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Review of ice and snow runway pavements

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Abstract

Antarctica is the highest, driest, coldest, windiest, most remote and most pristine place on Earth. Polar operations depend heavily on air transportation and support for personnel and equipment. It follows that improvement in snow and ice runway design, construction and maintenance will directly benefit polar exploration and research. Current technologies and design methods for snow and ice runways remain largely reliant on work performed in the 1950s and 1960s. This paper reviews the design and construction of polar runways using snow and ice as geomaterials. The inability to change existing snow and ice thickness or temperature creates a challenge for polar runway design and construction, as does the highly complex mechanical behaviour of snow, including the phenomena known as sintering. It is recommended that a modern approach be developed for ice and snow runway design, based on conventional rigid and flexible pavement design principles. This requires the development on an analytical model for the prediction of snow strength, based on snow age, temperature history and density. It is also recommended that the feasibility of constructing a snow runway at the South Pole be revisited, in light of contemporary snow sintering methods. Such a runway would represent a revolutionary advance for the logistical support of Antarctic research efforts.

Keywords: Runway; Pavement; Snow; Ice; Antarctic

Contents

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1. Introduction

Antarctica is the highest, driest, coldest, windiest, most remote and most pristine place on Earth and contains 89% of the ice in the world [1]. Antarctica is 14 million square kilometres in area, making it twice the size of Australia, and 98% is covered in ice, on average 1.9 km thick. This makes Antarctica the most logistically challenging location on Earth. Although less remote, the Arctic is also challenging.

Polar operations depend heavily on air transportation and support for personnel and equipment [2]. Polar terrain, climate and material availability do not allow for conventional runway construction [2]. Most polar runways are constructed of ice or snow, or a combination of the two. The current technologies and design methods for snow and ice runways remain largely reliant on the work performed by the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers, undertaken primarily in the 1950s and 1960s. Since that time, polar exploration, research, tourism and general interest have expanded.

More efficient logistics provides the opportunity to increase the research effort [1]. For every day of research, nine days of logistics effort is required in Antarctica. It follows that any improvement in snow and ice runway design, construction and maintenance will directly benefit polar research. Current challenges for air transportation in Antarctica include the short annual period for wheeled aircraft operations [3] the complex mechanical behaviour of snow and ice materials [4] the risk of short annual periods of above-freezing temperatures causing localised melting [2], glacial flow that occurs in many areas of Antarctica [5] the inability to compact snow at the very cold temperatures experienced at the South Pole [6] and the high cost of fuel in polar regions. The limited Governmental or private activities that have a need to understand snow and ice mechanics limits the motivation to address these challenges [7].

The aim of this paper is to review the design and construction of polar runways using snow and ice as geomaterials. Snow and ice processing and mechanics are discussed as well as material characterisation and pavement design. Comparison to conventional runway pavement materials and design methods is presented. Recommended further work focuses on modernisation of design methods for snow and ice runways as well as investigation of contemporary snow sintering and construction methods.

2. Historical perspectives

Aircraft fitted with skis have been landing on snow in Greenland since 1925 [8]. The associated equipment commonly used for snow processing and compaction was primarily developed in the USA during the 1920s and 1930s [9]. The first compacted snow runway in Antarctica was constructed by the US Navy in 1947, located over the Ross Ice Shelf [10]. Aircraft operated on skis. The first landing of a wheeled aircraft on a snow runway was in Greenland in 1955 [8].

Current polar runway options include wheeled aircraft on thick (permanent) bay ice, wheeled aircraft on annual sea ice, wheeled aircraft on glacial ice, wheel aircraft on prepared snow and 'ski-ways' on semi-prepared snow for use by aircraft fitted with skis [1]. A ski-fitted C130 became available in 1960 and first operated into Antarctica in 1967 [3]. Russian Ilyushin 76T aircraft have been successfully used at Russian developed compacted snow runways [10] and Australia operates a commercial A320 annually into Wilkins ice runway near Casey Station [11]. Significant aircraft frequently using snow and ice runways are detailed in Table 1.

Australia has operated wheeled C130 aircraft into the Wilkins ice runway since 2006. Currently, A320 wheeled aircraft also operate twenty times per season [11]. These flights provide valuable passenger transportation capacity at the start and end of each research season. However, with significant emergency fuel required to reach alternate air-

Table 1
Airport commonly operating in Antarctica ([*]).

