DOCTORAL THESIS

Properties of Snow with Applications Related to Climate Change and Skiing

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Soil Mechanics

Luleå University of Technology

Properties of Snow with Applications Related to Climate Change and Skiing

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-H.D. Thoreau

Abstract

Snow has been a subject of research since the mid-20th century. Research on mechanical properties of snow started as an off-shoot of soil mechanics, where methods, tools and instruments used often are the same. However, during the last decades the winter business industry has been growing requiring a number of new fields of research. The aim with this PhD thesis is to investigate and contribute to solutions of some of the new research problems appearing in this area.

Machine-made snow is commonly used for buildings and artwork of snow. Only minor scientific studies of machine-made snow and its properties have been published. Therefore, mechanical properties of machine-made snow were investigated. Strength and deformation properties were evaluated through uniaxial compressive tests where cylindrical test specimens were subjected to different constant deformation rates. Creep deformation, bending strength and ultimate load were also evaluated through beam tests. The results showed that the deformation rate is crucial if the snow will deform plastically or if brittle failure will occur. The grain size and structure of the snow had a strong influence on the strength properties.

Snow is a constantly changing material with a large variety of grain sizes and shapes. Therefore it is of importance to classify snow. Classification of snow can be done using different methods depending on the property that is to be investigated. Several non-contact detection methods to evaluate snow properties exist. In this thesis, spectral reflectance measurements were performed to investigate liquid water content in snow using two different systems, a spectrometer and an optical sensor called Road Eye. The Road Eye sensor was also used to classify snow in cross-country ski tracks. This method enables a fast classification of a complete track where different types of snow can be distinguished.

The properties of a ski track and the characteristics of the snow determine the type of skis that should be selected for optimum sliding properties. Cross-country skis have different mechanical properties, which to a large extent can be evaluated from the span curve of the ski. Depending on the skiing style, the skier's skills, terrain and track conditions different ski properties are required, which is particularly important for competitive skiing. Span curves of cross-country skis were measured using a digital instrument called Skiselector. Results from the investigations showed that skis within the same pair may have significantly different properties. Moreover, temperature influences the span curve and thus the mechanical properties of the skis. Therefore, skis should be measured at a temperature close to where they are aimed to be used. Field tests of skis with similar span curves but different ski base topography were tested during wet and cold snow conditions. The results indicate that different topographies are preferable during different snow conditions.

Due to the climate change, winters have become shorter and warmer with less natural snow. To compensate for the lack of natural snow, ski resorts and other stakeholders produce machine-made snow in order to run their business. Storing snow in insulated piles is an alternative and

sometimes a complement to snow production. Studies on stored snow show that the surface area of the pile should be minimized in order to reduce the melt rate. Furthermore, the pile should be covered with a sufficiently thick insulating layer, preferably with good evaporation properties. Theoretical calculations can be used to estimate the amount of snow that melts and to predict the efficiency of different materials as thermal insulation on snow. These calculations coincide well with experiments performed in northern Sweden where snow melt was measured.

This PhD thesis consists of five publications and an introduction to this area which in particular puts these publications into a more general frame.

Appended Papers:

Paper A: Study on basic material properties of artificial snow.
N.Lintzén, T.Edeskär.

Paper B: Uniaxial Strength and Deformation Properties of Machine-made Snow.
N.Lintzén, T.Edeskär.

Paper C: Liquid water content in snow measured by spectral reflectance.
L.E.Eppanapelli, N.Lintzén, J.Casselgren, J.Wåhlin.

Paper D: Span curve temperature dependence of classic style cross country skis.
N.Lintzén, A.Almqvist, N.Grip.

Paper E: Snow storage - modelling, theory and some new research.
N.Lintzén, S.Knutsson.

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Luleå, November 2016
Nina Lintzén

Part I

Chapter 1

Introduction

1.1 Background

Snow is the base of a widely investigated field of research with different scopes depending on the scientific discipline of study. Research on snow are for instance done by meteorologists (Sturm et al., 1995), avalanches researchers (De Quervain et al., 1973; Delmas, 2013) and scientists within the power industry (Homola et al., 2006), the ski industry (Nolin and Daly, 2006) the automotive industry and for road safety (Casselgren et al., 2012a).

Research on mechanical properties of snow began in the 1930's as an offshoot of soil mechanics (Bader, 1962). The first studies were related to avalanche defense construction problems. Studies in the avalanche field were later performed by Swiss researchers who established constitutive equations and failure criteria for natural snow (Mellor, 1977). In the 1990's further snow mechanical studies were performed in Antarctica and Greenland, where the emphasis of investigations for instance were stability and rupture of snow slopes, long-term creep of snow, structural loadings, bearing capacity and shear resistance of snow surfaces related to vehicle mobility on snow, blowing snow, avalanches and snow plowing (Shapiro et al., 1997). Moreover, snow mechanical properties were investigated by Delmas (2013), with focus on release mechanisms of avalanches related to temperature changes in snow. Increased temperatures due to climate change also affect the snow pack temperature and as a consequence also the viscous properties of snow (Delmas, 2013).

During the past years there has been a demand for new knowledge about snow within various fields of research. The winter business industry has been growing and at the same time winters has become warmer with a later arrival of natural snow and a shorter period with a long lasting snow cover on the ground. Snow has become a coveted product, both for ski resorts and other stakeholders in the winter business industry, such as places where snow is used as a material for constructions. Production of machine-made snow has increased, both to compensate for the lack of natural snow but also since properties of machine-made snow are considered more favourable for various applications. The characteristics of machine-made snow are different from those of natural snow. Still very few studies are published regarding properties of machine-made snow. In this thesis, new fields of research related to snow has been studied and new issues have been addressed.

Strength studies on snow to investigate mechanical properties and research on snow mechanics have been published for example by Bader (1962), Mellor (1963), Mellor and Smith (1966), Mellor (1977) and Salm (1982). It was early concluded that there seemed to be a close relation between strength of snow, ice and frozen soil. Despite the close correlation between the three materials, there is a lack of coordination between studies of these materials. Researchers within snow mechanics have used their own methods to evaluate material and mechanical data and no standardized methods exist. This makes it difficult to compare results from different investigations. According to Mellor (1977), no other material exists that under normal conditions display the enormous complexities found in snow. If general data, constitutive equations and failure criteria could be formulated for snow, they would probably cover most other materials as well (Mellor, 1977).

All early studies of mechanical properties of snow deals with natural snow. A report on strength and deformation behavior on machine-made snow based on field and laboratory tests at ICEHOTEL in Jukkasjärvi was published by Vikström and Bernspång (2002). This is the first study which was found regarding mechanical properties of machine-made snow. Generally buildings and constructions of snow seem to be built upon knowledge by experience, maybe as a consequence of lack of data of strength and mechanical properties of machine-made snow. To gain further knowledge on properties of machine-made snow as a material for constructions, field and laboratory tests were made to investigate properties of interest.

The importance of an accurate classification of snow used for different types of studies is emphazised by many researchers since snow of different types display a large variety of properties. The physical properties of snow are closely related to the mechanical properties. Changes in physical properties will likely change the mechanical properties as well. In 1954, the International Comission for Snow and Ice issued a classification for seasonal snow on the ground which has been updated during the years to meet requirements from various groups ranging from scientists to skiers (Fierz et al., 2009). This serves as a good basis for snow classification.

There are several different methods to classify snow. Within the automotive industry when classifying winter road conditions, non-contact sensors utilizing optical characteristics are commonly used (Casselgren et al. (2007b), Casselgren et al. (2016) and others). Non-contact methods for evaluating physical snow properties are advantageous since contact methods generally affect the grains and the structure and thus the properties might change as well. In this thesis, investigations aiming to classify snow in cross-country ski tracks were made using the optical sensor Road Eye which originally was developed for road conditions classification. Furthermore, laboratory studies were performed where bidirectional reflectance of snow with different liquid water contents were investigated using both the Road Eye ensor and a spectrometer.

Depending on the snow properties in a cross-country ski track, skis with different characteristics are desirable. To optimize the sliding friction the ski and the snow must be regarded as a system. As a basis it is important to understand the friction process between skis and snow. The properties of the skis, such as the span curve and the ski base surface topography, have to be adjusted to the prevailing snow conditions to achive the best sliding properties. The span curve of a ski tells a lot about the mechanical properties and is therefore important to measure and investigate. This was done using a digital instrument called Skiselector. The development within cross-country skiing has progressed in recent years. Skis with special features for different skiing styles, terrain and skills have been developed. To meet the demands from customers there is a need for knowing and controlling parameters of the skis which affect the performance. The performed studies in this thesis contribute to the understanding of parameters of cross-country skis that are important to take into account to optimize the sliding properties under different snow conditions.

Snow is the most important resource for winter tourism (Breiling and Charamza, 1999). However, global warming and climate change affect the length of the winter season and also the amount of natural snow (Bürki et al. (2003); Breiling (1998); Scott et al. (2003, 2006); Steiger and Abegg (2013) among many others). Currently the most common way for ski resorts to handle the warmer winters and to compensate for lack of natural snow is to increase the capacity of snow production (Steiger and Mayer, 2008). Storage of snow in insulated piles over the summer months has also become more common. The insulating material can be for instance bark, wood chips or large clothes of textile. Skogsberg (2005) published a thesis on snow storage for cooling purposes, which was one of the first published scientific studies on snow storage. There is so far little research done on snow storage. In this thesis knowledge on snow storage is reviewed and new results concerning melting losses of stored snow is presented. In addition, modelling and theoretical calculations of melt rate were performed and successively compared to practical studies. Factors affecting the melt rate is presented and suggestions on how to efficiently insulate snow to be stored.

1.2 Objective and scope

The objective with this research was to investigate different fields related to snow. In particular, machine-made snow for constructions, snow classification, snow storage and applications within skiing were studied.

Research topic 1: Mechanical properties of snow
Research questions: What are the strength properties for machine-made snow used for constructions? How do mechanical properties for machine-made snow differ from those of natural snow?
The aim was to:

- Review current state of the art of snow mechanics and snow properties.
- Investigate some basic material properties of machine-made snow by field and laboratory experiments.
- Compare and discuss differences between machine-made and natural snow.
- Provide recommendations for future work and investigations on machine-made snow.

This was done by a literature review regarding properties of natural snow and by summarizing current state of the art of machine-made snow for constructions. Furthermore field tests and laboratory experiments were performed.

Research topic 2: Snow classification
Research questions: How can essential properties of snow be classified using optical techniques? Can optical methods be used for snow classification in ski tracks and pistes?
The aim was to:

- Investigate if methods used for snow classification on roads are applicable also within other fields of snow research and in particular to characterize snow in ski tracks and pistes.
- Investigate how optical non-contact methods can be used to determine important snow characteristics.
- Find a method for snow classification in cross-country ski tracks.

This was done by applying optical techniques commonly used for road classification to classify snow in cross-country ski tracks. Spectral reflectance measurements were also used for laboratory experiments to classify snow of different types.

Research topic 3: Cross-country skiing
Research questions:
How can mechanical properties of cross-country skis be adapted to optimize sliding properties during different snow conditions?
The aim was to:

- Review and present current state of the art on sliding friction on snow.
- Determine mechanical properties of cross-country skis which are relvant for the sliding properties.
- Investigate differences between cross-country skis constructed for different snow conditions.
- Investigate how different ski base structures affect the sliding friction.

A literature review was done to summarize current state of the art on sliding friction on snow. This serves as a base for proper design of cross-country skis for different snow conditions. Mechanical properties of cross-country skis were analyzed using a digital instrument called Skiselector. Field tests were performed during different snow conditions.

Research topic 4: Snow and climate change
Research questions: How has climate change influenced winter activities? How has winter tourism adapted to lack of natural snow?
The aim was to:

- Review current state of the art of methods used to compensate for shorter winter seasons with less natural snow.
- Review current state of the art on snow storage.
- Study the efficency of different commonly used materials as thermal insulation on snow.
- Describe a method to theoretically esimate the melt rate in an insulated snow depot.

This was done by a literature review regarding snow production and snow storage. A theoretical method for estimating the volume of melted snow in insulated snow depots was developed. Practical experiments where the volume of melted snow was measured were compared to theoretical calculations. A survey was made on indoor skiing.

1.3 Thesis outline

This thesis consists of two parts. In Part I a brief overview of the current status of this field is presented. Chapter 2 of Part I consists of a short summary about natural snow, machine-made snow, snow production and snow mechanics. In Chapter 3, field and laboratory tests to investigate mechanical properties of machine-made snow are presented. Chapter 4 deals with classification of snow using optical non-contact methods. A new method to classify snow in ski tracks and pistes is presented. Research related to wintersports and in particular cross-country skiing is presented in Chapter 5. The effect of climate change on winter business industry is presented in Chapter 6, together with studies regarding snow storage. A discussion, including all the investigated fields of research in this thesis, is presented in Chapter 7. Finally, conclusions and suggested future research are presented in Chapter 8.

Part II consists of the papers covering the major results obtained in this thesis. In Paper A, in particular previous research on basic material properties of machine-made snow is summarized. In Paper B our laboratory studies on uniaxial strength and deformation properties of machine-made snow are presented. Spectral reflectance measurements to classify properties of snow are presented in Paper C. Moreover, in Paper D our investigations concerning cross-country skis and how the properties of skis are affected by temperature are presented. Finally, Paper E contains a description of the current knowledge on snow storage together with modelling and results from our new research on this subject.

Chapter 2

Snow

2.1 Snow

Consulting any encyclopedia for an elementary definition of snow the description is a precipitation consisting of ice crystals with different shape depending on temperature and humidity. Colbeck and Parssinen (1978) defines snow as a very porous material of ice and air which at temperatures above 0°C also contains liquid water. The ice is in the form of crystals and grains that are interconnected forming a texture which possesses some degree of strength (Colbeck and Parssinen, 1978). It is the characteristics of the bondings between grains that determines the strength of snow and accordingly much of the behavior of snow as a material (Shapiro et al., 1997).

2.2 Natural snow

Natural snow originates in the clouds where individual crystals nucleate, grow and fall down to the ground (Mellor, 1977). The shape of the snow crystals depend on humidity and temperature. If the humidity is low, simple shapes of snow crystals are formed, such as plates, columns and starlike crystals. Colbeck et.al. (1990) divided natural snow into different groups based on grain shape. One group consists of precipitation particles, which can be in the form of columns, needles, plates, stellar dendrites, irregular crystals, graupel, hail and ice pellets. The other basic classification groups are decomposed and fragmented precipitation particles which can be rounded grains, faceted crystals, depth-hoar, wet grains, feathery crystals, ice masses, crusts and surface deposits. There is a wide spectrum of snow qualities, from powder snow to ice.

Crystal shapes of snow formed under different conditions are shown in Figure 2.1 (Libbrecht, 2005). The growth of snow crystals depends on the incorporation of water molecules. When the humidity is low more simple shapes of snow crystals are formed whereas more complex shapes are formed at higher humidity. The water saturation line in Figure 2.1 corresponds to the super saturation of super cooled water, as might be found within a dense cloud. Temperature mainly determines whether snow crystals will grow into plates or columns, while higher super saturation produce more complex structures. Noteworthy is that the morphology switches with decreasing temperature; from plates at $T \approx -2°C$ to columns at $T \approx -5°C$ to plates at $T \approx -15°C$ to predominantly columns at $T < -30°C$.

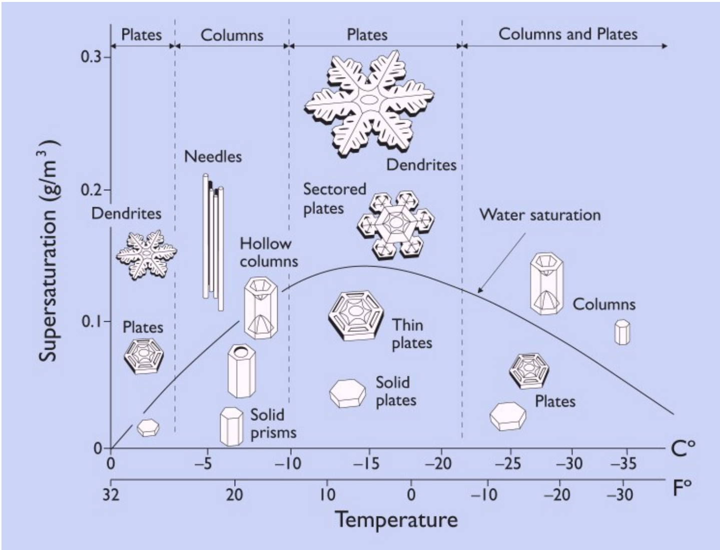

Figure 2.1: The snow crystal morphology diagram, showing different types of snow crystals that grow in air at atmospheric pressure, as a function of temperature and water vapour supersaturation relative to ice. (Figure from Libbrecht (2005)).

Compared to most other materials, snow always exist rather close to its melting temperature. This is one reason why snow crystals constantly change and thus also the snow properties. Snow crystals are transformed in size, shape and cohesion which affect the properties of the snow. This process is called metamorphism. Knowledge of snow type and a fundamental understanding of snow metamorphism is essential for snow research. Snow crystals falling to the ground will turn into more or less rounded grains, as shown in Figure 2.2. This process is called destructive metamorphism. Constructive metamorphism imply grain growth (Bader, 1962). Constructiv metamorphism is strongly dependent on density and is slow if the density is high and fast for densities lower than 300 kg/m^3.

As the shape of the crystals changes also other important material properties such as porosity and bulk density will change, which in turn will change the mechanical properties. Parameters affecting the metamorphism are for example time, temperature and wind. Other processes which transform snow are stress due to self-weight which causes volumetric strains resulting in higher density Kinosita (1957). Moreover, cycles between melting and re-freezing and intergranular bonds between grains which may develop or decay also transform the snow (Legagneux et al., 2004).

Natural snow on the ground gradually subsides by the load of its own weight and by successive snow falls (Kinosita, 1967). This is an example of slow compression of snow in the nature.

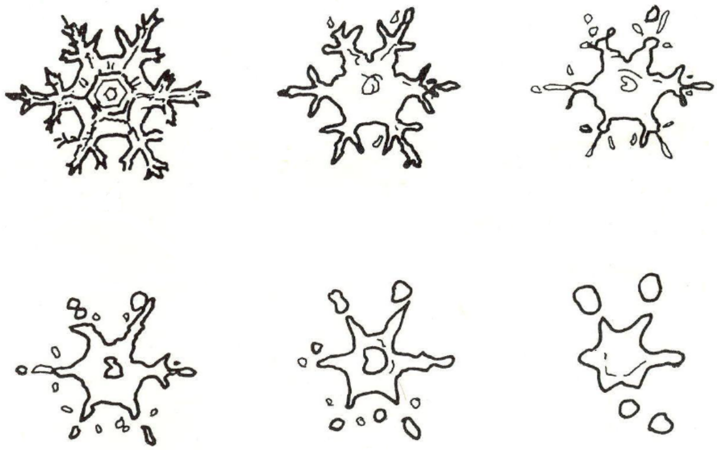

Figure 2.2: Destructive metamorphism, where the shape of snow crystals changes with time to eventually become rounded grains (Figure from Bader (1939)).

At glaciers snow is gradually transformed into ice. Avalanches is an example in the nature where compression of snow at a high rate cause fracture propagation and brittle deformation.

Bader (1962) considered snow as a non-Newtonian viscoelastic material where the viscous part comes from the permanent time-controlled deformation for very small stresses and the elastic part from the time-independent deformation component, recoverable upon stress release. Snow is non-Newtonian since the strain rate is not a linear function of stress. The strain rate increases faster than stress and at higher stresses the strain rate may become exceedingly rapid. In that case the material is considered plastic rather than viscous (Mellor, 1963).

2.3 Machine-made snow

Machine-made snow has become more common both for alpine skiing and cross-country skiing where it often is used to compensate for the lack of natural snow. It is also used as a construction material for buildings and formations of snow, such as ICEHOTEL in Jukkasjärvi, Sweden.

