done by laying a structural material – e.g. logs, steel beams, a geogrid – onto the ice cover at strategic locations and flooding it, so that it gets incorporated into the ice cover. An example is shown in Figure 28. Following are a few investigations on that topic.

- Gold (1971) gives three examples of ice bridge reinforcement with logs (2 cases) and steel cables (1 case).
- Michel et al. (1974) describes ice bridges constructed with wooden logs set in built-up layered ice near the bottom surface, where the ice cover was in tension

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[6] Albedo in this context is the amount of sunlight reflected by the ice. If the ice surface becomes dirty, for instance when it incorporates sand, it absorbs the sunlight, which accelerates melting.

[7] By analogy, this is like using re-bars and microfibers, respectively, to reinforce concrete, which is also a brittle material when loaded in tension.

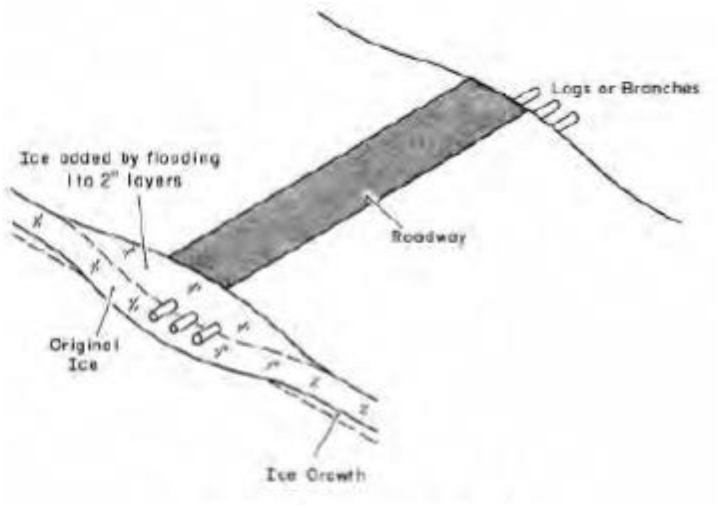

Figure 28: An example of an ice road locally reinforced with logs or branches (Ohstrom and DenHartog, 1976).

under load. The premise was that, if the ice failed, the logs would take up the load. This allowed the required design ice thickness to be reduced by 25-35%.

- Ohstrom and DenHartog (1976) investigated ice reinforcement with three different materials: tree branches, aircraft cables and wood dowels. Significant improvement – up to a five-fold increase – in bearing capacity was observed. Reinforcement also caused the ice to withstand the load even after beam failure. The branches afforded better bonding than the wood and the cables, for which slipping 'along the reinforcement' is reported.
- Jarrett and Biggar (1980) tested four fabrics frozen near the base of ice specimens, where the ice was in tension during flexural tests. Reinforcement increase beam strength up to 31%. It was also reported that the higher the initial elastic modulus, the higher the strength.
- Coble and Kingery (1963) investigated a number of options (fiberglass yarn, fiberglass insulating mat, wood fiber, asbestos fiber, newspaper mash, bond paper mash, bond paper strips, starch). A linear increase in strength with the fiber content is documented for all materials.
- Cederwall (1981) incorporated two steel bars 8 mm in diameter near the base of 300 x 160 mm ice beams, which were tested in flexure. Failure stresses were 320 to 400 MPa, sustained by the bars.
- Haynes et al. (1992) reported on the use of a polymeric mesh, which increased the ice bearing capacity in the laboratory by up to 300%. With this material embedded in the ice cover, failure was much more localized with reinforced ice; it also reduced ice deflection.

5.2.2.2 Microscopic reinforcement

For microscopic reinforcement, the ice itself can be produced by mixing water with another material (e.g. wood pulp, fiberglass) before freezing. Specimens produced from

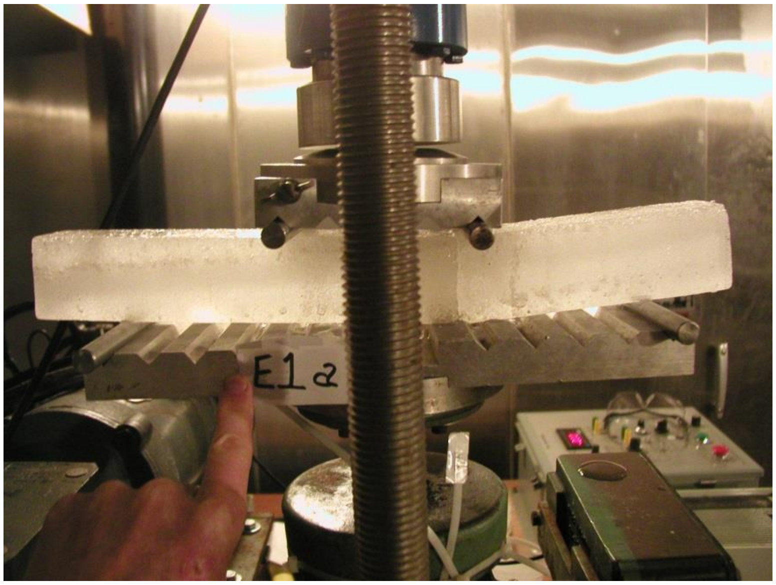

Figure 29: An example of a flexural test done in a laboratory, using the four-point method (the specimen is from the Rideau Canal skateway).

these mixtures are usually tested in the laboratory to assess their strength. An example of such a test is shown in Figure 29. Following are examples.