Aircraft	Name	Total Mass (t)	Wheel Load (t)	Tyre Pressure (kPa)
C130	Hercules	70.3	16.7	725
C141	Starlifter	156.5	18.6	1,310
C5A	Galaxy	348.8	13.8	730
C17A	Globemaster	265.4	21.0	951
A320	A319 variant	64.4	15.3	1,190
IL 76	Ilyushin 76	104.0	6.2	640

[*] Some aircraft types have multiple variants with significantly differing mass and tyre pressure.

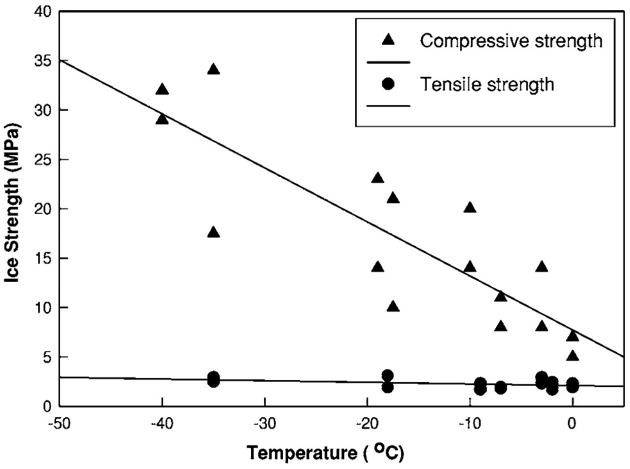


Fig. 1. Compressive and tensile ice strength as a function of temperature [13].

fields, the A320 provides limited cargo/freight capacity. The Australian Antarctic Division plans to introduce C17A operations in the future [11]. The C17A already operates into the USA controlled McMurdo Ice runway, providing a significant increase in cargo/freight capacity compared to the A320. However, the C17A is less suited to passenger transportation. The construction of a wheeled C17A capable runway at the South Pole would represent a revolutionary change to Antarctic research logistics [1]. A wheeled aircraft capable snow runway at the South Pole has long been the 'holy grail' of snow and ice runway construction.

3. Snow and ice mechanics

Ice is solid water. Pure water freezes at 0.0 °C and seawater freezes at −1.8 °C [12]. Snow is effectively a cellular form of ice in which individual particles are bonded together [13]. It follows that the mechanical properties of ice are simpler than those of snow.

3.1. Ice mechanics

There are many forms of ice and each reflects the mode of formation [14]. Solid sea ice is porous due to trapped air [2] and contains brine of salt water. Blue ice is formed by top-down freezing of lake water and white ice results from the flooding of snow [12]. When formed under low pressure, freezing of water results in a hexagonal crystalline ice structure and vapour accumulation forms ice with a cubic structure [13].

Pure air-free ice has a density of 920 kg/m^3 [10]. Despite its freezing point, a thin layer of water-like material can be identified on the surface of ice down to −40 °C [15]. Understanding this water-like film is important for explaining many other ice and snow properties, including snow sintering.

Like concrete, ice is strong in compression and weak in tension [12] (Fig. 1). Pure ice has a tensile strength generally between 0.7 and 3.1 MPa, with an average of 1.43 MPa between −10 °C and −20 °C. In contrast, compressive strength is between 5 and 25 MPa over that temperature range [13]. Ice modulus also increases with decreasing temperature [2].

The strength of ice is dependent upon density, temperature, grain size, brine content and strain rate. As the temperature of ice increases from −40 °C to near the freezing point, the compressive strength of ice decreases by 75%. The influence of temperature on tensile strength is less, with a decrease of 25% over the same temperature increase [13]. Between −5 °C and the melting point, ice is ductile and becomes prone to rapid creep under sustained strain [12]. At lower temperatures, ice has high resistance to creep [16]. However, ice is brittle. Its fracture toughness is low, at around 10% of that of glass [13].

Trapped air reduces the density of ice. At lower density, ice strength decreases, as does the modulus [2]. Increasing brine content also reduces ice modulus [2]. Ice grain size also affects ice properties with a smaller grain size providing a significant increase in compressive strength [17]. In contrast, Petrovic [13] reported a decrease in tensile strength with smaller grain size.

Strain rate has a significant impact on ice mechanics. Like many engineering materials, quickly loaded ice fractures while slowly loaded ice creeps [18]. The compressive strength of ice is dependent upon the strain rate [13,19] in contrast to the tensile strength, which is independent of strain rate [13].

In summary, ice is similar in many respects to other engineering materials. Like concrete, it is much stronger in compression than in tension. Similar to asphalt, when loaded fast, ice fractures, while it creeps when loaded slowly. The main complications for mechanical characterisation of ice are the proximity of polar temperature fluctuations to its melting point and the broad range of properties influenced by the way in which the ice was formed.