In contrast to natural snow where snowflakes are formed as a result of nucleation of tiny ice crystals in the clouds, machine-made snow is made out of water droplets. The round grains of machine-made snow give a structure which is close-packed and in general denser than natural snow which accordingly results in a higher density compared to natural snow. In a crystallographic point of view machine-made snow is already in an advanced state of metamorphism (Kuroiwa and Lachapelle, 1973).

Machine-made snow is known to be more durable and weather resistant than natural snow (ICEHOTEL, 2012). Ski areas can control the density of machine-made snow and thus produce very dense snow to increase the durability of the snow base (Scott et al., 2006). The higher density results in smaller snow depth requirements in pistes in order to assure good skiing conditions (Steiger and Mayer, 2008). According to the Swedish Organization for Ski Resorts, (SLAO, 2012), an amount of 10 cm of machine-made snow corresponds to about 40 cm of natural snow. Technically it is often easier to prepare good pistes using machine-made snow compared to natural snow (Kuroiwa and Lachapelle, 1973). Therefore, machine-made snow is often used to some extent although there is enough natural snow to construct more durable pistes and to enable better piste conditions throughout the season. Use of machine-made snow will also provide more equal and fair conditions for competing athletes. Yet another advantage with machine-made snow is the ability to produce a lot of snow during a short period of time, if the weather conditions are favourable and if there is access to water and energy.

Production of snow is currently the most common way for ski resorts to handle the warmer winters, to compensate for lack of natural snow and to satisfy the growing demand on winter tourism (Steiger, 2012). As examples from the European alp region, 36% of the total ski slope area in Switzerland consists of machine-made snow. In Austria the amount is about 60% whereas some Italian ski resorts have 100% machine-made snow (Steiger, 2012).

2.4 Production of machine-made snow

In a snow making machine water is cooled to above its freezing point and pumped under high pressure through nozzles. There are different kinds of snow making machines, handling different amounts of air and operating in different ways. The two major types of snow making machines are the fan-assisted machines, usually called snow guns, see Figure 2.3, and the high-pressure tower based machines which are called lances, see Figure 2.4.

Compressed air or electric fans are used to atomize the water into fine droplets in the continuous air flow and to disperse them over a wide area. The air-water mixture will need enough time to float in the cold air before it drops down to the ground in order to form snow. If the droplets don't freeze before hitting the ground the snow will be too wet. The higher above the ground the snow gun is placed, the longer time will the droplets have to cool and spread out before hitting the ground. Fan snow guns form snow in a pile 10-20 meters from the barrel outlet which later has to be shoveled out to the places where it is supposed to be used. Lances can be moved around easier and the snow can be produced directly at the place where it is supposed to be used, for example around a cross-country ski track. Lances can be as high as 10 meters above the ground. The injected water will nucleate and fall to the ground by its own weight, i.e. no fan is needed to blow out the snow.

Conditions of importance for snowmaking are seeding, air humidity, temperature, wind velocity and super cooling. Experiments have shown that small adjustments during manufacturing influence the properties of the snow produced (Chen and Kevorkian, 1971). With the proper size of droplets and cold enough air temperature, snow is still not formed unless the water droplets are seeded, which can be done using different techniques. Seeding means that nucleation sites are generated. Nucleation sites can be water molecules that coalesce alone, ions of fore example Ca^{2+} or Mg^{2+} or impurities like clay particles and organic matter. If the temperature is not low enough, which often means lower than -5°C, seeded materials are added to the water (Chen & Kevorikan, 1971). Seeding can also be done by a stream of compressed moist air directed against the water jet. It will cause the moisture content in the expanded air to freeze into tiny ice particles which act as seeds. For seeding with ice crystals to be effective the water has to be super cooled at the point of seeding. Super cooling occurs when the temperature of a liquid or a gas is lowered below its freezing point without becoming solid. If the water is above its freezing point, the ice seeds will melt as they come into contact with

Figure 2.3: Snow gun

Figure 2.4: Lance

the water droplets. When a water droplet super cools its temperature drops below 0°C before solidification takes place. The vapor pressure get lower and the heat transfer rate decreases. The droplet may then only partially freeze before it hits the ground and will then freeze to ice on the ground by conductive heat transfer. The size of the water droplets is also of importance for snow production. Too small water droplets may blow away by the wind and too big droplets may not freeze before they hit the ground. According to Chen and Kevorkian (1971), the optimal size of water droplets is between 200-700 μm during conditions typical for snow making.

Factors of importance during production of snow are air-water mixture, air humidity, pressure, temperature and wind velocity (Chen and Kevorkian, 1971). By optimizing these factors and adjusting the parameters, the desired quality of snow can be manufactured.

The ideal weather conditions for production of machine-made snow are a relative humidity lower than 80%, temperatures between -5 and -15°C and a light breeze (SLAO, 2012). As the humidity increases the threshold temperature for snow production decreases, i.e. lower temperatures are required.

2.5 Snow mechanics

Snow mechanics involves studies of forces and displacements in snow (Mellor, 1977). According to Cassel (1950), snow mechanics, like all new branches of science has developed its own terminology although there are similarities between soil mechanics and snow mechanics. Both diciplines originate from civil engineers who had to master the problems raised by both soil and snow. However, snow problems are limited to countries where snow is prevalent, whereas soil problems are wider with applications all over the world. However, the methods of research and the tools and instruments used are often the same. Mechanical properties of snow has been published by several researchers, for instance Salm (1982) who published a study on mechanical properties of natural snow, where the importance of different mechanical behaviour of dry and wet snow is highlighted. Another frequently cited paper by snow researchers dealing with mechanical properties of snow is a review of basic snow mechanics made by Mellor (1977). The review summarizes experiments performed with dry coherent snow performed as an effort to determine mechanical properties and to formulate manageable constitutive equations based on established continuum mechanics. The reason why quite few investigations are made regarding mechanical properties on snow is supposed to be due to the fact that stress, strain and time relations are so complicated since the properties of snow are so complex. The properties of snow are highly temperature sensitive as snow always exists rather close to it melting temperature. Snow exhibit nonlinear viscoelasticity and undergo large volumetric and deviatoric strains at typical load conditions. The high compressibility of snow makes the behavior much different from most solid and granular materials.

The mechanical properties of snow depend on its internal microstructure, density, temperature, wetness and rate of loading or deformation (Mellor (1963); Johnson and Schneebeli (1999) and others). Furthermore, Theile et al. (2009) mention mechanical processing and metamorphism. Determining mictrostructural and micromechanical parameters of snow require a determination of grain size and shape, intergrain bond size, shape and number of bonds, and a description of how chains of connected grins are located. The hardness is always directly connected to the bondings (Theile et al., 2009), which in turn affect most of the other mechanical properties. According to Mellor (1977) the internal microstructure forms the basis to kinematics, dynamics and energetics in snow. Mellor (1977) reported that field investigators and experimentalists have insufficient theoretical guidance when working on snow due to lack of well-structured experiments of snow properties while theoretical mechanicians also lack suitable comprehensive data on material properties. Therefore Mellor (1977) suggested simplified studies on mechanical properties of snow and theories which can be applied to boundary value problems.

2.6 ICEHOTEL

The machine-made snow used for the studies on mechanical properties in this thesis were produced at ICEHOTEL in Jukkasjärvi, a village in northern Sweden located about 200 km north of the arctic circle, see Figure 2.5. Machine-made snow is used since it is supposed to be more stable, reflect sunrays more effectively and melt more slowly (ICEHOTEL, 2012).

ICEHOTEL was founded in 1990 and was the first hotel built by snow and ice in the world. Each year an ice church and an ice bar are built in connection to the ice hotel, which have rooms and suites designed by artists and sculptors. Figure 2.6 shows a picture of the hotel entrance. The construction work at ICEHOTEL starts each year in November when some pre-fabricated blocks and arcs of snow and ice which have been stored in cold storage halls over the summer are used for constructing the first parts of the building. All blocks of ice used for the constructions are cut out from the nearby Torneriver, which also constitute the water supply for the snow production. In 2012, about 1000 tons of ice and 30 000 tons of machine-made snow was needed for the construction of ICEHOTEL (ICEHOTEL, 2012).

Figure 2.5: Location of ICEHOTEL, Jukkasjärvi.

Figure 2.6: ICEHOTEL, Jukkasjärvi. Photo: Big Ben Productions, ICEHOTEL.

Chapter 3

Field and laboratory investigations of machine-made snow

A survey was done to summarize previous research on machine-made snow as a material for constructions along with some basic field- and laboratory experiments. The results are presented in **Paper A**.

Physical and mechanical properties of different qualities of machine-made snow were investigated. Density measurements, uniaxial compressive tests and creep deformation tests were performed. The results were evaluated and compared to properties of natural snow. The test methods used for these experiments originate from research of ice where similar tests have been performed to evaluate mechanical properties. Results from uni-axial compressive tests are presented in **Paper B**.

Experiments where four point loading was applied on beams of machine-made snow were also performed to study ultimate load, bending strength and creep deformation. The method and results are presented in this chapter.

3.1 Material and methods

Material

Samples for field tests were taken out from different walls of ICEHOTEL in the middle of April 2012, the days after the hotel was closed for the season. Specimens were taken out from one wall which had been exposed to sunshine during the season, from one wall mostly located in the shade and from the inside of the building.

The laboratory investigations performed at Luleå University of Technology (LTU) were carried out on test specimens consisting of two different qualitites of machine-made snow. After the machine-made snow was produced, it was turned over twice with a snow blower and then put in rectangular molds of dimension $1.2 \times 0.8 \times 2$ m^3 where it was let to freeze. The conditions during snow production and the time period of storage affect the quality of the snow. The rectangular blocks of machine-made which were used for the tests were stored in climate chambers underneath diffusion proof plastic covers at temperatures between approximately -5°C and -10°C. The qualities used for the laboratory tests were fine grained snow, Figure 3.1, and coarse grained snow, Figure 3.2.

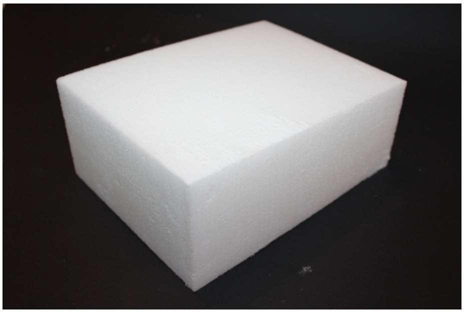

Figure 3.1: Sample of fine grained machine-made snow.

Figure 3.2: Sample of coarse grained machine-made snow.

The grain structure of the respective snow quality was studied by illuminating slices of snow using backlight projection. The slices were about 1 cm thick and the illumination enabled studies of the structures.

The density of all specimens used for the investigations were determined by weighing each specimen before the tests and dividing the weight by the initial volume.

Compressive tests

Test specimens for field tests were drilled out from the walls of ICEHOTEL. The drill used was a circular drill connected to an electrically driven drilling machine as shown in Figure 3.3. The diameter of the samples was 6.5 cm and the initial length was 15 cm. These specimens were used for uniaxial compressive tests, which were carried out in a nearby cold storage hall with a temperature between -4 and -5°C. The tests were performed at different constant deformation rates. The experimental setup for the compressive tests performed at ICEHOTEL is shown in Figure 3.4. The compressive test machine used for the tests at ICEHOTEL allowed deformation rates between 0.5 mm/min up to 5 mm/min to be used. The resistive force as a function of time was recorded for each test using the software EasyView.

Compressive tests were also performed in a climate chamber at Luleå University of Technology (LTU). Specimens were drilled out as shown in Figure 3.5 and then sawed into equal lengths using a mire box, see Figure 3.6. The initial dimensions of the specimens were the same as for the tests at ICEHOTEL, i.e. diameter 6.5 cm and initial length 15 cm.

The compressive tests were performed with an air-hydraulic type apparatus at deformation rates between 0.5 mm/min and 40 mm/min. The test temperature was $-10°$C. The resistive force versus longitudinal displacement was recorded for each test using the software Easy View. A test specimen from a laboratory test is shown in Figure 3.7.

Four-point load tests on beams

Tests using three or four point loaded beams are commonly used methods to measure flexural strength and effective modulus (also called apparent elastic modulus) for ice (Schwarz et al., 1981). The same method was used for load and creep tests with beams of the fine grained and coarse grained structure of machine-made snow. The tests were performed in a climate chamber at LTU at a temperature of $-13°$C.

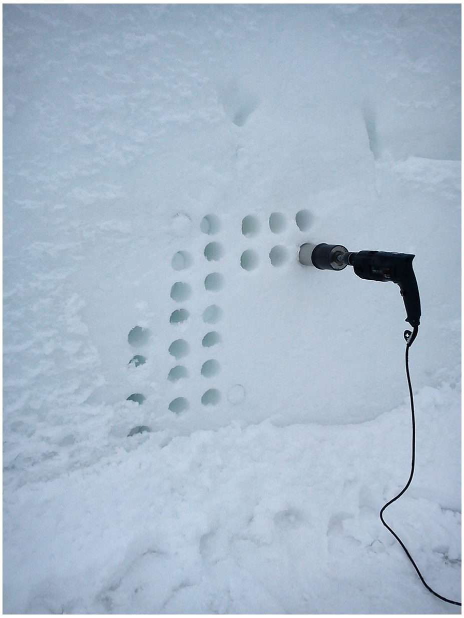

Figure 3.3: Snow specimens were dilled out using a hand held drill at ICEHOTEL in Jukkasjärvi, April, 2012.

Figure 3.4: Experimental setup for the uniaxial compressive tests at ICEHOTEL.

Figure 3.5: Specimen preparation at LTU.

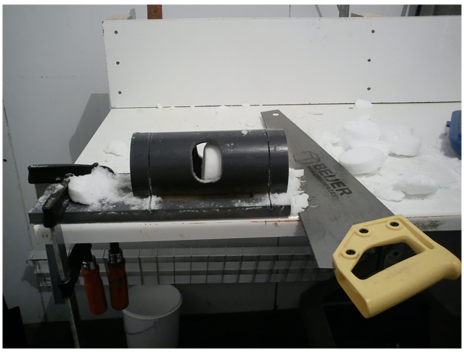

Figure 3.6: Specimen preparation at LTU.

Figure 3.7: Test specimen used for uniaxial compressive test at LTU.

Four-point loading is generally a preferable method for load tests with beams of materials which are inhomogeneous or brittle. By distributing the load over a larger area central stress concentrations which arise during three point loading are eliminated which gives more accurate test results. A special test equipment was constructed for the experiments where snow beams were loaded at four points. Load distribution plates were used to distribute the applied load over a larger area in order to eliminate impressions or deformations of the contact area. A construction drawing of the test equipment is shown in Figure 3.8.

The dimensions of the snow beams were $100 \times 200 \times 1000$ m^3. The beams were oriented in the test equipment so that the width of the beams was loaded by the two lower load distribution plates, which were placed at a reciprocal distance of 300 mm from each other according to Figure 3.8. The dimension of each load distribution plate was 100×240 mm^2 which gives a load surface area of 100×200 mm^2 on each of the four positions on the snow beams where the load was distributed. Two of the load distribution plates were provided with flexible roller bearings (in Figure 3.8 the upper right one and the lower left one) and the other two with a fixed semicircle bearing. The diametrically opposed placement of the different load distribution plates with one flexible and one fixed bearing at both the upper and lower positions enabled the beam to deform longitudinally during loading. The bearings and the load distribution plates are shown in Figures 3.9 and 3.10. The surfaces of the load distribution plates were coated with abrasive paper in order to prevent the beams from sliding or slipping off the plates.

The test equipment used for the load tests are shown in Figures 3.11. The load was hydraulically applied on the two lower load distribution plates and continuously recorded with a load cell. The deformation of each beam was measured with electronic length gauges on three

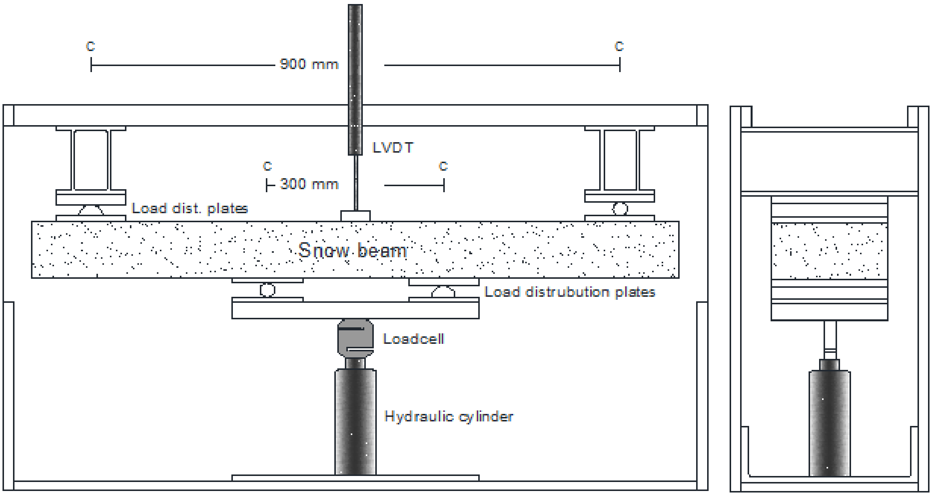

Figure 3.8: Construction drawing of the test equipment used for the four-point load tests.

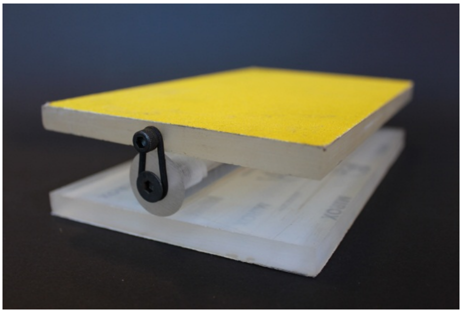

Figure 3.9: Load distribution plate with flexible bearing.

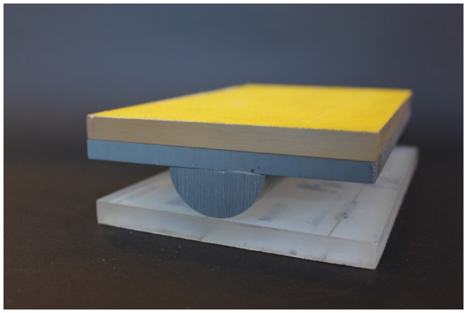

Figure 3.10: Load distribution plate with fixed bearing.

sections, one in the mid-section of the beam and the other two in immediate connection to each of the two lower load distribution plates. The accuracy of the length gauges was ±0.001 mm and of the load cell ±0.1 N. The measured values were registered with a data logger every minute. The range of measurement was limited to the maximum piston stroke for the hydraulic cylinder, which corresponds to about 70 mm.

Creep tests

Creep tests on beams of both fine grained and coarse grained snow were performed at four different loads; 300 N, 500 N, 750 N and 1000 N. The lowest load corresponds to about 20% of

Figure 3.11: Test equipment used for the four point load test.

an assumed maximum ultimate load based on a few initial trial experiments. The highest load corresponds to about 75% of the assumed ultimate load. The tests temperature was −13°C. The load was successively applied with a loading rate of about 20 N/min. The creep deformation as a function of time was registered until either failure occurred or when the maximum possible deformation in the experimental setup was reached.

3.2 Investigated properties

Compressive strength

When specimens of machine-made snow are compressed at a constant deformation rate the general behavior is a stress-strain curve where the stress increases linearly and quite rapidly until a peak value, F_{peak} is reached. After this point the stress value only slightly increases or flatten out. A typical stress-strain curve from a uniaxial compressive test at a deformation rate of 5 mm/min is shown in Figure 3.12.