- Perutz (1948) and Gold (1993) reported on an attempt by the allies during WWII to build an aircraft carrier made from a mixture of ice and wood pulp, a cheap and plentiful material whose resistance would unable the ship to withstand the enemy's torpedoes. Because of various technical difficulties, the project was eventually abandoned. That was an early example of how the mechanical resistance of ice could be increased by incorporating a different material into it.
- Nixon and Smith (1987) and Kuehn and Nixon (1988) tested ice specimens containing softwood sawdust, shredded bark and shredded newspaper. They report a reduction of required thickness by over one third compared to what would be needed without reinforcement). They also observed an increase in fracture toughness, the later being more noticeable for the fibers with the smallest diameter. Fibre pull-out and fibre debonding are thought to be responsible for that phenomenon.
- Nixon and Weber (1991) looked at the possibility of using alluvium to reinforce the ice, a material that is readily available in the field. They chose sand with a 80% weight content, and tested at different temperatures. They report an increase in flexural strength with decreasing temperature.

Ice reinforcement involves a number of factors:

- Material availability – the economic aspects of it are discussed (Coble and Kingery, 1963; Kuehn and Nixon, 1988; Vasiliev et al., 2014)
- Extra time needed (Michel et al., 1974; Ohstrom and DenHartog, 1976)
- The darker material absorbs solar radiations and contributes to ice deterioration (Haynes et al., 1992; Ohstrom and DenHartog, 1976)
- Depending on the reinforcing material, it may have to be recovered for environmental reasons, which may prove difficulty (Jarrett and Biggar, 1980)
- Material deployment in the field depends on its nature – it may be difficult to position and freeze in the ice cover (Haynes et al., 1992).

5.3 Recommendation for future work

Based on the foregoing, a number of avenues could be explored to address concerns about the reduction in length of ice roads operational lifespan related with climate change. Following are options of interest, which would address either or both the integrity of the ice sheet and traffic management issues.

- Future guideline editions in Canada should seek uniformity. As it stands, there is a lot of overlap between recommendations made by the existing guidelines, but significant discrepancies remain.
- One approach would be to collect information (technical issues, recurrent problems, remediation, etc.) from ice road operators, to consolidate that information and to make it available to all stakeholders. This would serve as a consultation platform as well as a source of information. For instance, an issue experienced by one operation may have been solved in another. Collectively, this information would be helpful to devise a uniform set of guidelines.
- A better understanding should also be sought about whether or not white ice at the top of an ice cover will reduce the effective thickness of that cover. It may prove instructive to address structural layering in the ice cover.
- Another avenue is to examine what has been done so far via numerical modeling and, if required, to conduct mechanical testing and pilot studies for validation and analytical purposes. This would also serve to generate information on the time factor, its effects on ice deflection and elastic behavior, and on cracking development in the ice cover.
- Laboratory work is an effective tool for gaining insight on the behavior of loaded ice sheet – it can also validate numerical models and guide field investigations.
- Gold’s formula is empirical – it is based on observations collected many decades ago for ice road usage and traffic conditions of these days. It might be rewarding to repeat Gold’s breakthrough analysis with more recent data, wherever they can be retrieved from (this might be a challenge).
- With the availability of new technologies, reinforcement methods should be revisited. The availability of cheaper, environment-friendly and more effective material would allow one to address weak links along an ice road.

This report did not address saline ice, a material known to be mechanically weaker than freshwater ice. However, according to Masterson (2009), the flexural strength of both materials have the same load bearing capacity, the reason being that “sea ice has far better ductility than fresh water ice, making it less prone to brittle failure and extreme cracking" (p. 104). This should also be investigated. Sea ice strength varies with brine content, which itself is a function of temperature.

6. Conclusion

The response of an ice cover to a vertical load depends on the nature of the ice (thickness, temperature, internal structure, presence of fractures, etc.) and on what the loading event entails (total weight, load distribution, duration, etc.). The main challenge for any ice road operation is to ensure a breakthrough never happens. Gold's formula is a practical and robust guiding principle to a safe ice road, as long as two conditions are met: 1) An appropriate value is assigned to the 'A' parameter, and 2) all other factors having an influence on bearing capacity are taken into account (ice quality, proper thickness determination, pre-existing cracks, road maintenance procedures, trafficability, etc.).

A global temperature rise associated with climate has been documented over the last number of decades and affects ice covers in different ways, depending on geographical location. The consequences are a reduction in the total number of freezing degree days and the delayed onset of freeze-up and earlier onset of melting. Global warming may also affect the operational aspects of the ice road.

The purpose of this report was, firstly, to survey the most important guidelines published by different organizations on the design, construction and management of ice roads. This served to establish a comparative basis for the different recommendations made by these organizations on the determination of design loads. In doing so, it was possible to identify the similarities and inconsistencies between guidelines.

Secondly, this report also provides prospective avenues to address concerns about the reduction in length of ice roads operational lifespan related with climate change. This includes consultation with the ice road operators in order to find out about the technical issues, recurrent problems, remediation, etc., and the consolidation of that information and to make it available to all stakeholders. Another avenue is to clarify the role of white ice on the bearing capacity of an ice cover. If it can be shown that it does not significantly affect it, this would result in a significant increase in effective thickness and a consequent extension in operational lifespan. Finally, means of investigating new technologies and reinforcement methods should also be revisited. The availability of cheaper, environment-friendly and more effective material would allow strengthening of segments of an ice road that represent a weak link.

7. Acknowledgements

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