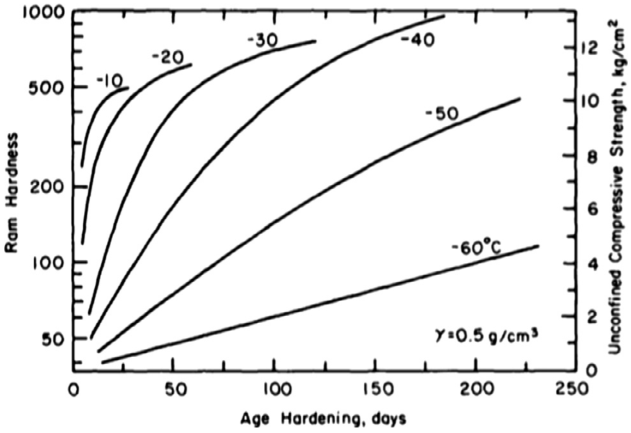


Fig. 2. Snow strength as a function of age and temperature [9].

3.2. Snow mechanics

In contrast to ice, snow properties are more complex with even the basic structure of snow being thermally unstable [20]. Snow is formed by the precipitation of flakes of crystalline water ice. Unlike ice, snow comprises only pure water. The properties of snow particles depend on the atmospheric conditions at the time of formation, with snow particle structures ranging from dendritic flakes to pellets [9,21].

Freshly fallen snow forms a blanket with 50–90% porosity [21]. The snow blanket is highly compressible [20] and temperature dependent. In addition to any natural densification due to overlying snow mass, snow porosity is reduced by three metamorphic processes [21]:

- Stabilisation of the inherently unstable dendritic flake structures, which occurs rapidly.
- Sintering of particles, the formation of mechanical bonds, occurring almost immediately after contact is made and continuing until recrystallization into ice commences.
- Recrystallization, as ice is formed at around 10% remaining porosity.

Sintering is an important process affecting snow mechanics. Sintering is the process of bonds forming between particles in contact while close to their melting point [15]. Sintering results from ice melting in areas of higher vapour pressure (the convex portions of particles) and re-condensing in the lower vapour pressure locations (where grains are in contact) [21].

Sintering occurs independent of stress. Larger snow particles sinter more slowly, but form stronger bonds in the long term [2]. Sintering rate is also highly dependent on temperature (Fig. 2). Sintering near the melting point occurs rapidly and results in rapid snow strength increase [8]. Below −4 °C sintering occurs significantly more slowly [2]. At temperatures typical at the South Pole (−25 °C to −50 °C) significant sintering takes months and years [9].

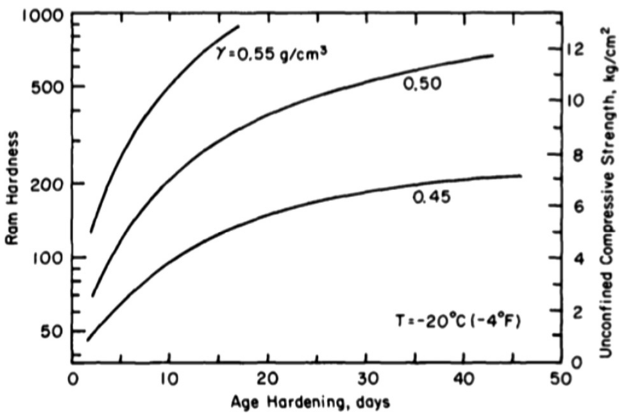


Fig. 3. Snow strength as a function of age and density [9].

Like ice strength, instantaneous snow strength is temperature dependent [8–9,21] as illustrated in Fig. 2. The most efficient way to create strong snow is to allow it to sinter near freezing point and then reduce its temperature to increase strength [8]. Low snow temperature later in the sintering process increases snow strength without significantly affecting the overall sintering rate [9].

In addition to temperature, snow density has a significant impact on snow strength (Fig. 3). A 10% reduction in snow porosity results in around a 100% increase in snow bearing strength [21]. Cold and dense snow is most advantageous. However, achieving dense snow relies on sintering, which occurs more rapidly closer to the freezing point. This creates a challenge for the characterisation of snow, as well as for its use as a polar construction material. It follows that snow properties complicate snow runway design.