The compressive strength, σ, for each snow sample was calculated as the ratio between the peak force, F_{peak}, and the initial cross sectional area, A, i.e:

$$\sigma = \frac{F_{peak}}{A}. \tag{3.2.1}$$

Young's modulus

Young's modulus, E_{tan}, is commonly known as the tensile modulus. It is a measure of the stiffness and is defined as the ratio of the difference in uniaxial stress, $\Delta\sigma$, and uniaxial strain, $\Delta\epsilon$, according to Equation (3.2.2). The modulus is generally evaluated based on results from tensile tests. In this study E_{tan} was evaluated based on results from the uniaxial compression

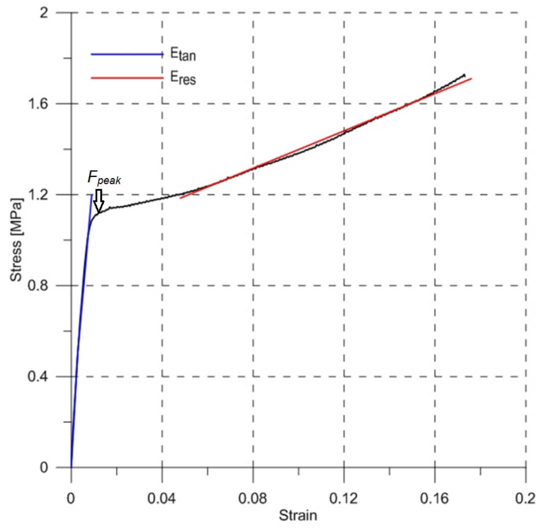

Figure 3.12: Typical stress-strain curve from a compressive test performed at LTU with homogeneous fine grained artificial snow at a deformation rate of 5 mm/min. Young's modulus is evaluated as the tangent modulus to the blue line and the residual modulus is evaluated as the tangent to the red line.

$$E_{tan} = \frac{\Delta\sigma}{\Delta\epsilon} \tag{3.2.2}$$

Residual modulus

The stage after the peak point was defined as the post-load process and corresponds to the residual strength. Unless the test specimen will crack or fail during the loadtest an almost linear relationship between $\Delta\sigma$ and $\Delta\epsilon$ can be observed after the peak point as seen in Figure 3.12. The residual value, E_{res}, was evaluated as the ratio between $\Delta\sigma$ and $\Delta\epsilon$ at this stage, i.e:

$$E_{res} = \frac{\Delta\sigma}{\Delta\epsilon}. \tag{3.2.3}$$

Effective modulus and creep deformation

When beams of ice are used for three or four point load tests the effective modulus, or also called apparent elastic modulus, E, can be calculated according to Equation (3.2.4) (Schwarz et al., 1981).

$$E = \frac{3}{2w}[(\frac{l-2c}{t})^3]\frac{c}{l-2c}\frac{F}{\delta}. \tag{3.2.4}$$

c is the distance between the center of the beam and the load distribution plates, w is the width of the beam, t is the thickness of the beam, l is the length of the beam, F is the applied load to the beam and δ is the corresponding beam deflection. This equation is based on beam theory assuming linear elastic behavior. However, ice and snow are inhomogeneous, anisotropic and viscoelastic materials, but so far no theory is completely developed to evaluate effective modulus and flexural strength for these materials (Schwarz et al., 1981). According to Schwarz et al. (1981), Equation (3.2.4) is an acceptable approximation for determining index values, which can be applied to compare mechanical properties.

The effective modulus, E, for the studied beams of machine-made snow was evaluated based on data from the creep deformation tests. No elastic deflections were however registered during these tests. The load was applied in steps of 20 N/min and the beams were plastically deformed when the full load was applied. The deflections one hour after the start of the test were instead measured and used as values for δ in Equation (3.2.4) together with the total applied load, F. In this way index values could be evaluated which could be used to compare the beams of the different qualities of machine-made snow.

Ultimate load

Ultimate load tests were performed as four point load tests on 12 beams of both the snow of coarse grained structure and with the fine grained structure. The beams were successively loaded at a test temperature of −13°C where 20 N was applied every minute until failure occurred. The maximum applied load at failure was registered for each tested beam, which was considered to constitute the ultimate load. Some beams of the coarse grained snow structure were so brittle that fracture or breakage occurred already in the initial phase of the loading process or when the beams were put into the load test equipment.

Bending strength

The bending strength, σ_b, was evaluated using the results from the ultimate load tests according to Equation (3.2.5). F_{max} is the maximum force required to break the beam, c is the distance between the center of the beam and the load distribution plates, w is the width of the beam and t is the thickness of the beam (Schwarz et al., 1981).

$$\sigma_b = 3 * \frac{F_{max} c}{w t^2}. \tag{3.2.5}$$

The equation is based on beam theory for four point loading of ice. Keep in mind that the results should be considered as index values.

3.3 Results from field and laboratory tests

Snow structure

Illuminating slices of snow by using backlight projection was used to study the structures of the different snow qualities used for the laboratory tests. An image of the coarse grained structure is shown in Figure 3.13 where a wide range of grain sizes and shapes were observed. There were also clusters of ice of various size which can be seen as the dark grey areas in Figure 3.13. An image of the fine grained structure is shown in Figure 3.14. Equally sized small grains and a homogeneous structure were observed.

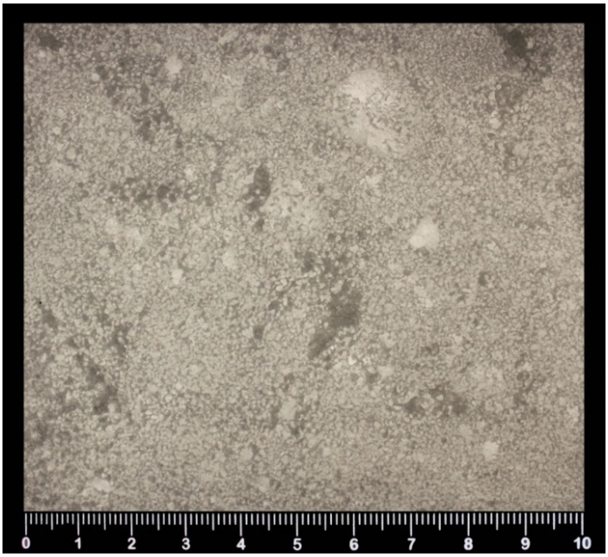

Figure 3.13: Machine-made snow with a coarse grained structure and clusters of ice.

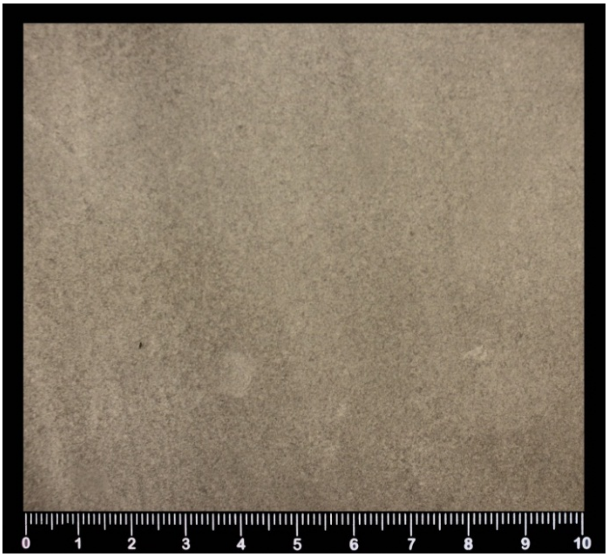

Figure 3.14: Machine-made snow with a fine grained and homogeneous structure.

Density

The densities for the specimens of the different qualities of machine-made snow used for the uniaxial compressive tests are presented in Figure 3.15. The densities for the specimens of fine grained machine-made snow were in the range between 510-560 kg/m^3 and the densities for the specimens of coarse grained machine-made snow were in the range 550-700 kg/m^3. The densities from the specimens from the walls of ICEHOTEL were in general in the range 550-650 kg/m^3. The wall exposed to sunshine had the most scattered values. The highest average density was from specimens from the wall which had been in the shade during the season. (The values are based on data from 33 samples of fine grained snow, 46 samples of coarse grained snow, 32 samples from the wall in the shade and 30 samples from the wall exposed to sunshine and the inside wall, respectively.)

The block of fine grained machine-made snow had lower density compared to the block of coarse grained machine-made snow and the density for the samples from the different walls of ICEHOTEL. The fine grained machine-made snow was produced with an improved snowmaking technique and during conditions which were more advantageous for snowmaking. The air-water ratio was adjusted so that less water was supplied and during less humid climate conditions compared to the previous production method, when the coarse grained snow was produced. The coarse grained snow was also stored for a longer period of time before testing.

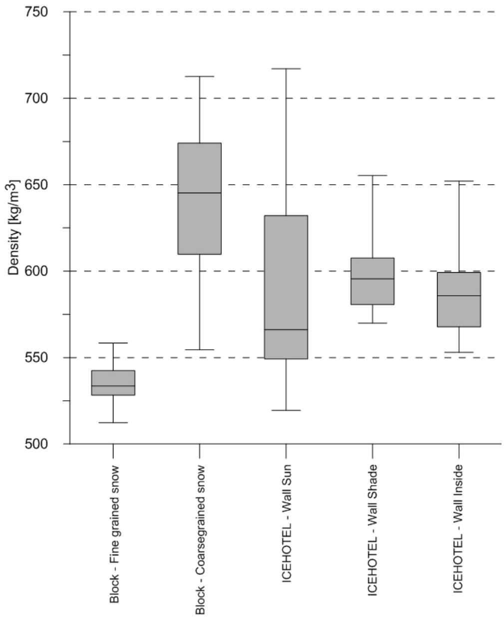

Figure 3.15: Boxplot showing density for all samples used in the compressive tests.

Compressive strength

The specimens taken out from the walls at ICEHOTEL were quite wet, especially those taken out from the outside walls. After preparation, the specimens were re-frozen in the cold storage hall where the compressive tests were performed. These specimens had a coarse grained structure were clusters of ice formed during re-frezing which made the samples brittle. The results from the performed uniaxial compressive tests at both ICEHOTEL and LTU showed an increasing compressive strength with increasing density. The compressive strength versus density for specimens of machine-made snow from different locations is shown in Figure 3.16. These tests were performed at a deformation rate of 1.5 mm/min which is considered to be a slow rate of deformation. The compressive strength appears to increase almost linearly with increasing density for the specimens tested at equal deformation rate.

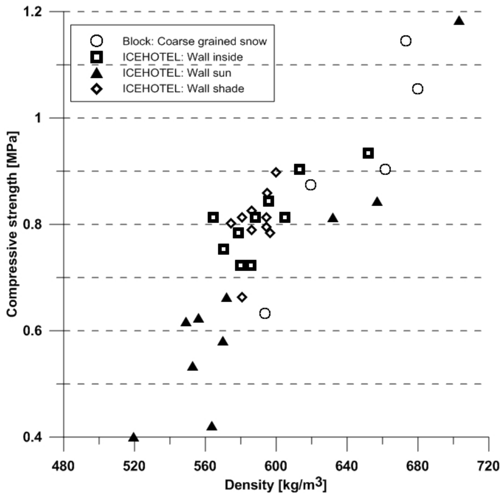

Figure 3.16: Compressive strength versus density for specimens of machine-made snow tested a deformation rate of 1.5 mm/min.

Not all performed compressive tests with snow of high density resulted in high values of compressive strength. In some cases test specimens of high density contained clusters of ice which acted as initiation points for cracks to form. Those specimens showed instead a brittle behavior and cracked in the initial state of the loading process also at low deformation rates. If a crack formed without complete breakage of the specimen, the recorded resistive force suddenly dropped but continued to rise again with a slope similar the one before the crack was formed. It was not possible to calculate a value of the compressive strength for the specimens which failed completely during the initial loading process and results from those tests are hence not included in the graphs. The compressive strength versus strain rate for the specimens of fine grained snow is shown in Figure 3.17. A break point between plastic behavior and brittle fracture of the specimens could be observed. The critical deformation rate was about 27 mm/min, corresponding to a strain rate of about 0.003 s^{-1}. The specimens appear to deform plastically up this critical deformation rate, after which the deformation behavior seemed to change and become brittle or destructive.

A corresponding critical value of the deformation rate was not observed from compressive tests using the coarse grained type of snow. Those specimens were very brittle and failure occurred at random deformation rates.

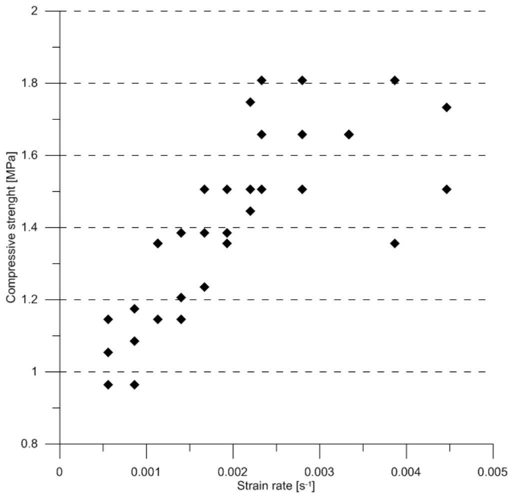

Figure 3.17: Compressive strength versus strain rate for samples of fine grained machine-made snow. The breakpoint between plastic and destructive behavior occurs at about 0.003 s^{-1}.

Young's modulus

Young's modulus versus density evaluated from compressive tests performed at deformation rates of 1.5 mm/min and 5 mm/min from different walls of ICEHOTEL are shown in Figure 3.18. The results indicate that Young's modulus increase with increasing density. Results for the fine grained and coarse grained snow are shown in **Paper B**. No clear connection between Young's modulus and density was observed for these tests.

Residual strength

The increased size of the cross sectional area during compression was not taken into account when calculating the residual strength. This is however assumed to have a minor influence on the results. The increased stress which is observed after the peak point, see Figure 3.12, is supposed to be due to an increase of relative density as the compression of the specimens proceeds. This results in a harder more close-packed structure. The results from the evaluations of the residual modulus, E_{res}, showed no correlation between residual modulus and density of the snow samples. The residual modulus seemed to increase with increasing strain rate as can be seen in Figure 3.19 where the residual modulus for samples of fine grained snow has been

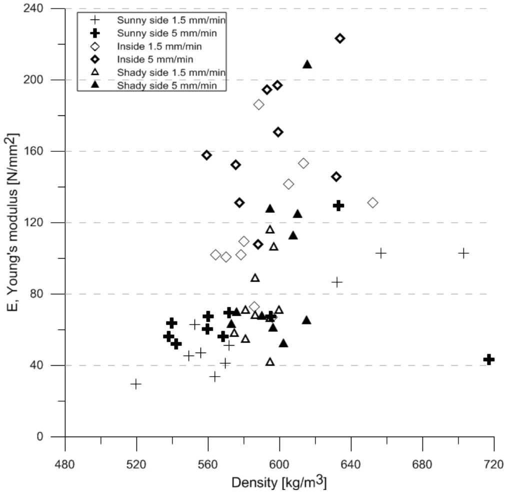

Figure 3.18: Young's modulus versus density machine-made snow from different walls of ICEHOTEL tested at deformation rates of 1.5 mm/min and 5 mm/min.

evaluated. The residual modulus for samples from different walls of ICEHOTEL showed similar values for tests carried out at the same strain rate. As for the compressive strength, the residual strength increased with increasing strain rate up to about 0.003 s^{-1}, where a drop in strength with incresed strain rate was observed.

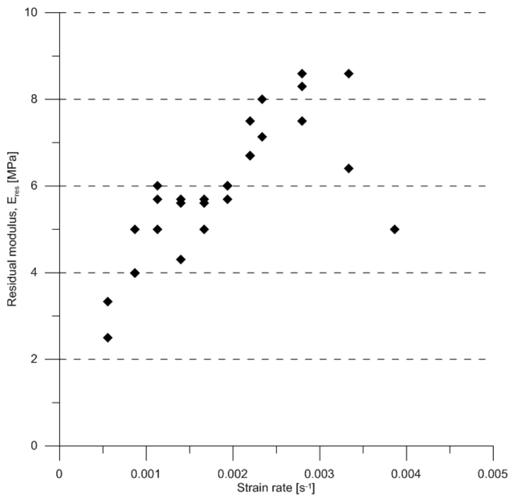

Figure 3.19: Residual modulus versus strain rate for samples of fine grained machine-made snow.

Effective modulus

The effective modulus was calculated according to Equation (3.2.4), based on the results from the four point load tests with beams. The deformation rate was much faster for the beams of fine grained snow compared to the beams of coarse grained snow. The results from the evaluations of the effective modulus, E, showed that the values of fine grained snow ranged between 21-43 MPa and of coarse grained snow between 45-257 MPa. These values should, as mentioned, be regarded as index values, which can be used to compare results from equally performed tests to each other.

The deflections of the beams of fine grained and coarse grained snow for the respective test loads are shown in Table 3.1. The values correspond to deflections measured one hour after the initial load was applied.

Table 3.1: Deflection of beams one hour after the initial load was applied. The load was applied stepwise with 20 N/min.

Total load [N]	Fine grained machine-made snow. Deflection [mm]	Coarse grained machine-made snow. Deflection [mm]
1000	16.5	1.4
750	12.9	2.5
500	4.2	1.4
300	2.5	2.4

Ultimate load and bending strength

The deformation behavior during the four point load tests varied for the two different snow qualities tested. The beams of coarse grained snow were brittle and the total deformations were quite small while the beams of fine grained snow showed a plastic deformation behavior where the total deformation of each beam was large. The ultimate tensile load ranged between 0.4-1.4 kN for beams of coarse grained snow, i.e. highly scattered values. More uniform and repeatable results were achieved with the beams of fine grained snow where the ultimate tensile load was between 1.2-1.4 kN.

The bending strength was evaluated based on the results from the ultimate load tests. As the maximum applied load at failure had a wide range of values for the coarse grained snow, also the bending strength were spread over a wide range, 180-630 MPa. The bending strength for fine grained snow was between 540-630 MPa, i.e in general higher compared to the coarse grained snow although the total deformations of the beams of fine grained snow were much larger. The values should be regarded as index values which are representative for comparing results from similar tests of bending strength.

Creep deformation

Results from the creep tests performed with the beams of coarse grained machine-made snow are shown in Figure 3.20. The creep deformation rate was low also when the highest load level, about 75% of the approximate ultimate load, was applied. The brittle structure of the coarse grained snow made the sample preparation difficult, some beams cracked already during test preparation or in the initial phase of the load process, before the desired load was reached. The beams which did not fail before the maximum desired load was appled had a varying creep deformation rate independent of magnitude of the applied load.

Results from the creep tests with beams of fine grained machine-made snow are shown in Figure 3.21. Note the difference in time scale on the x-axis in the respective figure. The creep deformation rate increased with increasing applied load and was considerably higher compared to the beams of coarse grained snow. The radius of curvature of the tested beams reached maximum possible in the load test equipment without any failure of the beams.

The importance of slow load application rate in order to permit large plastic deformations without failure of the beams was observed during the experiments. Applying the load fast would most likely have resulted in failure also for the beams of fine grained snow instead of the large plastic deformations which now was observed.

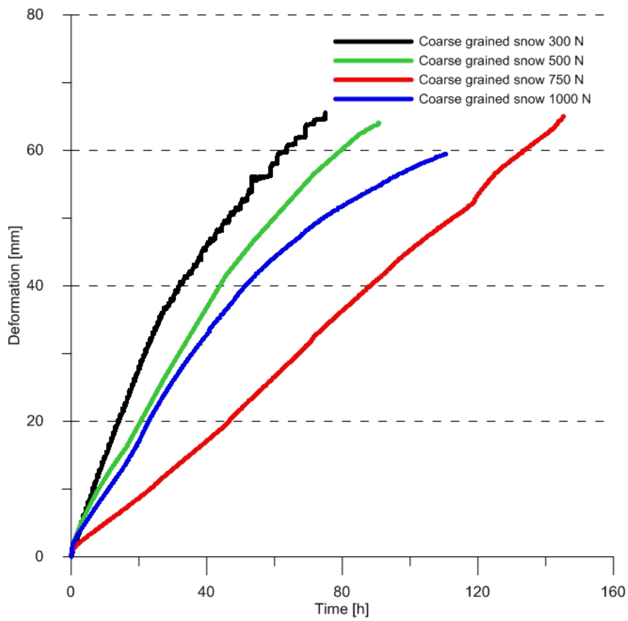

Figure 3.20: Creep deformation versus time for beams of old and coarse grained machine-made snow.

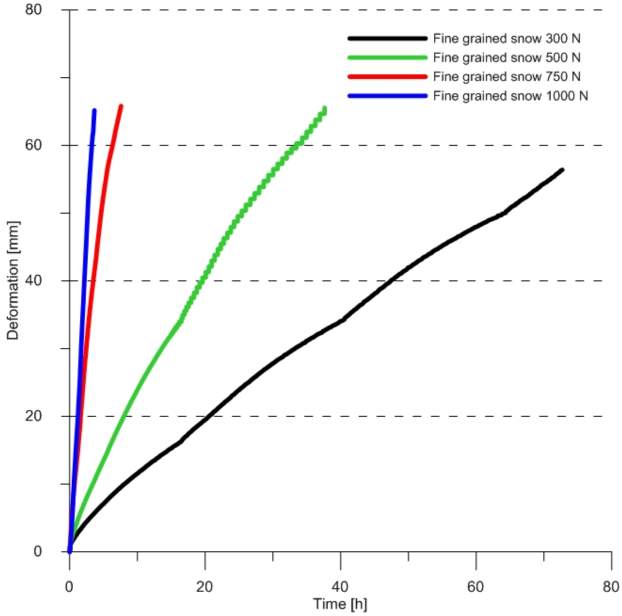

Figure 3.21: Creep deformation versus time for beams of fine grained machine-made snow.

CHAPTER 4

Classification of snow

4.1 Classification of snow

Classification of snow are of interest within avalance research (De Quervain et al., 1973), climatologoly (Sturm et al., 1995), hydrology (Colbeck, 1986), snow mechanics (Shapiro et al., 1997), skiing (Nolin and Daly, 2006), vehicle mobility on snow and road safety (Casselgren et al., 2012a) among many others.

Classification of snow has developed throughout the years. As new instruments and methods have been developed, the conditions for evaluating properties have improved. Pielmeier and Schneebeli (2003) describes the acvancement of descriptive methods, optical methods, morphological methods, mechanical methods and textural methods from the 18th century until today. Depending on the property that are supposed to be characterized, different methods are used.

In 1954, the International Commission of Snow and Ice issued a classification for snow on the ground, The International Classification for Seasonal Snow on the Ground, which has been updated throughout the years to meet requirements from various groups ranging from scientists to skiers (Fierz et al., 2009). The physical characteristics of snow depend on texture, temperature and the relative proportions of its constituents. The system which was developed defines symbols, units and terms for primary physical characteristics of deposited snow, i.e. density, grain shape, grain size, liquid water content, strength, hardness and snow temperature.

For the grain shape classification, a quite extensive table has been put together with both morphological and process-oriented classifications including additional information on physical processes and strength (Fierz et al., 2009). The precipitation particles are divided into different subclasses based on the shape. Within each class there are also subclasses according to size. The physical properties of the subclasses are also described. The International Classification for Seasonal Snow on the Ground provides a base for describing the type of snow used in experimental studies, where it is of importance to classify snow in order to accurately compare and evaluate different research results.

In addition to type of snow, grain structure and grain size also temperature, density, liquid water content and hardness are recommended to be determined when classifying snow. Temperature and density are easy to determine. Liquid water content can be determined using different techniques and instruments. Determining the dielectric constant is according to Denoth et al. (1984) the most efficient method, since the relationship between liquid water content, porosity and texture is well understood. The liquid water content can also be measured using optical methods as discussed in **Paper C**.

Hardness is generally measured by penetrating an object into the snow and recording the resistive force. Hardness measurements produce an index value which depends on the instrument used for the measurements (Fierz et al., 2009). The Rammsonde is a large-diameter penetrometer which is commonly used in the field, for example for avalanche hazad evaluation (Johnson and Schneebeli, 1999). There are also other penetrometers using cones or objects with a smaller diameter. The "SnowMicroPen" is a high resolution penetrometer which can be used both for field and laboratory tests to characterize different snow types (Schneebeli et al., 1999). The most simple method to determine hardness is the so called hand hardness test where the fist, four fingers, one finger, a pencil or a blade of a knife are pressed into the snow and correlated to a hardness scale.

4.2 Classification of snow using optical methods

In the International Classificatation for Seasonal Snow on the Ground, snow types are qualitiatively classified based on the shapes which are described. Arakawa et al. (2009) reported that qualitative determination of snow types may become subjective and suggest quantitative methods to evaluate snow properties. By utilizing optical methods parameters that reflect geometric characteristics and microstructure can be determined. Many important snow properties are directly correlated to the snow structure. Therefore it is advantageous with non-destructive methods for measuring snow properties, as the optical methods are.

Optical techniques for snow classification are generally based on albedo measurements. The albedo of a given wavelength, A_λ, is defined as the ratio of reflected radiation and incoming radiation (Sergent et al., 1993), i.e.

$$A_\lambda = \frac{Fr_\lambda}{Fi_\lambda}. \tag{4.2.1}$$

The albedo is in addition to wavelength also dependent on the degree of absorption, reflection and scattering. If the albedo equals to 1, all radiation is reflected, if the albedo equals to 0, no radiation is reflected. Snow and ice exhibit in general high albedo, i.e. a high degree of reflection in the visible region, but a low albedo, i.e. a high degree of absorption in the near-infrared (NIR) region. Casselgren et al. (2007a) and others reported that the NIR wavelength bands from 900 nm to 1600 nm are optimal to investigate the distinct absorption properties among different snow types.

Water, ice and snow absorb light differently in the NIR-region. Water has for example high absorption at approximately 1500 nm and 1900 nm (Jonsson, 2011). The reflectance in the range 750 nm to 1400 nm is to a large extent controlled by the snow grain size (Wiscombe and Warren, 1980).

The albedo is generally higher for new and fine grained snow but drops at all wavelengths as the snow ages and as the grain size increases (Warren, 1982). This is because a photon has a chance to become scattered when it crosses an air-ice interface, while it only has a chance of being absorbed if it pass through the ice. An increase in grain size causes an increase in path length that must be travelled through the ice between scattering opportunities (Warren, 1982). In addition to grain size, also impurity content, liquid water content and other physical properties affect the albedo of snow.

Radiation reaching a surface of any material will either be transmitted, reflected or absorbed. Reflections that undergo scattering are called diffuse reflections wheras unscattered reflections are called specular reflections. The scattering in the backward direction is higher from a rough surface compared to a smooth surface as shown in Figure 4.1. For opaque materials, the majority of light is transformed into reflected light and absorbed light. When an observer views an illuminated surface, what it sees is the reflected light, i.e. the light that is reflected towards the observer from all visible surface regions (Wynn, 2000).

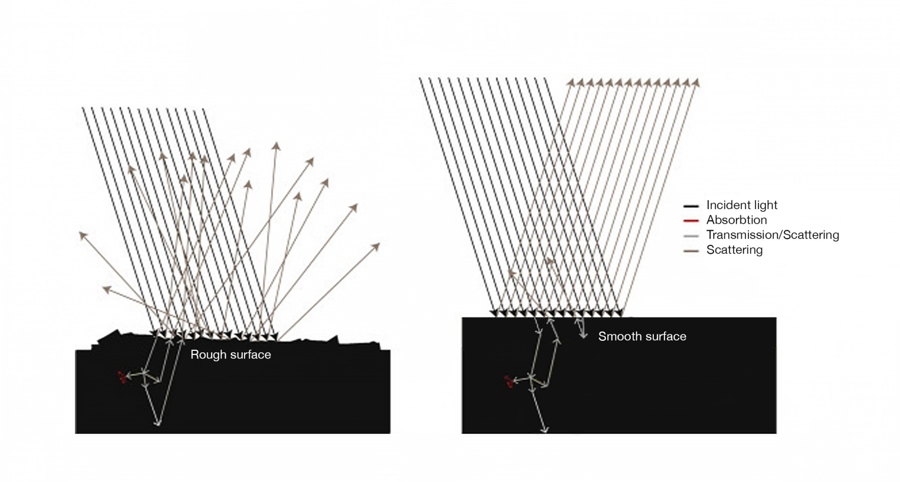

Figure 4.1: Scattering of light on a rough and smooth surface respectively. (Figure from: Casselgren et al. (2016)).

Optical methods used for snow measurements are based on the fact that incident radiation is partly back-scattered and partly absorbed (Sergent et al., 1993; Casselgren et al., 2016). By measuring reflected light from snow surfaces in the backward scattering direction different types of snow can be classified.

For snow surfaces most of the scattering is a result of change in direction of the light beam upon transmission through the ice grains, rather than reflection (Bohren and Barkstrom, 1974). Snow, ice, soils and other materials in the nature are composed of granular elements with scales comparable to the wavelength of incident radiation (Coakley, 2003). Nearby grains may reflect light differently. Moreover, photons scattered form the sample may be re-scattered from neighboring particles prior to reaching the instrument detector. Thus, reflected radiances from a surface of a granular material adopt an angular pattern that has suffered multiple scattering. Reflectance from such surfaces can be modelled using radiative transfer theory.

Radiative transfer theory is based on the physical phenomenon of energy transfer in the form of electromagnetic radiation. The propagation of radiation through a medium is affected by absorption, emission and scattering. The radiative transfer equation (RTE) describes these interactions mathematically. The RTE can be rewritten in different forms but the meaning of the equation is simply stated that as a beam travels, it loses energy through absorption, it gains energy by emission and it redistributes energy by scattering. Hapke (1981) used the fundamental principles of radiative transfer theory to derive an equation for the bidirectional reflectance distribution function (BRDF). The BRDF describes how much light that is reflected in a specific direction. The incident light is directional in the BRDF. The degree of reflectance (or transmission) depends on the viewer and light position relative to the surface normal and tangent. The BRDF is a function of incoming direction of radiation and the outgoing (view) direction relative to a local orientation at the light interaction point as shown in Figure 4.2.

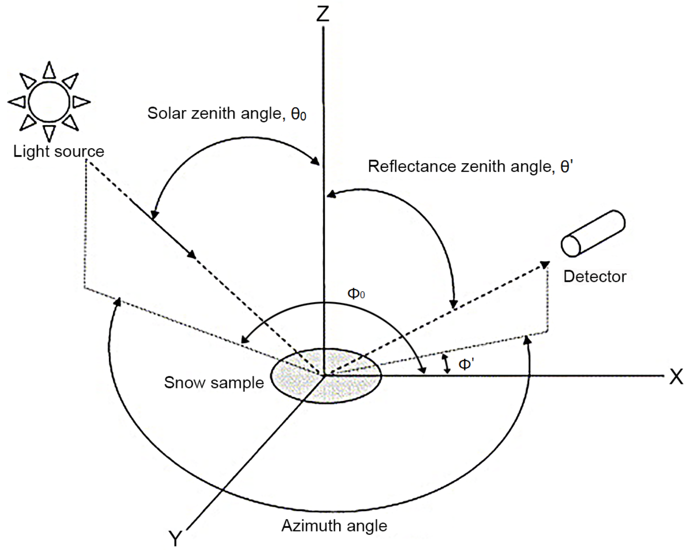

Figure 4.2: Illumination and viewing angles to describe the bidirectional reflectance distribution function (BRDF). (Figure from:Chappell et al. (2006)).

Furthermore, when light interacts with a surface, different wavelengths may be absorbed, reflected and transmitted to varying degree depending on the physical properties of the material. Thus, the BRDF is also a function of wave length. The bidirectional reflectance has units sr^{-1} and is defined as the ratio of the reflected intensity along a direction toward the detector to the incident intensity according to the Equation 4.2.2 (Warren, 1982; Xie et al., 2006).

$$R_\lambda(\theta_0, \theta', \phi_o, \phi') = \frac{dFr(\theta', \phi', \lambda)}{dFi(\theta_0, \phi_0, \lambda)}, \tag{4.2.2}$$

where θ_0 is the solar zenith angle, ϕ_0 is the azimuth angle, θ' is the reflectance zenith angle and ϕ' is the reflection animuth angle, λ is the wave length, Fi is the incident flux and Fr is the reflected intensity (Warren, 1982; Steffen, 1987). The relative azimuth angle, θ' in Figure 4.2, is $0°$ for an observer facing the light source and $180°$ in the opposite direction, a convention often used for radiative transfer in the atmosphere (Coakley, 2003). The azimuth angle is further $0°$

if only back-scattered light is analyzed. By measuring in the incident plane, the azimuth angle can be ignored in BRDF and RTE models, which simplifies the solution to the RTE.

The albedo is calculated as the integral of R over all reflection angles, or simply stated the ratio of the reflected radiation and the incoming radiation as described in Equation (4.2.1).

The BRDF provides essential information on optical properties of snow such as the grain size, grain structure, surface roughness as well as age and type of snow (Xie et al. (2006); Eppanapelli et al. (2016); Steffen (1987) and others). One viewing angle in the backward or specular direction can be considered to classify different snow types based on the absorption, for example age of snow and surface roughness. However, the angular distribution of reflected light needs to be measured when investigating physical properties of snow, such as grain size, grain structure and microstructure. The BRDF can be modelled using a solver based on RTE to obtain single scattering albedo, asymmetry parameter and a phase function which are related to the absorption, scattering behavior and angular distribution of light.

4.3 Spectral reflectance measurements to investigate liquid water content in snow

The physical properties of dry snow are closely related to the density whereas the properties of wet snow change both with density and liquid water content (Davis et al., 1987). Any change in liquid water content may rapidly change the structure, texture and most other properties as well (Denoth et al., 1984). Measurement techniques to determine liquid water content should preferably be rapid and non-destructive.

Spectral reflectance from snow samples of different known liquid water contents were measured using two different optical systems; a near-infrared (NIR) spectrometer and a Road Eye sensor. This study is presented in **Paper C**. The measurements were carried out in climate chamber at LTU. The results were coupled to field measurements where the Road Eye was used to classify snow in a cross-country ski track.

Material and method

Snow samples

The freezing of water containing a solute is fundamentally different from the freezing of pure water (Klein-Paste and Wåhlin, 2013). In pure water the freezing starts at 0°C. When adding foreign molecules the freezing point changes. In order to obtain samples of snow with a known amount of liquid, a NaCl-solution was prepared with a concentration of 16.2-16.5%, corresponding to the liquid concentration of a NaCl-solution at the experiment temperature (Weast et al., 1988), which was -12 to -12.5°C (Weast et al., 1988).

Five samples with solution contents according to Table 4.1 were studied. The dry density of each snow sample was approximately 460 kg/m^3. The desired amount of solution and snow were mixed thoroughly by shaking a contaniner with the mixture for one minute. Each sample was the compressed into a container with dimensions 24x16x13 cm^3, see Figure 4.3.

Table 4.1: Snow samples used for laboratory experiment to study liquid water content.

Sample number	Solution content [wt%]	Absolute amount [g/m^3]
I	0	0
II	5	0.024
III	10	0.051
IV	15	0.081
V	20	0.115

Figure 4.3: Snow sample used for the spectral reflectance measurements.

Spectrometer measurements

The experimental setup for the laboratory experiments is shown in Figure 4.4.

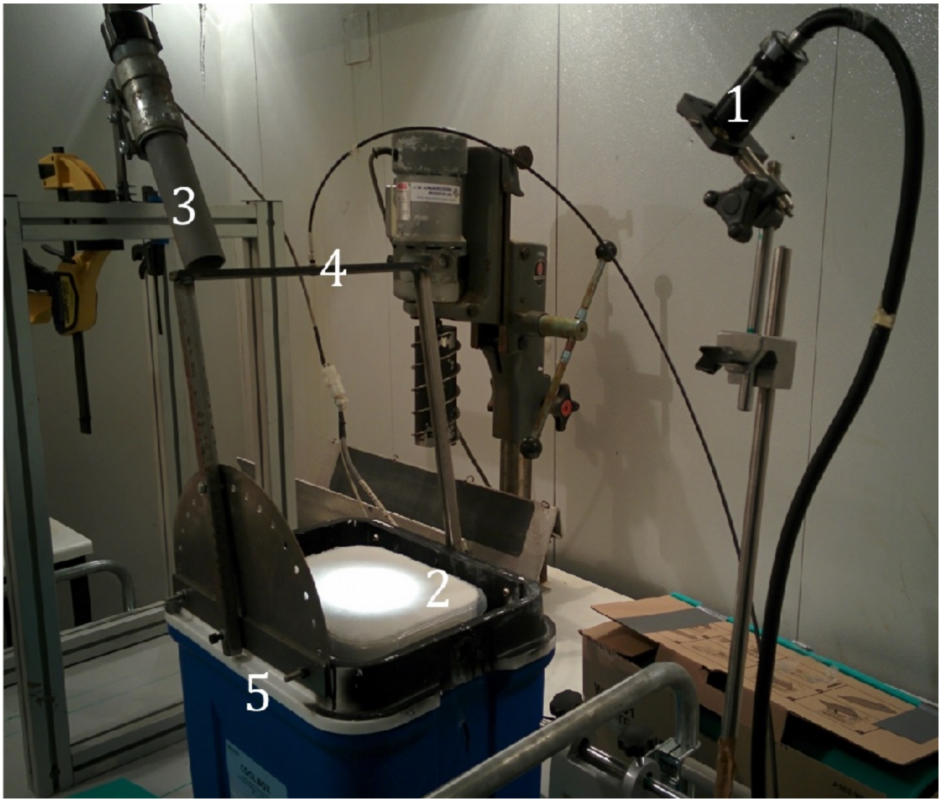

Figure 4.4: Experimental setup for the laboratory tests. 1 = Light source, 2 = Snow sample, 3 = Road Eye sensor, 4 = NIR Spectrometer probe, 5 = Cooling box.

The NIR InGaAs spectrometer (STE-DWARF-Star NIR) with an extra aperture (field of view 3°, ∅5 mm) was used to measure the reflectance in the wavelength region 920 nm to 1650 nm with spectral resolution of 1.75 nm. The illumination source was a 250 W EKE quartz halogen lamp (Dolan-Jenner MI-150 Fiber Optic Illuminator) coupled with a ∅6.35 mm fiber optic light guide. The output was focussed by a focussing assembly (focal length 40 mm, ∅30 mm). The illumination beam was collimated and formed a bright spot of ∅13 cm on the center of the surface of the snow sample, see Figure 4.4. The spectrometer probe was mounted on a radial arm (4 in Figure 4.4) 33 cm from the surface of the snow sample. The spectrometer measured reflected light within an area of ∅1.73 cm. The height of the snow sample was adjusted so that the surface of the snow and the center of rotation were in the same plane. The spectormeter measured reflected light with a solid angle in the same plane as the incidence, i.e. in the incidence direction, global normal of the snow and the detector direction were in the same plane.