Fresh snow density is around 100 kg/m^3. Natural densification and sintering will increase this to 300–400 kg/m^3. At the South Pole, snow rarely exceeds 360 kg/m^3 regardless of treatment or age [3]. This reflects the cold and dry nature of the snow particles at typical South Pole temperatures [6]. To create a material that is suitable for snow runway construction, processing is required. Processing of snow disaggregates the snow particles. The sintering process recommences after disaggregation. Processed snow generally has density of 500–700 kg/m^3 and may take days, weeks or months to achieve full strength, during which time the snow can also be mechanically improved by compaction [17].

Snow is one of the most brittle materials known [22]. The fracture toughness of snow is two to three orders of magnitude lower than that of ice and the tensile strength of snow is also much lower than that of ice [13].

Traditionally snow has been characterised by its bearing or shearing strength. Recent attempts to develop mechanical models for snow have achieved limited success. The specific properties of snow make micromechanical model development challenging [23]. Like bitumen and asphalt, snow behaves in a viscous or viscoplastic manner during short duration tests at natural density [4]. However, for high stress conditions of compacted and aged snow, linear elastic models are more appropriate [7]. For most polar applications, snow transitions from one state to the other and back [7]. A unified constitutive model of snow would likely be so complex that it would also be applicable to many other engineering materials [20]. As a result, the bulk density of snow is commonly used for characterisation [23] similar to fine crushed rock for conventional pavement design. Mohr–Coulomb shear-based failures models are employed by designers and engineers of snow structures [20].

In summary, sintered snow is an aggregated mass of bonded particles of crystallized pure-water ice. The properties of snow are dependent upon the strain rate, temperature, particle size distribution and density. In turn, the density of snow is influenced by the age and temperature history throughout the sintering process. This complex mechanical behaviour complicates the development of micromechanical models for snow. For practical purposes, snow remains characterised as an aggregated mixture with interactive age, temperature and stress dependent properties.

4. Material characterisation

Similar to conventional geomaterials, snow strength can be classified by surface bearing loading, sample strength measurement or probe penetration resistance [9]. The applicability of the test and the usefulness of the result are inversely proportional to the convenience of the test method. For example, the Australian-developed surface loading device known as the Clegg Hammer is easy and fast to operate, but its effective measurement depth is very limited. In contrast, the in situ California Bearing Ratio (CBR) test is internationally recognised as the 'gold-standard' for granular material bearing strength, but is impractical to perform regularly in the field.

Snow is routinely tested for strength by 'Ram hardness' and Unconfined Compressive Strength (UCS) [2]. Bearing strength is preferred to UCS for snow runway design [10] and density alone is not a reliable indicator of snow strength due to the sintering process resulting in significant strength increase without a proportional increase in density [9]. Ram hardness (measured by the Rammsonde) is preferred due to its ease and the short time required to perform [24]. The Rammsonde is a Swiss device, not dissimilar to a Dynamic Cone Penetrometer (DCP). The Rammsonde has a 60° conical cone of 40 mm maximum length on a 19 mm diameter stainless steel shaft and uses a hollow ring mass of 1, 2 or 3 kg dropped over a fixed distance [10]. The Rammsonde was superseded by its automated cousin the 'resistograph' [20]. However, the standard 60° cone is not suited to very hard snow so a sharper (30°) cone is used instead and a conversion has been developed [9]. More recently, McCallum [25] described the use of a modified, friction-sleeve-equipped, cone penetrometer to efficiently assess the strength and physical characteristics of polar snow.

Since its development in the 1970s the Clegg Hammer [26] has been a valuable addition for near-surface snow bearing capacity assessment. The Clegg Hammer is 4.5 kg flat-faced hammer and electronic decelerometer [10]. It is easy to operate in the field and has been used extensively in Antarctica [9,27]. The Clegg Impact Value (CIV) is calculated from the rate of deceleration of the hammer as it impacts the test specimen.

Correlation between Ram hardness and UCS was presented by Abele [24]. Lee at el. [6] developed relationships between Ram hardness, CBR and CIV. Similar formula and conversion scales for Ram hardness, CIV and CBR are available, and reproduced in Fig. 4. For significant works, a snow-specific conversion between the various strength measuring devices is recommended. For example, CBR and Ram hardness may be used for design purposes, with CIV from the Clegg Hammer used for construction quality control.

5. Runway pavement design

Conventional (non-polar) runways are designed by one of two general approaches. Flexible pavements are designed based on protection of the subgrade or foundation. A combination of cover material stiffness and thickness is determined to reduce the vertical strain at the subgrade to a level that is (empirically) not expected to result in excessive permanent vertical deformation (ie. rutting). Rigid pavements are designed similar to a floating beam or slab, using Westergaard's equations to limit the flexural stress within the concrete. Protection of the subgrade is of less importance, although the subgrade provides support to the concrete base.

Snow is similar to an aggregate of fine crushed rock. Ice is not unlike concrete, a solid material of high compressive strength and relatively low tensile strength. It follows that snow and ice runways are designed using similar principles to conventional flexible and rigid pavements. However unlike conventional runways, the ability to 'construct' a pavement in polar environments is limited. Importation of material is not feasible and the cost of energy is high,

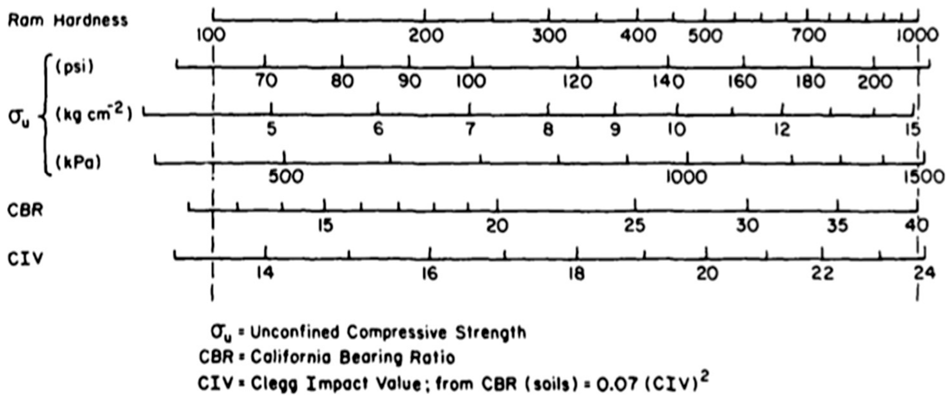


Fig. 4. Interrelationship between various snow strength indices [9].

making any energy-intense construction methods logistically difficult and cost prohibitive [1]. Further, the annual seasons and prevailing weather conditions significantly affect material properties and limit constructability. For example, some Antarctic runways are constructed of seasonal sea ice, with inter-particle cohesion that resists shear stress. The medium-term prevailing conditions determine the thickness of the sea ice. It is impractical to increase the structural capacity of the runway. Similarly, short annual periods of above-freezing temperature result in snow melt that affects the structural capacity of snow runways in coastal Antarctic areas. Further, the significant difference in temperature between the South Pole (generally −25 °C to −50 °C) and those experienced in coastal areas (generally −5 °C to −30 °C) requires substantially different construction processes. This reflects the vastly different sintering rates as a function of snow temperature.

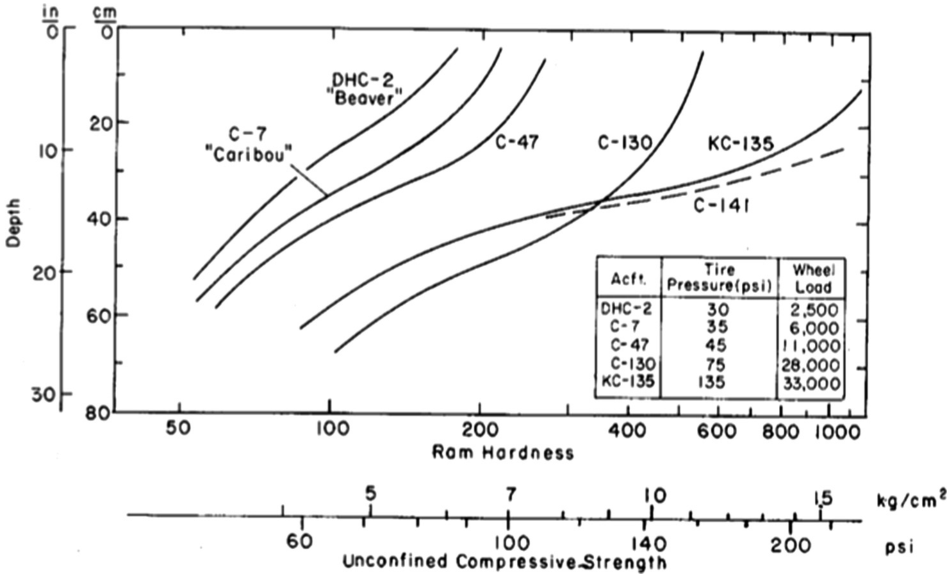
5.1. Snow pavement design

Similar to conventional flexible pavements, snow pavement design relies on stress distribution and spreading of loads. Boussinesq's equation is used to estimate stress dissipation with depth [2]. Controlling shear stress resistance is the basis of failure with a 5 cm rut depth, after a single aircraft pass, indicative of an inadequate pavement [21]. Although aircraft can continue to operate on snow pavements with greater rut depths, 5 cm was selected as it discriminated between stable pavement performance and rapidly accelerating failure [21].