Reference measurements were performed using a sample consisting of compacted $BaSo_4$ powder on a matte black painted plexiglass. The reflected light from the $BaSo_4$ surface was recorded, $\mathrm{B}(\lambda)$. A dark measurement was also recorded by turning the illumination source off, $\mathrm{D}(\lambda)$. This was done to calculate normalized values of the reflectance according to Equation (4.3.1).

$$R = \frac{\mathrm{R}(\lambda) - \mathrm{D}(\lambda)}{\mathrm{R}(\lambda) - \mathrm{B}(\lambda)} \tag{4.3.1}$$

Reflectance measurements were performed at viewing zenith angle and 60°. The illumination was kept at 45° for all measurements. Three measurement runs were performed for each of the studied snow samples to determine the bidirectional reflectance, R, i.e.

$$\begin{aligned} &\mathrm{R}_k^i(\lambda), \\ &\qquad \lambda = 921.5\ \text{nm}, 902.25\ \text{nm}, ..., 1651\ \text{nm}, \\ &\qquad i = 1, 2, 3, \\ &\qquad k = \text{snow type}. \end{aligned} \tag{4.3.2}$$

The mean value of the bidirectional reflectance (M) was then calculated as

$$\mathrm{M}_k(\lambda) = \sum_{i=1}^{3} \frac{\mathrm{R}_k^i(\lambda)}{3}. \tag{4.3.3}$$

Road Eye

The Road Eye is a non-contact sensor developed for road surface classification. The sensor consists of three laser diodes with the wave lengths, $\lambda_1 = 980$ nm, $\lambda_2 = 1310$ nm and $\lambda_3 = 1550$ nm. There is one photo detector for each wavelength measuring the reflected light. The sensor was placed at an angle of 60° and a distance of 90 cm from the snow as shown in Figure 4.4.

The laser diodes and the detector were placed at the same angle, i.e. back-scattered radiation was measured. Data from the measurements were logged with a computer. Five measurements were obtained at each wavelength and mean reflectance values (I) were calculated as:

$$\mathrm{I}_k(\lambda) = \sum_{i=1}^{5} \frac{\mathrm{R}_k^i(\lambda)}{5}. \tag{4.3.4}$$

The normalized reflectance values (M) were then calculated by dividing the mean reflectance values by the reference reflectance from the $BaSo_4$ sample, i.e.

$$\mathrm{M}_k(\lambda) = \frac{\mathrm{I}_k(\lambda)}{\mathrm{B}(\lambda)}. \tag{4.3.5}$$

Normalized difference water index (NDWI)

The normalized difference water index (NDWI) is an index commonly applied in remote sensing to describe changes in liquid water content (Gao, 1996; McFeeters, 1996; Xu, 2006). The index was calculated for the snow samples investigated in this study and also for measurements where the Road Eye sensor was used to classify snow in cross-country ski tracks, as will be further described in Section 4.5. The NDWI ranges between -1 and 1 and was calculated as

$$\mathrm{NDWI} = \frac{\mathrm{M}_k(980\ , 60°) - \mathrm{M}_k(1310\ , 60°)}{\mathrm{M}_k(980\ , 60°) + \mathrm{M}_k(1310\ , 60°)}, \tag{4.3.6}$$

where the mean reflectance values for the wavelengths 980 nm and 1310 nm were chosen in this study.

Results from the laboratory tests

The mean value of the bidirectional reflectance, $M_k(\lambda)$, measured with spectrometer at 60° is shown in Figure 4.5. As observed in the figure, three regions of wavelengths can be defined. These regions are WR1: 960 nm - 1100 nm, WR2: 1200 - 1400 nm and WR3:1480 - 1600 nm. Part of the reflectance spectrum in WR3 is zoomed in for better resolution.

The different snow samples exhibit similar spectral features but the degree of absorption varies due to the different liquid water content. As shown in Figure 4.5, the samples were separated at the wavelengths 980 nm, 1310 nm and 1550 nm, which were the wavelengths recorded with the Road Eye sensor. The samples were most clearly separated at 1310 nm, but 980 nm and 1550 nm can be considered as a reference, since the reflective properties at these wavelengths are prominently higher and lower respectively.

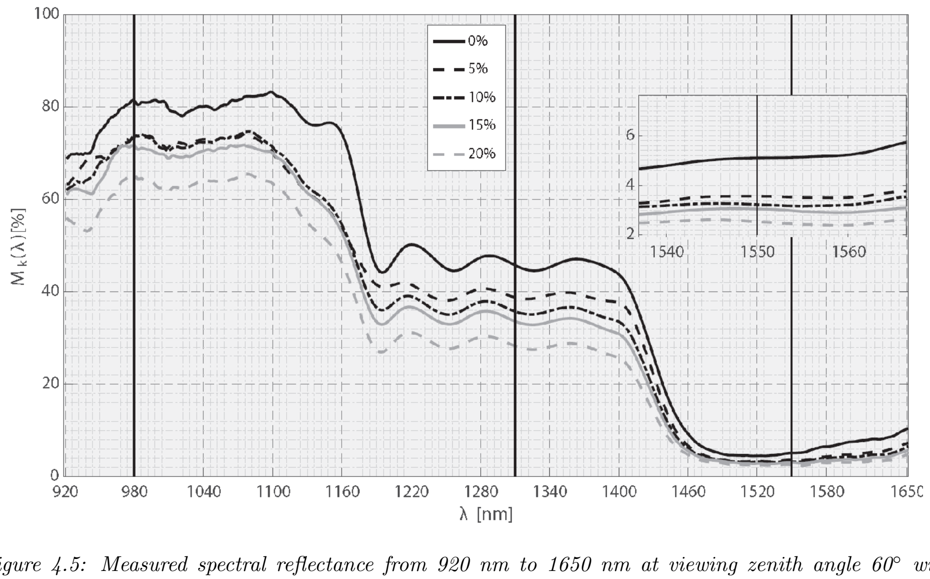

Figure 4.5: Measured spectral reflectance from 920 nm to 1650 nm at viewing zenith angle 60° with illumination source fixed at 45°.

The mean bidirectional reflectance, $M_k(\lambda)$, for both the spectrometer and Road Eye measurements is shown in Figure 4.6. An approximately linear relation between liquid water content and reflective properties was observed. As the water content in the snow increased the reflection decreased. Comparing the results from the spectrometer with the Road Eye further shows that the reflectance was higher using the Road Eye sensor. However, both sensors captured the linearity between water content and reflective properties of snow. A decrease in reflectance was observed as the amount of water increased.

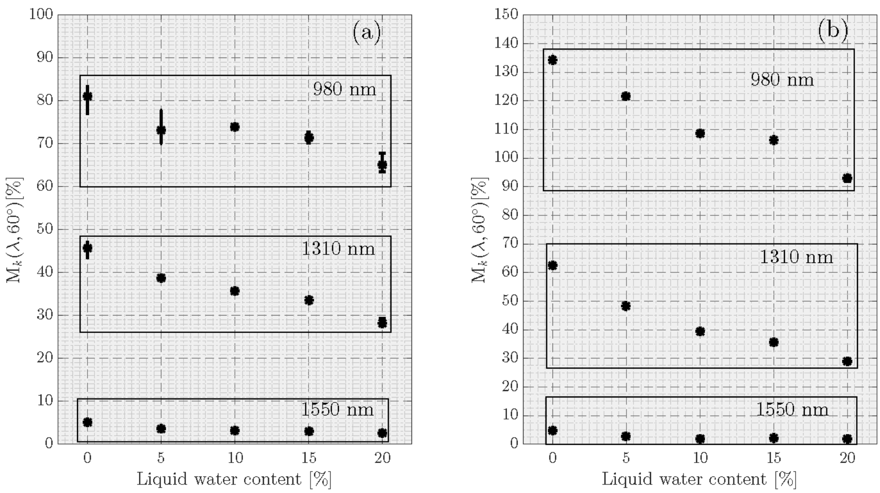

Figure 4.6: Comparison between the bidirectional reflectance at wavelengths 980 nm, 1310 nm and 1550 nm for the spectrometer measurements and the Road Eye sensor.

The measured reflectance at the wavelengths 980 nm and 1310 nm were used to calculate the NDWI values. These were related to the liquid water content for the investigated snow samples as shown in Figure 4.7. A linear regression line and the associated regression equation is also shown in the figures. It was observed that the NDWI is sensitive to liquid water content. NDWI values were also calculated from three different Road Eye measurements in a cross-country ski track, as further detailed in **Paper C** and in Chapter 4.5. The water content in the snow during these three measurements was estimated using the regression equation. The results show that the water content in the snow was approximately 19% in the morning on April 13, rising to about 20% in the afternoon the same day. The water content on April 16 was approximately 4% according to these calculations.

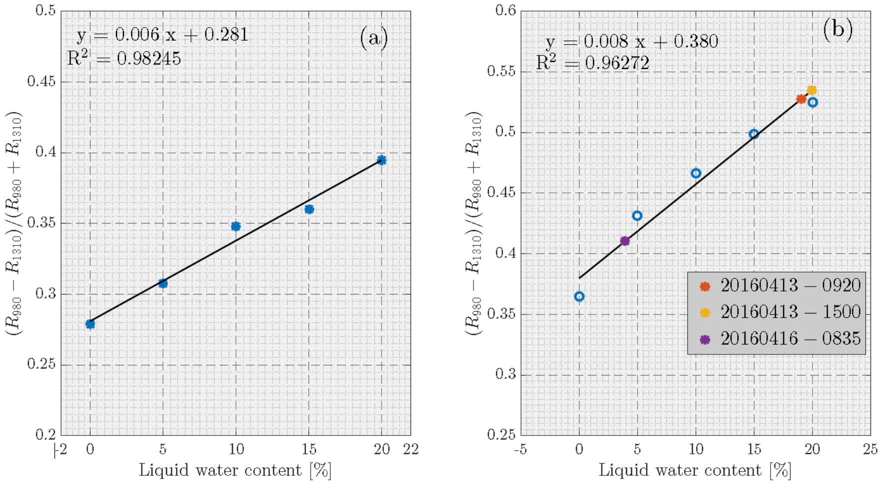

Figure 4.7: A linear regression plot for the measured bidirectional reflectance from both the sensors. Figure (a) shows the calculated NDWI values from the measurements performed using the spectrometer. Figure (b) shows the calculated NDWI values from the measurements recorded using the Road Eye sensor.

4.4 Classification of snow in ski tracks and pistes

Classification of snow in ski tracks and pistes are of importance for ski resorts, skiers and ski technicians. Customers demand a snow report, which in addition to snow depth should include type of snow in pistes and tracks. Furthermore, the snow conditions constitute the base when choosing skis for optimum performance, which is particularly important in competitive skiing, as further discussed in **Chapter 5**.

Fresh, cold and machine-made snow in ski tracks and pistes are called aggressive, since usually needles or dendrites are formed. The sharp edges of this type of snow erode the ski base and increase the friction coefficient (Colbeck, 1993). When snow has aged enough, sharp edges and faceted crystals are usually eliminated.

Skiers and ski technicians use different test protocols to log snow and weather conditions during ski tests and ski wax tests. Properties commonly determined during ski tests performed by the major ski wax companies are shown in Table 4.2 (SWIX, 2016). This classification seem to be based on the guidelines in the International Classification for Seasonal Snow on the Ground. Measuring these properties generally constitute the base for choice of skis, topography and ski wax.

Table 4.2: Test protocol for determining snow properties in ski tracks and pistes.

Machine-made snow	Natural snow	Grain size
A1 Falling new snow	FN Falling new snow	G0 0-0.2 mm Extra fine
A2 New snow	NS New snow	G1 0.2-0.5 mm Very fine
A3 Irregular new snow	IN Irregular new snow	G2 0.5-1.0 mm Fine
A4 Irregular transformed snow	IT Irregular transformed snow	G3 1.0-2.0 mm Medium fine
A5 Transformed snow	TR Transformed snow	G5 > 4.0 mm Very coarse
Liquid water content	**Hardness of ski track**	**Characteristics of ski track**
XDS Dry	H1 Very soft	T1 Partly clean
W1 Humid	H2 Soft	T2 Clean
W2 Wet	H3 Medium hard	
W3 Very wet	H4 Hard	D1 Partly dirty
W4 Slush	H5 Very hard	D2 Dirty
	H6 Ice	

4.5 Using Road Eye to classify snow in ski tracks

There are several non-contact sensors utilizing optical characteristics to make classificiations of different road conditions (Casselgren et al., 2007a,b, 2016). Since various surfaces have characteristic spectra, it is possible to detect changes in road conditions by exploring the difference in reflection (Casselgren et al., 2007a, 2012a). Investigations have shown that it is possible to detect changes in roughness of asphalt and to detect snow and ice (Jonsson, 2011; Casselgren et al., 2007b,a). Moreover, different types of ice has been classified (Casselgren et al., 2012b).

By utilizing the same technique as used for road classification, a new method to classify snow in ski tracks and pistes was developed. The idea behind the new method was to use the Road Eye sensor, described in Section 4.3, to determine different snow properties. The sensor operates at 12 V and has a sampling rate of 30 measurements/sec. This enables snow classification measurements at high speeds. For road classification, the sensor has been successfully used in speeds up to 120 km/h (Casselgren et al., 2012b). For the field test meaurements in a ski track, a motor cycle battery was used as power supply, which together with the computer was placed inside a sledge. The sensor was placed inside a tube to protect it from splash and dirt. The tube with the sensor was then mounted on the sledge so that the viewing angle was about 45°, see Figure 4.8.

Figure 4.8: Sledge used for classification of snow in a cross-country ski track using the Road Eye sensor.

In addition, a GPS was attached to the sledge and connected to the computer, registering the exact route for the ski track measurements, see Figure 4.9. The GPS coordinates from the measurements on the different dates are shown in the figure. (The interruptions in the blue line is because the GPS lost contact with the satellites during the measurements on April 15.)

Measurements were performed on April 13 - 16, 2016. The measurements on April 13 and 14 were performed during similar snow conditions. Based on the classification in Table 4.2 the grain sizes ranged between medium-fine to very coarse. The snow temperature was between -1 – -3°C. The days prior to these measurements, the weather was warm and the snow was classified as slush according to the definitions in Table 4.2, which according to the International Classification of Seasonal Snow on the Groud corresponds to a water content above 15%. The track was groomed in the morning on these days. On the 15th of April the track was not groomed, the snow was coarse grained and the snow temperature was between -0.5 – -1.5°C. The measurements on the 16th of April were performed on newly fallen snow with a temperature of around 0 °C and an air temperature of +2°C. The track had not been groomed and the snow was fine grained.

Data from the measurements were analyzed and the reflectance are shown in Figures 4.10 and 4.11. A linear relationship is observed among the measurements where the snow in the track was coarse grained whereas the fine grained new snow is clearly separated from the other measurements. Ongoing work is in progress to further develop this method. Measurements will be performed during multiple snow and track conditions to identify different snow properties. As shown in Figure 4.7, some of the results were compared to the laboratory investigations, as further discussed in **Paper C**.

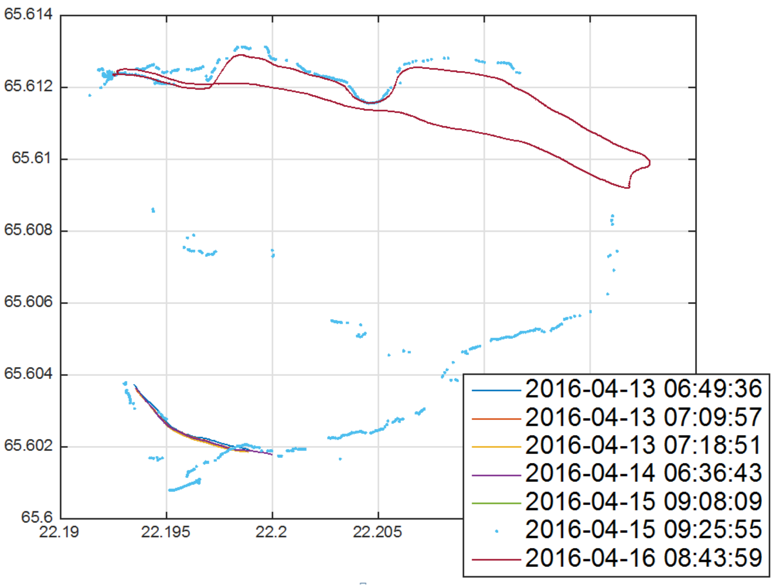

Figure 4.9: Routes for snow classification in cross-country ski tracks. The values on the x and y axis shows the GPS coordinates in latitide and longitude respectively.

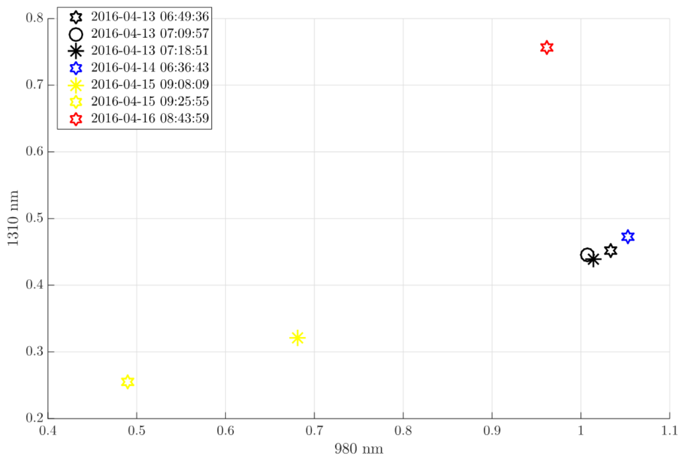

Figure 4.10: Spectral reflectance at wavelengths 1310 nm vs. 980 nm.

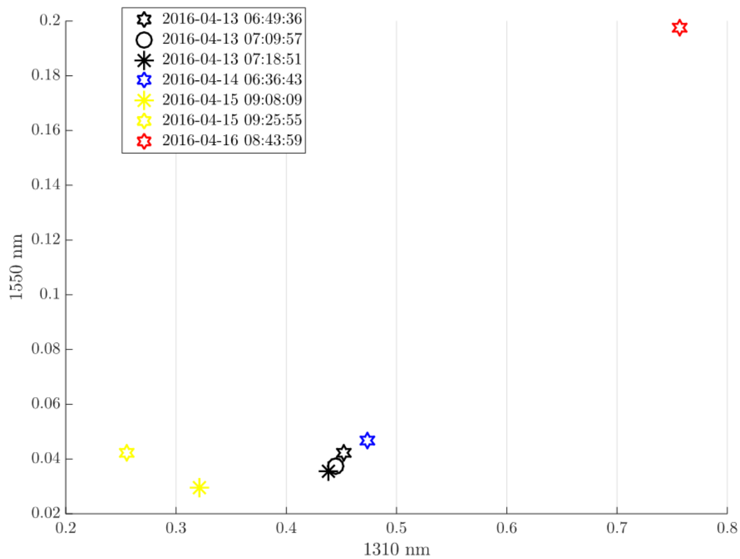

Figure 4.11: Spectral reflectance at wavelengths 1550 nm vs. 1310 nm.

Chapter 5

Snow and Winter Sports

5.1 Snow and winter sports

An important field of snow research is that related to winter sports. In this thesis, the focus has been some aspects related to cross-country skiing. A widely researched subject is the sliding friction of skis on snow, which is of great importance in competitive cross-country skiing. This has been studied by different researchers and there are also some earlier PhD theses written on this subject namely *"Some Aspects of Ski Base Sliding Friction and Ski Base Structure"* by Moldestad (1999), *"Sliding Friction of Polyethylene on Snow and Ice"* by Bäurle (2006), *"Interfacial Kinetic Ski Friction"* by Kuzmin (2010) and *"Technical aspects to improve performance in cross-country skiing"* by Breitschädel (2014).

In competitive skiing it is of outermost importance to choose skis and adapt the topography of the ski base surface to the prevailing snow conditions in order to minimize the sliding friction. The ski and the snow must be regarded as a system to fully understand the process of sliding friction. Sliding on snow is more complicated than sliding on ice since there is such a large variety of possible snow conditions, which have a direct influence on the sliding properties (Colbeck, 1988). This further illustrate the importance of classifying snow in ski tracks, as discussed in Chapter 4.

In addition to tribological aspects of the interface between skis and snow, also the mechanical properties of the skis will affect the overall performance. Important properties of cross country skis can be divided into those related to:

1. the ski itself, i.e. the mechanical properties and the span curve,
2. the ski base material and its texture,
3. the surface finish and the ski wax.