Like flexible pavements, the contact stress at the pavement surface is critical to pavement performance. The shear stress reduces rapidly with depth below the runway surface. It follows that materials of reducing shear stress resistance are acceptable as the depth from the pavement surface increases [21]. For conventional flexible pavements this results in lower quality materials being selected. In the case of snow runways, the same snow is accepted at a reduced density. However, deeper snow is likely to be older and better insulated from solar radiation. It follows that without mechanical improvement, the deeper snow often has a higher shear resistance than the snow nearer the surface. This is not conducive to efficient snow runway construction.

Based on empirical performance determined from full scale testing conducted between 1960 and 1963 [21] a minimum snow strength is required for a depth that is equal to the radius of the tyre contact area [2]. Repeated loading trials determined a 50% increase in snow strength was required for two aircraft repetitions within an hour. Ten repetitions required a 100% increase in snow strength [21]. A number of design charts were developed for common aircraft and snow strengths, such as the example in Fig. 5. This is similar to the US Army Corps of Engineers approach to the early design of conventional runway pavements.

In summary, the design of snow runways is similar in principle to that developed and still used for the design of flexible pavements for conventional roads and runways. The primary difference is the estimation of stress with depth under the aircraft tyre remains based on Boussinesq's equation. In contrast, the design of conventional flexible pavements has progressed to layered elastic and even finite element stress calculation tools. It is recommended that the current snow runway design method be revisited to allow snow runway design to be performed using modern layered elastic pavement design tools. This would require an analytical method for the characterisation of snow based on temperature history and density.



Acft.	Tire Pressure(psi)	Wheel Load
DHC-2	30	2,500
C-7	35	6,000
C-47	45	11,000
C-130	75	28,000
KC-135	135	33,000

Fig. 5. Example of snow hardness with depth required for various aircraft [9].

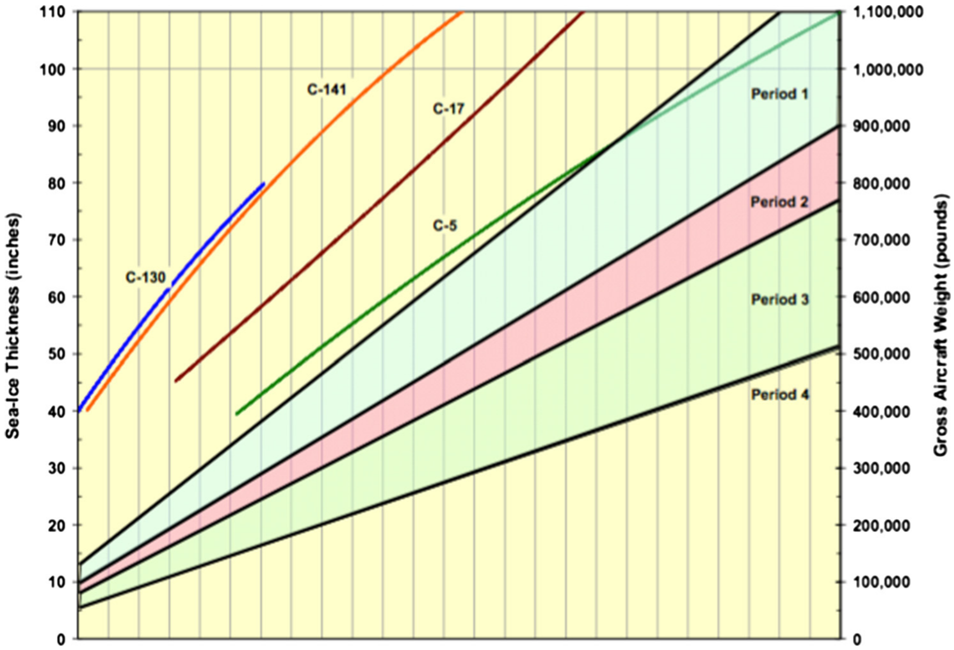


Fig. 6. Example nomograph for sea ice runway at McMurdo Station [16].

5.2. Ice pavement design

Ice pavement design varies depending on the type of ice. The design of an ice-on-ground pavement is based on the load spreading ability of the ice to protect the underlying subgrade [12]. This is similar to snow pavement design except the ice is working in flexure rather than an aggregate mass. In contrast, floating (sea) ice design is based on the ability of the ice layer to resist tensile stresses at the bottom of the ice layer [12]. This is analogous to conventional rigid (concrete) pavement design methods. Either way, as the flexural strength of the ice increases or the ice increases in thickness, the strength of the ice runway increases. Design graphs were developed for common aircraft and ice properties. Due to the large number of variables compared to the small number of ice runways, runway specific charts are more common than a general set of charts that can be selected from for a particular design scenario. An example for the McMurdo Sound annual sea ice runway is shown in Fig. 6.

Further, the McMurdo Station ice runway design was based on wheel load and contact pressure [16]. This was compared to the flexural strength determined from testing of ice samples. To confirm the structural capacity of the pavement, proof rolling was performed. At temperatures greater than −5°C, re-testing of ice samples is required to confirm the strength of the pavements remain adequate. Similarly proof rolling and testing is also performed at the nearby glacial ice runway.

For ice runways constructed over shallow water, the increase in pressure induced by the moving aircraft load must be considered. The shallow water pressure wave increases the stress in the ice layer by up to 50% [12]. Thicker or stronger ice is required for the portion of the runway located over the shallower water.

Ice runways are also often constructed on moving glacial ice. For example, the Wilkins glacial ice runway near Casey Station moves around 12 m per year, as the ice flows downhill [28]. The flow of the variable depth ice over the bedrock also changes the shape of the ice runway surface. This requires periodic correction by ice milling [11]. The ice milling also reinstates frictional properties when aircraft lands directly on the ice surface.

Ice runways are often surfaced with a layer of snow [16]. The snow insulates the ice from solar radiation. Rubber deposits and other small dark particles cause pitting in ice. Rubber deposited on the ice surface during aircraft landing absorbs solar radiation and melts into the surface. The locally melted ice then refreezes, trapping the rubber particles inside the ice layer. Following a number of landings, the touchdown zone becomes grey in colour, leading to broader but less intense solar radiation [11]. To counter this, rubber is removed, similar to a conventional asphalt or concrete pavement surface. However, ice runway rubber must be removed after every aircraft landing.

6. Material processing and construction

Similar to conventional pavement construction, processing the naturally occurring geomaterial is a reliable method for improving material properties and pavement performance. Material processing is problematic for ice runways as there is little ability to change the in situ ice. Similarly, the practical inability to influence the temperature of snow, in combination with the high cost of fuel in Antarctica, limits reliable and significant improvement in snow pavements.

6.1. Snow processing

Mechanical disaggregation of snow increases the density to between 250 kg/m^3 and 500 kg/m^3 [21]. Optimum snow strength is achieved when the snow reaches around 700 kg/m^3 [17]. The disaggregation process improves the distribution of the snow particle size and allows sintering to occur rapidly. Snow bearing strength can be further improved by mechanical compaction during the sintering process. Timely compaction is equivalent to six days of sintering [21]. The most efficient and effective approach to snow processing is to disaggregate and compact around −2°C, followed by sintering below −10 °C. However, the inability to control the snow temperature complicates snow runway construction.

To reduce reliance on favourable weather conditions there have been attempts to temporarily and artificially warm snow during the disaggregation and compaction process. A heated snow processing capability was developed but was restricted to 45 cm processing depth and fuel requirements were logistically prohibitive [21]. Localised snow warming by watering at a rate of 3 cm per 25 cm of snow thickness was found to be more efficient than direct heating of snow, but remained logistically problematic.

The first equipment developed for snow disaggregation was a modified mechanical pulveriser, capable of processing to a depth of 45 cm. The Peter Plow was introduced in the 1960s and has the capability to process snow up to 130 cm thick [2]. The Peter Plow remains the primary equipment for snow processing during runway construction [11].

Snow has been also been reinforced with sawdust to improve the physical properties. Around 3 cm of sawdust was added to 15 cm of snow with some success [21]. Dark sawdust resulted in localised snow melting and white sawdust was preferred [6]. More recently snow has been compacted into ice bricks. A pressure of 6.9 MPa was applied to a 15 cm diameter round mould filled with snow. The resulting ice bricks were strong and durable with a density of 800–900 kg/m^3 [17]. Despite these processes being viable, practical limitations has seen almost all snow runways constructed by disaggregating and compaction of naturally occurring snow [9].