These three topics are addressed in the following chapters. Section 5.2 consists of a summary of sliding friction during skiing. The theories presented lie behind the understanding of the overall performance for cross-country skis. Parameters influencing the sliding friction is presented in Section 5.3. In Section 5.4 properties of cross country skis are discussed which was a subject of research in this thesis. Mechanical properties of cross-country skis were studied by measuring span curves. Results from some of the studies are presented in **Paper D**. The ski base material and the topography of the ski base surface are discussed in Section 5.5, together with some new results from field tests. Previous studies regarding ski wax is briefly summarized in Section 5.6.

5.2 Sliding friction during skiing

Friction between the skis and snow depend on a number of different factors, some of them are attributed to the ski and others to the snow. There are also factors such as load and velocity, which influence the sliding friction, but which neither is associated with the ski nor the snow.

According to Moldestad (1999), the friction against a moving skier consists of two parts; the air resistance and the ski base sliding friction. The ski base sliding friction can be expressed as:

$$F = \mu N, \tag{5.2.1}$$

where F is the ski base sliding friction, μ is the sliding friction coefficient and N the normal load from the skier. Depending on the weather and snow conditions, there are different types of friction mechanisms that dominate (Buhl et al., 2001). The total friction force, F_{TOT}, is the sum of the individual friction components, which according to Glenne (1987) consists of four parts:

1. dry friction
2. wet friction
3. compaction resistance
4. impact resistance.

Other authors makes a similar division of the friction components, see e.g. Bäurle (2006); Sturesson (2008) and others. Kuroiwa (1977) divided the friction of skis on snow into two parts, the resistance due to ploughing and compression of snow and the friction between the ski base and the snow. In order to exclude the resistive force due to ploughing when aiming to study only the kinetic friction between the ski base and the snow, Kuroiwa (1977) performed measurements in order to determine how much the snow was compressed by the ski.

The low sliding friction between skis and snow can be explained with lubrication by a thin water film which is generated during skiing (Moldestad, 1999). The water film is essential for sliding to occur (Colbeck, 1992; Colbeck and Perovich, 2004). At low temperatures the water film is positive for the sliding friction since it separates the two surfaces (Glenne, 1987). According to Glenne (1987), there are four sources which can generate the water film; the free water content in the snow or the ambient interstitial snow moisture, the percolation of snow moisture to the sliding interface due to snow compaction, melt water due to high local pressures and melt water due to frictional heat.

For snow temperatures close to 0°C, and when the liquid water content in the snow is high, the water film may instead increase the sliding friction due to suction or viscous drag (Moldestad, 1999; Colbeck, 1992; Colbeck and Perovich, 2004). The water film is further discussed in Section 5.3.

Dry sliding friction

Dry friction is friction between two bodies in the absence of a lubricating film (Bäurle et al., 2007). If the lubricating film is insufficient, then friction arises from elastic and plastic deformation of the surfaces and from very thin lubricating water films exhibiting high friction due to shearing (Kuroiwa, 1977; Colbeck, 1992).

Dry sliding friction or adhesion occurs at low temperatures (Kuroiwa, 1977). During these conditions snow crystals are sharp, hard and abrasive. Dry friction is also called adhesive friction and involves adhesive shearing or ploughing at the junction of crystal asperities (Glenne, 1987; Sturesson, 2008). The critical parameters for snow friction at low temperatures are the material hardness, the surface smoothness and the heat conductivity (Glenne, 1987). To optimize the sliding properties the ski base surface should be smooth and hard. When the snow is gradually compressed it will yield until the snow stress equals the bearing stress. At this point the dry contact area, A_C, can be described as

$$A_C = \frac{P_N}{\sigma_C}, \tag{5.2.2}$$

where P_N is the normal load and σ_C is the unconfined compressive strength of the snow. The unconfined compressive strength is according to Glenne (1987) a function of the snow density, grain size, grain structure and temperature.

The total dry friction force, F_{DRY}, can according to Glenne (1987) be described as

$$F_{DRY} = A_C\tau = \frac{P_N}{\sigma_C}\tau = \mu_{dry}P_N, \tag{5.2.3}$$

where τ is the shear strength of the softer material and the dry friction coefficient, μ_{dry}, is the ratio between the shear strength and the compressive strength.

For ski base sliding friction the real contact area, A_R, is of interest which is further discussed in Section 5.3. Sturesson (2008) describes the contact area and the total dry friction force in a slightly different way, taking the hardness of the material into account. If two surfaces of the same roughness are pressed together they collide at many microscopically small contact spots, a_i (Sturesson, 2008). The real contact area is considered as the sum of all these spots:

$$A_R = \sum_{i=1}^{n} a_i. \tag{5.2.4}$$

Each spot carries the load f_i, and the sum of the load on all contact spots constitutes the total normal load P_N;

$$P_N = \sum_{i=1}^{n} f_i. \tag{5.2.5}$$

To be able to carry the load, the contact spots will either increase in number or in area. The hardness of the material, H, the size of the contact spots, a_i, and the load f_i is related to each other as:

$$a_i = \frac{f_i}{H}. \tag{5.2.6}$$

Since the softer material will yield before the harder, the real contact area, A_R, can thus, according to Sturesson (2008), be described as:

$$A_R = \sum_{i=1}^{n} a_i = \sum_{i=1}^{n} \frac{f_i}{H} = \frac{P_N}{H}. \tag{5.2.7}$$

Hence, it is the softer material that determines the contact area. The deformation resistance due to adhesion, F_T, is then the sum of the shear stress, τ_y, of every contact spot of the softer material, so that the friction force can be written as

$$F_T = A_R \tau_y. \tag{5.2.8}$$

Noteworthy is that both the hardness of the ski track and the snow crystal hardness has to be taken into consideration. In addition to adhesion, the friction due to ploughing as the asperities collide mechanically contributes to the dry friction force. This force is denoted F_P, and is the product of the collision areas, A_P, and the resistance against deformation which approximately is equal to the hardness of the material, H, i.e.

$$F_P = A_P H. \tag{5.2.9}$$

The total dry friction force, F_{DRY}, can be written as

$$F_{DRY} = F_T + F_P. \tag{5.2.10}$$

or

$$F_{DRY} = F_N(\mu_a + \mu_p), \tag{5.2.11}$$

where μ_a is the friction coefficient due to adhesion:

$$\mu_a = \frac{F_T}{P_N} = \frac{A_R \tau_y}{A_R H} = \frac{\tau_y}{H} \tag{5.2.12}$$

and μ_p is the friction coefficient due to ploughing:

$$\mu_p = \frac{A_P H}{A_R H} = \frac{A_P}{A_R}. \tag{5.2.13}$$

Wet sliding friction

The thickness of the water film increases at higher temperatures. For wet snow, capillary attachments will increase the drag on the ski (Colbeck, 1992). In this case, wet friction will be the dominating friction mechanism. The Reynold's number, R_e, is a dimensionless quantity that is used to predict flow patterns in different fluid flow situations. The number is defined as the ratio of momentum forces to viscous forces. By determining the Reynold's number, it is possible to predict whether laminar flow or turbulent flow can be expected. In this case it can be shown that a laminar flow is to be expected (Sturesson, 2008). The velocity gradient, S, for the water molecule layer can be written as

$$S = \frac{v}{d}, \tag{5.2.14}$$

where v is the velocity of the skier and d the thickness of the water film. Furthermore, according to the definition of a Newtonian fluid, the shear resistance,τ_w, will be the product of the viscosity, η, and the velocity gradient, S, i.e.

$$\tau_w = \eta S. \tag{5.2.15}$$

In this case the contact area is considered to be the area of the water film, not the sum of the contact spots. If the fluid is assumed to be Newtonian and if the area that is sheared is constant, then the resistance will increase linearly with increasing velocity and increasing wet contact area, and decrease with increasing water film thickness (Glenne, 1987). Hence the total laminar resistance force, or the total resistance force due to wet sliding friction, F_{WET}, can be written as

$$F_{WET} = \tau_w A_w = \eta S A_w = \frac{\eta v A_w}{d}. \tag{5.2.16}$$

This is in agreement with Colbeck (1988), where the wet friction, or also called lubricated component of friction, was shown to vary with speed and thickness of the water film.

Compaction and impact resistance

When a skier moves on snow a displacement of the snow can be expected, especially during soft snow conditions or when there is newly fallen snow in the track. The resistive force due to snow compaction influence the sliding friction. Glenne (1987) has written a simplified equation describing the impact resistance force, where the quotient between the vertical snow compaction, Δy, and the ski length, L, is multiplied by the normal force, P_N, i.e.

$$F_C = \frac{\Delta y}{L} P_N. \tag{5.2.17}$$

The compaction of the snow by the skier will increase the snow density and the interstitial snow moisture (Glenne, 1987). The water generated may be sufficient to induce lubrication or wet sliding friction. Glenne (1987) considered momentum to determine the frontal impact resistance of a moving ski or the impact resistance force, F_I:

$$F_I = \rho_S B (\Delta y) v^2, \tag{5.2.18}$$

where ρ_S is the snow density before compaction, B is the total width of the ski and v the skier velocity.

Total sliding resistance force

The total sliding resistance force, F_{TOT}, is according to Glenne (1987) the sum of the individual friction components, i.e.

$$F_{TOT} = F_{DRY} + F_{WET} + F_C + F_I. \tag{5.2.19}$$

Different snow conditions, such as temperature, snow crystal shape and structure, wetness and ski characteristics are examples of parameters that lead to different dominating friction mechanisms (Colbeck, 1992; Buhl et al., 2001). These parameters will hence determine if the friction process should be described as dry sliding friction, wet sliding friction or lubricated friction (Buhl et al. (2001); Sturesson (2008); Glenne (1987) and others). In reality, the total friction is a composition of the individual components, of which all contribute to the total friction to a different extent. The distribution of the contribution from the different components depends on the thickness of the water film (Buhl et al., 2001). It is very difficult to determine the exact influence from each component since they also depend on each other. The components of friction vary with the water film thickness (Colbeck, 1988). The friction due to ploughing (dry friction) decreases as the water film becomes thicker since there are fewer solid to solid contacts when the surfaces are separated by a lubricating water film. Moreover, Colbeck (1988) reported that the dry friction component is higher than the wet friction component at least at intermediate values of the water film thickness.

Schindelwig et al. (2014) showed that the coefficient of friction changes significantly along the ski. This implies that optimum sliding properties might be achieved if a different structure and different wax are used along the ski to reduce the total friction.

The most favorable sliding properties are achieved when both solid to solid and melt water lubrication occurs. A thin melt water layer is the key to most theories of sliding friction of skis on snow (Bowden and Hughes (1939); Bäurle (2006); Coupe and Spells (2009) and others). A common agreement seem to be that the thickness and behaviour of the water film along with the real contact area, A_R, are crucial parameters for the friction. The water film can according to Bäurle (2006) explain the friction process.

5.3 Parameters influencing the sliding friction

Some of the most important snow properties that affect the sliding friction are temperature, density, compressive strength, moisture and liquid water content, grain size, grain shape, snow crystal hardness, thermal conductivity and bearing load or the local contact pressure (Buhl et al., 2001; Colbeck, 1992; Glenne, 1987). The most influential one is temperature, which according to Buhl et al. (2001) is intimately linked to the thickness of the waterfilm, which in turn is essential for the sliding friction (Bäurle, 2006; Colbeck and Perovich, 2004). The load and the speed are properties which neither are related to the snow, nor to the ski, that have a great influence on the sliding friction. Furthermore, the real contact area is, as mentioned, regarded as one of the most important parameters when studying the ski base sliding friction (Kuroiwa (1977); Bäurle et al. (2007); Theile et al. (2009) and others). These parameters are discussed in the following sections.

The snow temperature

A friction map is shown in Figure 5.1, where approximate regions of dry friction, mixed lubrication and wet friction are shown. The sliding friction is lowest in the mixed lubrication region. Bäurle et al. (2007) found both during field and laboratory tests that the friction is lowest at about -3°C. Furthermore, the friction increased for lower temperatures and when the temperature was close to 0°C (Bäurle et al., 2007).

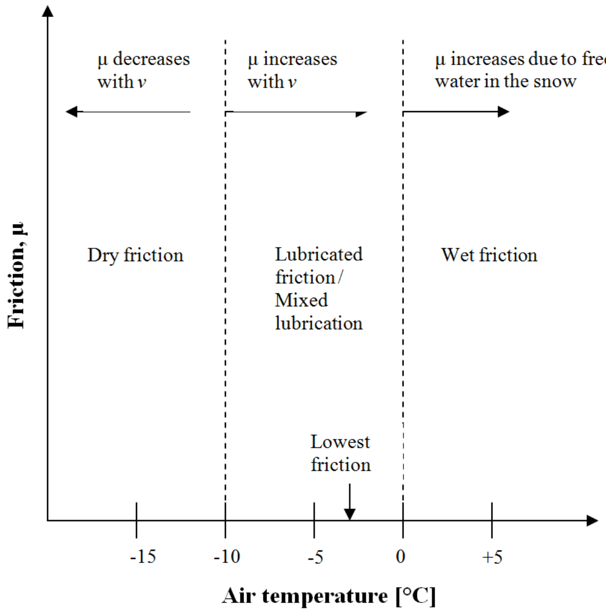

Figure 5.1: Friction map showing the friction coefficient as a function of temperature. The regions where dominating friction mechanisms are dry friction, mixed lubrication and wet friction respectively are also shown.

At temperatures below about -5°C, any source of heat should reduce the friction according to Colbeck and Perovich (2004). More heat will, according to Bäurle et al. (2007), result in more heat available to melt ice, and thus generate a thicker water film. At temperatures near the melting point, the snow is already wet and generation of more water leads to increased friction due to capillary drag. Increased friction at temperatures near 0°C can be explained by increased melt water and thus considerably increased real contact areas (Bäurle, 2006; Bäurle et al., 2007).

Schindelwig et al. (2014) measured the temperature along the ski during sliding using four temperature sensors placed 32 cm behind the ski tip, 93.5 cm behind the ski tip (which was at the balance point), 143 cm behind the ski tip (which was just behind the rear pressure area) and 10 cm from the tail of the ski. The temperature was found to vary significantly along the ski, and also with different sliding velocities. The lowest temperature was registered at the ski tip. The second temperature sensor registered an increase in temperature whereas the third temperature sensor, located behind the rear pressure area, showed the highest temperatures. The temperature was then found to drop again at the tail of the ski. The change in temperature between the first and the third sensor was as high as 3°C at a speed of 10 m/s. The results from the study show that different structures and wax along the ski could reduce the total friction.

According to Glenne (1987), critical parameters affecting the snow friction at low temperatures are material hardness, surface smoothness and heat conductivity. At high temperatures material hydrophobicity, wax impregnation and surface texture are mentioned as critical parameters.

To conclude, there is a temperature region where the best sliding properties are achieved as a result of mixed lubrication. At lower temperatures the thickness of the water film is too thin and solid to solid contact or dry friction will occur. At higher temperatures, the water film will be too thick, resulting in a widespread real contact area and capillary suction.

The load

At low temperatures the dry friction force increases since the produced heat is not enough to create a complete lubrication. However, the higher friction coefficient will result in an increased contact area, which in turn will enable more snow to be melted. Buhl et al. (2001) declare that a higher load will result in lower friction at low temperatures, since the higher load will allow more heat to be produced by the friction. At higher temperatures, when lubricated friction is dominating (around -3 – -4 °C), the load was assumed to have a negligible influence on the friction. The load was also assumed to have negligible influence on the friction when the temperature increases further, and capillary drag effects will be present.

Colbeck (1988) showed that the lubricated component of friction, or the wet friction force, is independent of load, which agree with theoretical calculations according to Equ. 5.2.16.

Buhl et al. (2001) performed laboratory tests with a rotating mandrel with snow attached to a stamp of polyethylene to measure the coefficient of friction at different loads. It was found that the load only influenced the coefficient of friction at low temperatures, where an increased load resulted in a decreased friction coefficient. For temperatures higher than -10°C, the friction was independent of load. In addition to the laboratory tests, sliding tests on skis were also performed in a downhill slope. The results showed that the load influenced the result when the temperature was lower than -6°C, where a heavier skier was faster. At temperatures above -6°C the results were independent of load.

Sturesson (2008) found that an increased load lowered the friction at temperatures below -12°C, whereas the friction was rather independent of load at higher temperatures.

Bäurle (2006) performed laboratory experiments to study the sliding friction of polyethylene on ice. The results showed that the friction force increased linearly with load for temperatures below -10°C. The same trend was observed at intermediate temperatures. For temperatures close to the melting point the friction coefficient decreased with increasing load, which was assumed to be due to more heat released per area, leading to thicker water films and therefore a lower friction coefficient.

A conclusion from these studies is that the sliding friction decreases with load at low temperatures but is independent of load at higher temperatures.

The speed

Apart from variables related to the snow or to the ski, the speed is stated as a main variable affecting the sliding resistance (Glenne, 1987).

Colbeck (1988) reported that previous studies have shown that at low speeds the value of friction is close to the static value. As the speed increases it was shown that the lubricated friction component decreases, especially at higher temperatures. The friction passed through a minimum at an intermediate value of speed. This was said to be caused by two counteracting effects. Firstly, as an object begins to move and the water film is generated, the friction will decrease due to the formation of the lubricating layer. Secondly, when everything is at melting temperature this will occur at any finite speed. Colbeck (1988) showed that at this temperature, friction increases proportionally to the square root of the speed, because of the shear force in the water film. At lower temperatures there is a combination of these two effects so that the lubricated friction initially decreases but then increases at higher speeds. The high friction at low speeds was further explained by Colbeck (1988) to be a result of heat flowing away from contact spots, which begin to dominate the heat balance. In another study Colbeck (1993) reported that the higher friction force at very low speeds is a result of too little heat and melt water generation, resulting in an insufficient lubricating water film. Bäurle (2006) found that the friction decreased with increasing speed at low temperatures due to more heat being able to melt ice and thus increasing the water film thickness.

Kuroiwa (1977) explained the friction at very low speeds to be mainly due to plastic deformation of the snow whereas at higher speeds, fracture and partial melting of ice grains occurred. Therefore Kuroiwa (1977) suggested to apply the adhesion theory at low speed whereas the theory with the lubricated water film was considered most appropriate at higher speeds. Furthermore Kuroiwa (1977) found that the kinetic friction increased with increasing speed, and assumed that this might be related to an increased real contact area between the ski base surface and the snow, but mentioned also that this needed further investigation.

Sturesson (2012) found that the friction decreased with speed at temperatures below -12°C. At temperatures between -10°C and -2°C the friction increased with speed and at temperatures near 0°C the speed seemed to have low influence on the sliding friction.

Summarizing these studies, there seem to be a common agreement that the friction at low temperatures decreases with increasing speed due to more frictional heat generating a thicker water film. At high temperatures the friction increases with increasing speed.

At air temperatures above 0°C, the increased friction is instead a result of an increased amount of free water in the snow.

Colbeck (1993) pointed out that a problem with the measurements of sliding friction for skis on snow is that many measurements are done at speeds which are not relevant for skiing. Colbeck mentioned studies where the friction decreases when the speed increases from 0-5 m/s, and increases for speeds above 5-10 m/s. The reason for the increased friction at higher speeds is according to Colbeck (1993) both due to the dynamics of the water film and because the average heat flow into the ice grins and the convective heat losses from the ski will increase with speed.

The waterfilm

The thickness of the water film is believed to be the most important parameter for the kinetic friction and it also determines the distribution of the different friction mechanisms (Buhl et al., 2001). The water film is formed when friction induced heat melts ice crystals (Kuroiwa (1977), Bäurle (2006), Sturesson (2008) and others). As the temperature decreases the rate of melt water production will also decrease, and hence also the thickness of the water film (Buhl et al., 2001). If the water film is insufficient, dry friction, or solid to solid interaction, will occur. As the temperature increases the water film gets thicker and the overall friction will be at a minimum when the water film lubricates the whole contact area. If the temperature increases further and there will be too much liquid water in the snow, water bridges develop which exert a drag on the ski without supporting any weight (Colbeck, 1988). This means that capillary suction and viscous drag will occur and thus significantly increased friction.

The snow temperature, the liquid water content, the normal force, the material and the structure of the ski base surface are parameters that influence the thickness of the water film (Schindelwig et al., 2014). In addition to these parameters, Colbeck (1988) reported that the size of the contact spots, speed, temperature and thermal characteristics of the ski also affect the water film thickness.

A friction map with the water film thickness as variable on the x-axis is shown in Figure 5.2. It is obvious that the lowest friction is achieved in the mixed lubrication region. According to Colbeck (1988), the thickness of the water film never exceeds approximately 2 μm.

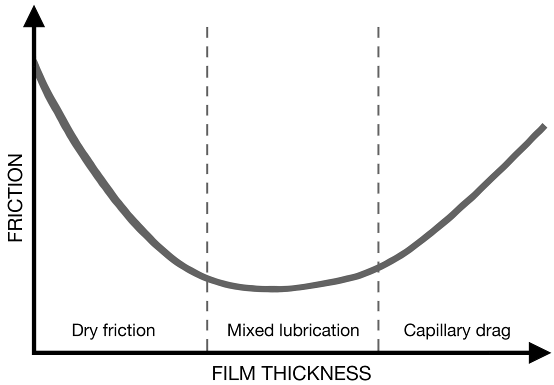

Figure 5.2: Sliding friction as a function of water film thickness. (From: Karlöf et al., 2005).

Ambach and Mayr (1981) developed a method for measuring the water film thickness by using a probe through which the dielectric constant in the contact zone between the ski and the snow was measured. The dielectric constant for liquid water is higher than for dry snow, and the measured signal was proportional to the water film thickness. Sliding tests showed that the thickness of the water film increased as the temperature increased. Moreover, Ambach and Mayr (1981) found that the use of different ski wax produced different thicknesses of the water film. During cold conditions, the wax producing the maximum film thickness resulted in the best sliding properties, but it was stated that this result can not be generalized since wet snow or very high speeds may have the opposite effect, and roughening of the surface during such conditions is suggested to optimize the film thickness.

Once the water film is formed the thickness increases and reaches an equilibrium value, which is sensitive to slider properties, speed and temperature (Colbeck, 1988). Friction is minimized once the water film thickness approaches this equilibrium value, which means that the length of the slider not is directly connected to the friction. A long slider does not have proportionally higher friction than a short slider. Colbeck (1988) showed that the lubricated component of friction decreased as the size of the load-bearing surfaces increased, i.e. as the snow became icy, the water film thickness increased. The thickness of the water film increased along the length of the ski, but the rate of increase was smaller at lower temperatures. Furthermore, the thickness of the water film decreased with temperature. Perla and Glenne (1981) also showed that the water film thickness increased with increasing grain size.

The real contact area

The real contact area is by several authors pointed out as one of the most important parameters when studying the ski base sliding friction (Kuroiwa (1977); Bäurle et al. (2007); Theile et al. (2009) and others). The real contact area is connected to the formation of the melt water film, and thus the sliding friction (Bäurle et al., 2007). A good estimate of the relative real contact area and the contact spot size is essential for a quantitative model of the sliding friction on snow and ice.

The force on a single ice grain, f_i, is the total normal force, P_N, divided by the number of grains, n, in contact, i.e.

$$f_i = \frac{P_N}{n}. \tag{5.3.1}$$

In the beginning of sliding, only a few grains are in contact with the ski, which means that the force on each grain is enormous (Theile et al., 2009). As more grains come into contact with the ski, the force decreases. The ice on top of the grains will fail, and the failure of grains will in turn lead to an increased real contact area until the average stress drops below a certain critical value. According to Theile et al. (2009), the penetration hardness of ice, H_{ice}, is related to the unconfined compressive strength, σ_C, as

$$H_{ice} = 3\sigma_C. \tag{5.3.2}$$

Theile et al. (2009) then estimate the real contact area, A_R as the ratio of the normal force to the penetration hardness of ice, H_{ice}, i.e:

$$A_R = \frac{P_N}{H_{ice}}. \tag{5.3.3}$$

Thus, the size of the contact spots is according to Theile et al. (2009) determined by the hardness of solid ice. In reality it is always the softest material, at the prevailing temperature which should be considered when estimating the real contact area. It could be the snow, or the ice grains, but most often the ski base material is softer than the microscopical hardness of the individual ice grains.

In a ski track it is important to remember that it is the hardness of the snow grains that determines the real contact area and that not all of the snow grains carry load. Relatively few of the grains develop a pressurized water film that supports the weight (Colbeck, 1988). Colbeck (1988) showed that the lubricated component of friction decreased as the size of the load-bearing areas increased. The load bearing area was further shown to be proportional to the load. This statement is supported by the theoretical and experimental conclusions that friction is independent of load.

Due to the very low number of grains actually in contact with the ski base, very high local stresses develop on the top of the grains (Theile et al., 2009). The stress far exceeds the compressive strength of ice which leads to localized failure of the ice. The failure mechanism is a mixture of plastic flow, microcracking and pressure melting at contact spots, depending on the actual stress and strain rate experienced by the ice grains.

The real contact area increases with temperature which is assumed to be due to an increased amount of melt water (Colbeck, 1993).

Self-oscillations or vibrations of skis due to geometric roughness of the surface, non-linearities in material properties, thermo-elastic instabilities or instabilities due to decreasing friction with increasing velocity may lead to changes in the real contact area (Koptyug and Kuzmin, 2011).

The real contact area is hard to define and dependent on the bearing load and the compressive snow strength, which in turn depends on the snow crystal hardness, age, density and moisture of the snow (Glenne, 1987). There are different methods where the real contact area has been estimated, for example using scanning electron microscopy (SEM) images and X-ray computer tomography. Different investigations have shown different sizes of the relative contact area. Colbeck (1994), Bäurle et al. (2007) and Huzioka et al. (1963) found that the real contact area was about 2-4 % of the total area. Theile et al. (2009) reported contact areas of as small as 0.4%, at least in the front part of the ski. The relative contact area increases as the melting of ice grains starts, since this leads to lubricated contact spots. Hence it could be assumed that the relative contact area increases towards the rear part of the ski.

Kuroiwa (1977) tried to estimate the real contact area of a rotating clean surface of a circular glass plate, which was brought into contact with a snow sample. Careful observations in microscope where the flat surfaces of ice grains were inspected showed that these small areas of the ice grains only was about 3.8% of the total geometrical area.

Static measurements of the real contact area and the sizes of contact spots were done by Bäurle et al. (2007) by using scanning electron microscopy (SEM) and X-ray computer tomography. The relative real contact area of test specimens studied was found to be 6.4%. According to Bäurle et al. (2007) few contact spots oriented in the sliding direction is beneficial. Real contact area is hard to determine experimentally, especially for dynamic processes (Bhushan, 2013).

5.4 Properties of cross-country skis

It is commonly believed that the construction of the ski, its stiffness and span curve are the most important parameters attributed to the ski, which influence the sliding friction. The second most important parameter of those attributed to the ski, is the texture of the ski base surface and finally the ski wax is believed to have some influence on the sliding friction.

Cross-country skis are manufactured to have different properties to suit different snow and track conditions, for different disciplines of skiing (classic style, skating and double poling) and for different weights and skills of the skier.

5.5 Span curve analysis

There are different methods to determine relevant mechanical properties of cross-country skis. In former days, estimations of the skis span curve was generally done by using a simple hand held equipment such as a thickness gauge. Nowadays the span curve of cross country skis can be measured using different instruments. The shape of the span curve demonstrates the identity of the ski and shows the glide zones and the grip wax pocket, see Figure 5.3. Different span curves are generally recommended for different track conditions and also for different skiers with respect to their weight and personal skills. For the present studies the digital instrument Skiselector was used to determine span curves and stiffness curves of cross-country skis.

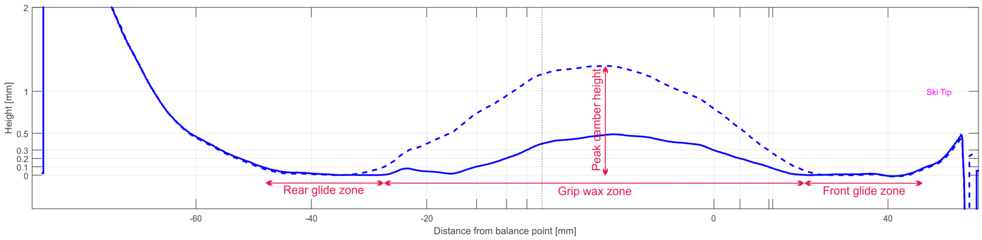

Figure 5.3: Span curve of a classic style cross-country ski.

Although skis are matched so that skis within the same pair are similar, there might still be large differences in properties such as glide zone lengths, peak camber height etc. as is further discussed in **Paper D**. The stiffness of the skis, the length of the grip wax zones for classic style cross-country skis and the length of the glide zones are believed to be highly significant for the sliding properties according to ongoing work. Furthermore, these properties were found to be temperature dependent as presented in **Paper D**. Span curve measurements are generally done at room temperature, so thermo-related changes are therefore of importance to be aware of.

Material and Method

The digital instrument Skiselector consists of a rigid aluminum frame with a completely flat surface of stone, on which the ski was placed during the measurements as shown in Figure 5.4. The load was applied through a load unit and controlled by a computer. During the span curve measurements, a sensor travelled underneath the ski from the rear end to the front and back. When the sensor travelled towards the ski tip, the half weight of the given load was applied. When the sensor traveled back again the full weight of the given load was applied. For classic style cross-country skis, the span curve is generally determined both for full weight load, corresponding to when the skier has the full load on only one ski, which is the case during diagonal stride, and for half weight load which implies that the weight is evenly distributed on both skis. Noteworthy is that only longitudinal measurements can be performed with this instrument, i.e. no transverse measurements across the ski can be done. The longitudinal resolution of the measurements was about 0.6-0.7 mm.

The data from the span curve measurements was saved as a text file, which was analyzed using a Matlab script. Parameters which was calculated was for instance the lengths of the grip wax zones and the glide zones, the peak camber height and opening angles. Furthermore the half and full weight span curves were visualized. In Figure 5.3 the full weight span curve is depicted as a continuous line and the half weight span curve as a dashed line. The curves give a graphical description of peak camber height and grip wax zones. For the half weight curve it was assumed that the full load, which equals the skier's bodyweight, was equally distributed

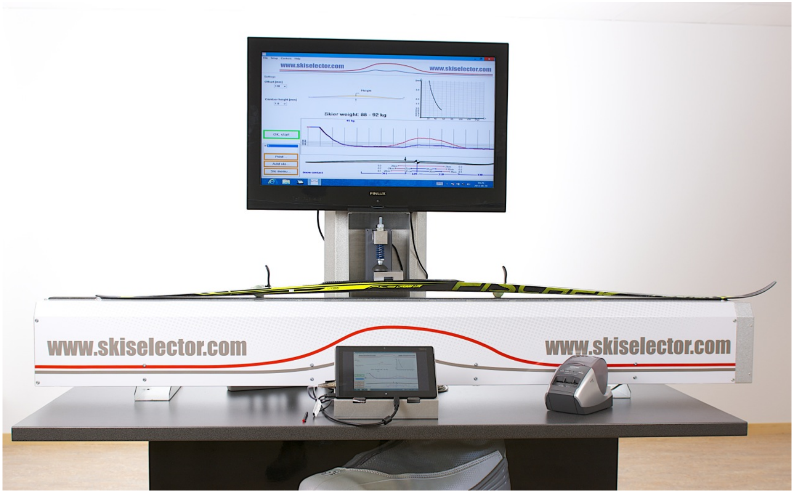

Figure 5.4: Instrument used for the span curve measurements. Photo: Skiselector.

between both skis. To calculate the length of the glide zones at the front and rear part of the ski, span curve heights lower than 0.05 mm was defined as being in contact with the track.

The length of the glide zones and the grip wax pocket, the stiffness of the skis and the shape of the span curve are of importance for the overall performance of the ski. Different span curves are designed for different snow conditions to optimize the performance. The ski manufacturers sell skis for different conditions, generally divided into so called "cold" skis and "warm" or "plus" skis. Classic style cross-country skis graded as "cold" and "warm" were analyzed.

Analyzing span curves of cross-country skis using any measuring device is generally done at room temperature, whereas skis are used at temperatures below 0°C. Classic style cross-country skis were measured at room temperature and at −15°C to investigate temperature dependence of mechanical properties. This study is presented in **Paper D**. Span curves from all major ski brands were analyzed. In addition to temperature dependence also other non thermo-related differences for skis within the same pair where investigated.

Results from span curve measurements

Typical span curves recommended for cold snow conditions and wet snow conditions respectively are shown in Figure 5.5. The red lines represent span curves for a ski recommended for warm conditions and the blue curve represent a ski recommended for cold conditions. The dashed lines correspond to half weight curves and the solid lines correspond to the full weight curves.

The analysis of ski properties show that skis recommended for cold conditions have longer glide zone lengths than skis recommended for warm or wet conditions. Furthermore, skis for warm conditions are in general stiffer with a higher peak camber height than skis for cold conditions. The opening angles, or the slope of the curves in the front and rear part, are different in that span curves for warm conditions have larger angles or steeper slopes as seen in Figure 5.5.

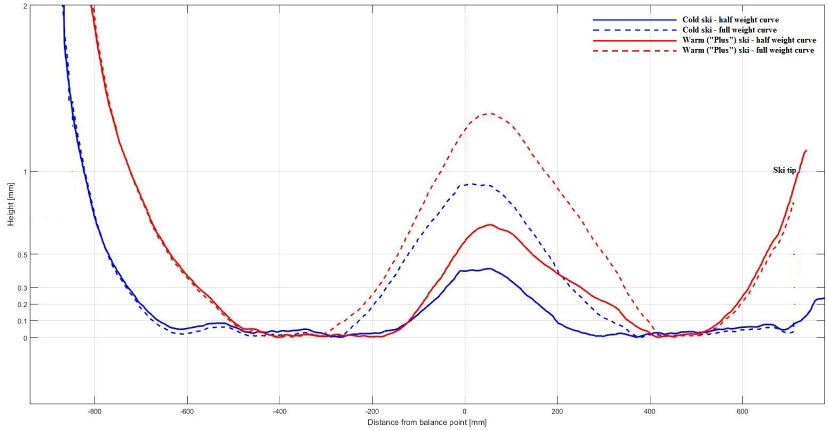

Figure 5.5: Typical span curves for skis recommended for cold and warm conditions respectively.

The results from the span curve measurements at different temperatures showed thermo-related changes in mechanical properties for all ski brands tested as is further discussed in **Paper D**. Properties such as grip wax zone, glide zone lengths etc. which influence the sliding properties might be misleading if skis are analyzed at another temperature than the one where they are supposed to be used. The same conclusion was also drawn by Breitschädel et.al. (2010), who studied the span curves of skating skis.

5.6 Ski base surface

Ski base material

In addition to the properties of the ski also the roughness, the hardness, the wetability and the thermal conductivity of the ski base are important parameters for the sliding friction (Buhl et al., 2001). The material used for the ski base surface is Ultra High Molecular Weight Polyethylene, UHMWPE. Some advantages with UHMWPE are according to Colbeck (1993) outstanding abrasional resistance, favorable elastic properties, hydrophobic characteristics and that it is hard and highly elastic. UHMWPE can also be made porous and easily coated with binders. It can also be made smoothed and imprinted with different patterns. It does not adhere to ice and the friction is according to Colbeck (1993) not greatly affected by surface contamination.

Polyethylene surfaces are known to have low friction compared to most other polymers, although water is not a very efficient lubricant for polyethylene (Colbeck, 1993). UHMWPE is a sintered grade of polyethylene (Fischer et al., 2010). To adjust the material properties, additives or fillers are added at compound level, e.g. carbon black, paraffines, silicones and metal salts. The production process from the polyethylene raw material to a finished ski based surface consists of many steps (Fischer et al., 2008, 2010). Formulated polyethylene compounds are first extruded or sintered to semi-finished films, which the are further post-treated and glued to the core of the ski (Ducret et al., 2005).

By adding graphite the hardness, electrical and thermal characteristics and therefore the frictional characteristics of the ski base change (Colbeck and Perovich, 2004). Colbeck and Perovich (2004) found that black ski base surfaces are considerably warmer than white ski base surfaces in sunny weather, although the top sides of the skis were the same and the base was facing downward. A difference in absorption of solar radiation is mentioned as the reason to this result. The black ski bases had higher temperatures also during overcast conditions although the difference was smaller than during sunshine. Diffuse solar radiation is assumed to penetrate the snow surface also during overcast weather conditions. Conclusions drawn from the results are that black ski base surfaces might be advantageous at low temperatures, where heat production is necessary to produce melt water, and that white ski base surfaces, which absorb less solar energy, are advantageous at high temperatures where too much melt water is present and capillary drag increases the sliding friction.

The ski base deforms elastically during the ski-snow interaction while the ice fails when the stress exceeds its compressive strength (Theile et al., 2009). The ski base material has higher mechanical strength than ice but lower Young's modulus.

To minimize the dry friction and the friction due to ploughing, the ski base material has to be harder than the snow crystals (Kuzmin, 2010). UHMWPE is according to Kuzmin (2010) not hard enough, and an even harder material should be used for the ski base. If the ski base is harder than the snow crystals, its movement over the snow will generate more melt water, because in this case the ski running surface will deform and melt the snow crystals, not otherwise. Therefore Kuzmin (2010) points out that a hard ski base is advantageous for any snow conditions. The ski base surface has to deform and abrade the snow crystals for melt water generation, and should thus be as hard as possible to thaw more water under the same snow conditions.

Topography of ski base surface

The topography or the structure of the ski base is one of the major ski parameters influencing the ski glide properties (see e.g. Moldestad and Løset (2003)). The ski base structure contains grooves aligned along the ski that is in the order of 10^{-1} mm wide and 10^{-2} - 10^{-1} mm deep. It is well known that different structures are preferable during different snow conditions. Most common is to use finer structures at low temperatures and coarse structures at higher temperatures. Selecting the correct structure may influence the skis speed on snow with up to 10 % (Moldestad and Løset, 2003). Colbeck (1994) states that the orientation of the roughness elements, which constitute the structure in the ski base surface, influence the thickness of the water film. When the elements are oriented transversely across the ski, the thickness of the water film will increase as fluid pressure increases on the upstream sides of the asperities (Colbeck, 1994). If the roughness elements are oriented longitudinally along the ski, the water film is assumed to be thinner. This means that a transverse structure likely is favorable at low temperatures whereas a longitudinal structure is beneficial at high temperatures. The orientation of the roughness elements are assumed to be most important when the surface roughness elements on the ski are not as thick as the water film would be if the surface was smooth, which further is stated to be the case during most situations when skis are sliding over snow. According to Colbeck (1994) the optimum lubrication was achieved when the lubricant separated the solids by at least 2-4 times the root mean square of the surface roughness. Moreover a hard but elastic sliding surface with gently sloping surface relief was assumed to be advantageous for the sliding properties (Colbeck, 1994).

Making a structure on the ski base by indentation would allow the surface to be smooth, but the indentations allow increased flexure of the polyethylene (Colbeck, 1994). The indentations in the ski base are then assumed to act as shock absorbers, which flex as the ice grains passes by. The ice grains are further assumed to be smoothened by melting to accommodate the scale of roughness of the ski. Colbeck (1994) further states that a smooth gliding surface is desirable at low temperatures in order to allow melt water to slip along the base of the ski. At high temperatures a rough ski base is to prefer in order to disrupt water attachments which otherwise increase the drag.