6.2. Ice processing

There is little that can be done to improve or process ice. Fissures or cracks are filled with a slurry of ice, snow and water, which rapidly freezes. Such repairs are usually denser and stronger than the surrounding naturally occurring ice [11]. Ice has also been made by the flooding of snow with water. Although effective, the energy required to melt water in polar regions is logistically challenging and cost prohibitive.

6.3. Runway construction

Ice runway construction generally includes the levelling of the existing ice and correction of cracks and fissures. Ice mills are used to provide a smooth and flat surface [11]. Broader areas are shaped by a bulldozer with laser guided and chisel-tooled blade [5]. Runways with ice surfaces are maintained and corrected for changes in the ice surface level. Regular treatment with an ice mill, to provide surface texture for friction as well as the continuous removal of rubber deposited during aircraft landing, is also common [11]. During temperatures above −5 °C, an insulating layer of snow is used to protect the ice against melting [16]. In areas of ample annual snow fall, the insulating layer of snow is maintained as a wearing course, negating the need to create texture and friction in the underlying ice.

Snow runway construction remains more common. This reflects the majority of Antarctica being covered with significant thickness of snow. Despite this, some areas of Antarctica are snow ‘shadows’ and blue ice runways are provided, such as Australia’s Wilkins Runway near Casey Station. Snow runway construction is a multiple step process including disaggregation, compaction, leveling and then sintering time.

Snow disaggregation is most commonly performed by Peter Plow for increased processing depth. The Peter Plow has a closed drum with rotating cutting blades over 1.2 m in diameter and 2.7 m wide. It rotates between 225 and 305 rpm and can cut up to 1.5 m deep [21].

Shaping and compacting must be performed immediately behind the processing [21]. A laser guided fine grader is used with a large volume blade. For compaction, a D8-sized bulldozer with crawler tracks has long been found to be effective [29]. Australian engineers developed a 38 tonne towed proof roller for deep snow compaction [3]. During the construction of Wilkins Runway, a larger, 60 tonne, proof roller was used [11].

The key to snow runway construction is timing [3]. Processing and compaction must be performed during periods of warm weather and then sintering permitted to occur during the colder weather. The strength of the snow must be monitored throughout the sintering process [9] and whenever the temperature or conditions change significantly.

7. Future needs and opportunities

The introduction of larger and more demanding aircraft creates a challenge for the operation of runways constructed from snow and ice. The empirical basis for design and performance of Antarctic runways was developed for aircraft significantly smaller than the A320 and C17A that will form the basis of future summer aircraft operations in Antarctica [11]. Reliance on the work performed in the 1960s and 1970s requires supplementation to reflect the equipment and aircraft technology advances that have occurred since that time.

The ultimate goal for Antarctic aviation is the development of a wheeled aircraft snow runway at the South Pole [1] particularly if it was C17A capable [3]. However, the low summer temperatures at the South Pole (below −25 °C) inhibit snow sintering. At temperatures below −18 °C snow processing and compaction alone cannot produce snow capable of resisting heavy aircraft operations [6]. An all-year wheeled A320 (or equivalent) capable runway anywhere in Antarctica would also be of great benefit [3].

Any technology that allows construction of a C17A capable snow runway to be built at the South Pole would likely also provide significant capability to build and maintain coastal Antarctic airfields. Alternate methods to induce sintering at temperatures below −25 °C appear to be the most viable opportunity. Laser treatment, heated roller tyres, chemical additives and sawdust have been trialed, all with success [6]. However, overcoming the logistical burden of operating in the most remote location on Earth has resulted in technically viable options remaining impractical.

8. Summary and recommendations

Snow and ice runway design is similar in principle to that of conventional runway pavement design. Snow runways are analogous to conventional flexible pavements, while ice runways are similarly comparable to conventional rigid pavements.

The challenges for polar runway design include the complex nature of snow and ice mechanics, particularly near the melting point, as well as the limited ability to control or predict the temperature or thickness of the snow and ice comprising the runway pavement. Comparing to conventional runway pavements, polar runway design is more like an evaluation of an existing weak pavement for compatible aircraft, rather than determining a new pavement composition that will accommodate a particular or desired aircraft.

It is recommended that an analytical model for snow strength be developed from existing data. This must be age, temperature-history and density dependent. The model would form a key element of a modern layered elastic design tool for snow runways. A similar ice runway design tool, based on conventional rigid pavement design, is also recommended. Finally, it is recommended that the feasibility of constructing a snow runway at the South Pole be revisited, in light of contemporary snow sintering methods. Such a runway would represent a revolutionary advance in the logistical support of Antarctic research efforts.

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