The two most common processes to set a structure in a ski base surface is steel scraping and stone grinding (Breitschädel, 2015). These methods to set a structure can be regarded as a permanent structure in the ski base. Breitschädel (2015) describes also a new milling machine which can be used to set a permanent structure in the ski base surface.

Since UHMWPE is a material which can be imprinted with different patterns or structures, it is a common routine that ski technicians use different hand held rilling tools prior to a race, in order to refine the ski base surface topography according to the present snow conditions. Thus, rilling tools are used to set an additional structure, in addition to the permanent structure, or to change the ski base surface topography, in order to further optimize the sliding properties according to the present snow conditions (Breitschädel et al., 2010). Rilling tools which generate a fine rougness are generally used during dry to moist snow conditions, a medium roughness is generally best during wet snow conditions and a very coarse roughness is common during wet to very wet snow conditions (Moldestad, 1999).

5.7 Study of the influence of topography on the sliding friction

Material and Method

The effect of ski base structure on the sliding friction can be quantified by performing accurate sliding tests of ski pairs with various ski base structures, but otherwise equal qualities, i.e. similar pressure distribution, ski base material and ski wax (Moldestad, 1999).

Two hypotheses were aimed to be investigated. Firstly, what difference commonly used rilling tools actually do to the ski base surface. Ongoing work of taking replicas of the structure pattern of the skis which will be analyzed using a microscope is assumed to answer this question. Secondly, it was investigated how the rilling affect the sliding properties in both wet and cold snow conditions.

Ten pairs of classic style cross-country skis were used for the tests, all with similar span curves, the same ski base material and grinded with the same permanent stone grinded structure pattern. The skis were waxed prior to each test using a waxing machine as shown in Figure 5.6 to eliminate possible differences when hand waxing skis. With the ski wax machine, wax is applied on the skis from a rotating roll (1) which was heated prior to applying it to the ski base surface. The skis were then brused with two different rotating brushes also attached to the waxing machine (2).

Ski pair 1 was left without additional structuring with rilling tools. The other ski pairs were structured using rilling tools according to Table 5.1.

Figure 5.6: Waxing machine used for waxing of the test skis. Roll with ski wax (1). Brushes (2).

Table 5.1: Rilling tools used for the ski tests.

Ski pair n.o.	Rilling tool
1	Only stone grinded structure
2	Red Creek, Linear 1 mm
3	Red Creek, Linear 2 mm
4	Swix, Cutting riller 1 mm
5	Swix, Cutting riller 2 mm
6	Speedy Skiroller, Fine "christmas tree"
7	Speedy Skiroller, Coarse "christmas tree"
8	RS riller, Linear 0.3 mm
9	RS riller, Linear 0.3 + 0.5 + 0.75 mm
10	RS riller, Diagonal + Cross-structures

Two locations were chosen for the sliding tests; Sognefjellet in Norway were the snow conditions were wet and Torsby ski tunnel in Sweden, during cold snow consitions. The tests were carried out in downhill slopes in classic style cross country ski tracks. Two photocells were placed beside the track and the time between these two were recorded.

The start position was placed 20 meters ahead of the first photocell during the wet tests at Sognefjellet and 10 m ahead of the first photocell during the cold tests in Torsby. The distance between the two photocells was 126 m during the wet tests and 78 m during the cold tests. At the start of each glide test, the skier released the poles and adopted glide position, i.e. a semi-squat position. All skis were tested ten times and in the order 1-10, i.e. the skis were changed after each test in order to identify any differences in sliding properties which could be attributed to changes of snow properties in the ski track.

A classification of the snow and weather conditions during the respective test is shown in Table 5.2.

Table 5.2: Classification of snow conditions during glide tests.

	Sognefjellet	Torsby
Snow temperature	-1.1 - -0.8 °C	-3.2 - -1.4 °C
Air temperature	+9 °C	+1.7 °C
Air humidity	57.8%	52.8%
Cloudiness	100%	-
Precipitation	0 mm	0 mm
Snowtype	Natural snow	Machine-made snow
Grain size*	G3 - G4	G1 - G2
Liquid water content*	Wet	Dry
Hardness**	Medium	Hard-Very hard

*Based on the International Classification for Seasonal Snow on the Ground (Fierz et al., 2009).
**According to the hand hardness test.

Results from sliding tests

Average values of the results from the sliding tests at wet conditions are shown in Figure 5.7. The first six test runs were made continuously after each other. The last four tests were made after a break where the track was salted and re-groomed. Average values of the results from the glide tests at cold conditions are shown in Figure 5.8.

A list with results in descending order is presented in Table 5.3. The results show that ski pairs 1, 2, 3, 8 and 9 were the slowest skis at both test locations. Note that all these ski pairs were structured with the linear rilling tools.

At wet conditions, the best sliding properties were achieved with ski pair 7 followed by ski pair 5, which both had deep or coarse rilling structures. Thereafter followed ski pair 6, 4 and 10 which indicate a decrease in sliding properties the finer the rilling structure was.

At cold conditions the best sliding properties was achieved with ski pair 10 followed by ski pair 4, 6, 5 and 7 respectively. Note the exact opposite order of the top five ski pairs at cold conditions compared to wet conditions. If the cutting rillers, i.e. those creating a permanent sturecture into the ski base (Ski pair 4 and 5) are excleded, the results show that fine broken structures result in better sliding properties during cold conditions.

Ongoing research on measuring the R_a-values, sizes and shapes of contact spots and other parameters which have an influnce on the friction process are believed to further explain the results.

Table 5.3: Results from the sliding tests at wet and cold snow conditions.

	Sognefjellet - Wet conditions	Torsby - Cold conditoions
1	Ski pair 7	Ski pair 10
2	Ski pair 5	Ski pair 4
3	Ski pair 6	Ski pair 6
4	Ski pair 4	Ski pair 5
5	Ski pair 10	Ski pair 7
6	Ski pair 2	Ski pair 2
7	Ski pair 9	Ski pair 3
8	Ski pair 3	Ski pair 9
9	Ski pair 8	Ski pair 8
10	Ski pair 1	Ski pair 1

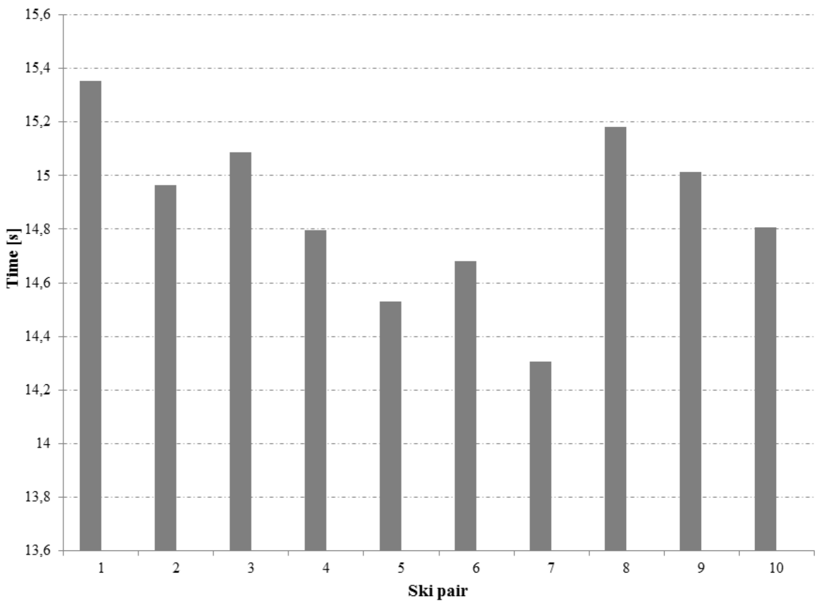

Figure 5.7: Average value of the 10 test runs for each ski pair during wet conditions.

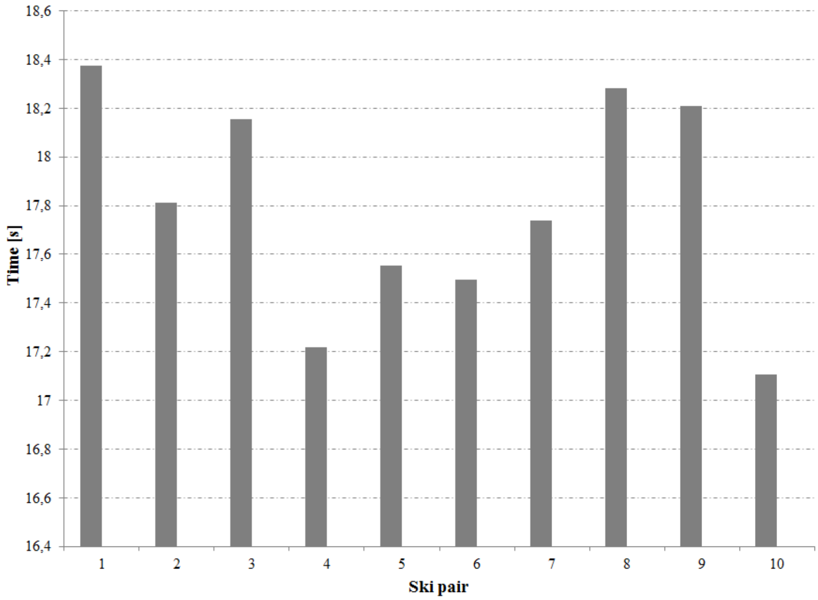

Figure 5.8: Average value of the 10 test runs for each ski pair during cold conditions.

5.8 Ski wax

The use of glide wax on skis is a controversial and much discussed subject. Researchers seem to disagree on the exact use and the benefits with glide wax.

Ski gliding wax consists of a mixture of hydrocarbons in order to create chemical affinities between the ski base and the wax, and special additives depending on the snow characteristics (Rogowski et al., 2005).

According to Colbeck (1994) ski wax is used to control the hydrophobicity and hardness and to increase the electrical discharge and to prevent oxidation and wear. Increasing hardness of the ski wax is said to result in a lower coefficient of friction, since the harder ice surfaces are able to penetrate the polymer bases. The wax layer should be very thin and well-bonded to the surface in order to effectively alter the hardness and hydrophobicity of the ski, but without changing the surface roughness (Colbeck, 1992).

According to Rogowski et al. (2005) the gliding waxes should have a hardness which is similar to that of the snow, which means that harder waxes are used during cold conditions when the snow hardness generally is higher. The manufacturers use different recommendations based on temperature for the utilization of different waxes. Cold snow is defined as snow at temperatures of less than -10°C , intermediate snow is snow at temperatures between -10 and -5°C and warm snow is assumed to be snow at temperatures above -5°C (Rogowski et al., 2005). The waxes are also classified according to fluorine content, where there are so called low fluorine waxes, high fluorine waxes and waxes without any fluorine. Rogowski et al. (2005) found that three groups of waxes could be defined; waxes consisting of long, intermediate and short alkane chains. These waxes are aimed to be used during cold, intermediate and warm snow conditions respectively. However, Rogowski et al. (2005) reported that the terminology low and high fluorine content is not comparable between different manufacturers. The alkane composition followed the same trend for different manufacturers though, so that long alkanes correspond to cold snow, intermediate alkanes to intermediate snow and short alkanes to warm snow. The waxes aimed to be used during warm conditions were more hydrophobic than the waxes recommended for cold snow conditions.

Kuzmin and Tinnsten (2008) question the theory that ski wax is a necessity to adjust the hardness of the ski base to be similar to the snow crystals actual hardness. Instead Kuzmin and Tinnsten (2008) showed that wax not can make the ski base surface any harder than it initially was. Therefore a completely un-waxed ski base might give the best sliding properties during cold and dry snow conditions.

Moldestad (1999) states benefits with using glide wax on skis to be decreased surface tension of the ski base and thereby decreased surface wetted area and contact area between the ski base and the snow. The relative dielectric permittivity at the interfacial contact between a contact point at the ski base surface and the water film or snow surface may be changed by using ski wax, which may lead to changed electrostatic or capillary pressure and hence also change the friction coefficient. Moldestad (1999) further states that the glide wax can introduce ions to the water film or to the snow surface, which may increase the electrical conductivity in the water film and thereby electrical discharge. This is assumed to decrease the potential differences between the ski base and the snow and the friction coefficient. However, Moldestad (1999) also questions the contribution of ions since one of the primary characteristics with fluorocarbon wax is its inertness. Furthermore less dirt is assumed to adhere to a waxed ski. The reason for this is the decreased electrostatic charging and dielectric permittivity that the wax is supposed to generate. When the ski base is charged it will attract dirt. The ski wax is also assumed to influence the thermal conductivity of the ski base, which in turn affect the water film and the friction. Moldestad (1999) also state that the wax can influence the hardness and wear of the ski base surface. Microscopic impact and compaction resistances during skiing is said to be influenced by waxing.

5.9 Ski testing

Friction between skis and snow has been studied in several field and laboratory experiments. Laboratory experiments are often done on test-samples and not the whole ski. Furthermore, laboratory tests are not always done at speeds which are relevant for skiing. Tests of cross country skis in the field are generally done in a down hill slope measuring the time between to points or the length a skier glides when the slope levels away horisontally. These measurements can however be misleading due to variations in ski-snow friction or in the drag (Spring, 1988). Sliding differences are best observed at higher velocities and sliding tests should therefore according to Spring (1988) be carried out at velocities above 5 m/s. Spring (1988) propose a method for properly studying the sliding properties of skis where the velocity between two sensors placed at a suitable distance from each other is measured. The velocity should be higher than 5 m/s when the skier pass both sensors. A methodology for glide testing is also presented by Coupe and Spells (2009), who suggest a test run which is longer than 50 m and a start point set at least 3 m above the first measurement sensor for more accurate timings at an early stage. Moreover, Coupe and Spells (2009) found that the initial phase, which involves the development of the melt water film, may affect the test results. Furthermore, the accuracy of the timing system should be at least 0.001 s and it is also suggested to carry out at least ten test runs on each ski pair. It is beneficial to carry out a large number of test runs so that variations in positions of the skier etc. can be taken into consideration. The importance of classifying the snow during the tests is also pointed out since this is highly significant.

Manually testing skis is always connected with sources of error. In addition to the skiers position, which may change slightly between each test, also the surface of the snow change. When testing skis in a down hill slope, there is a continous acceleration. In cross country skiing the retardation might influence the overall performance even more, which should be considered when ski tests are carried out.

A ski-snow tribometer is presented by Hasler et al. (2016), where the skis have been tested at sport-specific speeds in the laboratory.

Chapter 6

Snow and climate change

6.1 Influence of climate change on snow and winter activities

Winter tourism and winter sports all around the world is highly sensitive to climate change (Bürki et al. (2003); Breiling (1998); Scott et al. (2003, 2006); Steiger and Abegg (2013) and many others). Changes in climate can affect how much snow that falls and influence the timing of the winter snow season, which is a challenge for the winter business industry.

Between 1966 and 2010, the amount of land and sea ice that was snow-covered each year decreased with about 10% in the northern hemisphere regions (Moen and Fredman, 2007; NSIDC, 2016). The decrease was especially apparent during the spring snowmelt season. Scientists have modelled how the Earth's climate might change over the next 100 years. The results showed that snow will cover less of the planet, particularly over Europe and Asia. The Arctic region is expected to be most vulnerable to the climate change (Larsen, 2006). The consequences of the climate warming is presumed to be reduced snowfall, earlier spring melts and shorter snow cover seasons (Larsen, 2006; Moen and Fredman, 2007). This scenario has been observed on several places already, for instance in Alaska where warmer air has caused the snow to melt earlier each spring, lengthening the snow-free summer season. Furthermore, in regions where the average winter temperature is close to 0°C, precipitation as rain instead of snow has become more common (Larsen, 2006). It has also become more frequent with warm periods of spring-like weather during the winter with unusual melting during a normaly cold period. Together with rain this cause melting and refreezing of snow.

Research carried out by Swedish Regional Climate Modeling Program (SWECLIM) show that the last decade in Sweden was warmer and wetter than the preceding 30-year period. Moreover, the annual mean temperature in Sweden is expected to rise by 3.8°C by the year 2100 (Koptyug et al., 2006). The annual precipitation is expected to increase but most likely due to an increase in rain during the summer and autumn and not as snowfall during the winter. The Intergovernmental Panel on Climate Change (IPCC) anticipate a similar scenario as SWECLIM, where the global increase in temperature between the years 1990 and 2100 is estimated to be between 1.8-4.0°C. Regional changes are anticipated to be more significant. The prognosis for Sweden is illustrated in Figure 6.1.

In the European Alps, a temperature increase of 1°C will cause the line of natural snow to

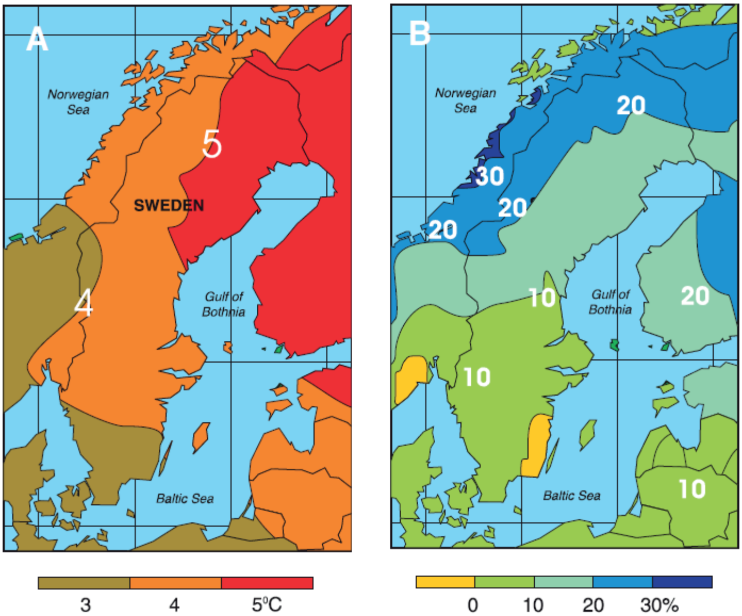

Figure 6.1: Predicted increase in winter temperature (A) and yearly precipitation (B) for northern Europe (Koptyug et al., 2006).

rise 150 altitude meters (Steiger and Mayer, 2008). The long-term effect of the temperature increase might be very devastating, since winter tourism is the most important source of income for many countries in the alp regions (Bürki et al., 2003). However, all stake-holders in the winter business industry are affected by the reduced snow fall and shorter snow seasons. Snow has come to be regarded as currency (Burakowski and Magnusson, 2012). A lack of snow may lead to late openings for ski resports, cancellation of sport events and thus immediate consequences on the economy and profitability. Tourists demand good snow conditions, which thus has to be offered by ski resorts. However, this is assocciated with significant costs due to the climate change (Bürki et al., 2003).

Snow reliability has become a common conception, but the scientific definition of snow reliability is quite different (Steiger and Mayer, 2008). Abegg (1996) implemented the "100-day rule", which means that ski resorts can be considered snow reliable if there in seven out of ten winters will be a snow cover of at least 30-50 cm available for ski sports on at least 100 days between December 1 and April 15.

The winter sport industry would benefit from being less dependent on meteorological conditions. Both ski resorts and other stakeholders in the winter business industry need to be able to set an opening date for the winter season. Currently the most common way for ski resorts to handle the warmer winters and to compensate for the lack of natural snow is to increase the capacity of snow production (Steiger, 2012). The most common methods for production of snow requires temperatures below 0°C. New techniques for production of snow at warm temperatures are being developed but the cost for such snow is substantially higher. According to Steiger and Mayer (2008), the most important question in the future will be wheter it is possible to produce enough snow at an acceptable cost level. Scott et al. (2006) address the same question and further emphazise the profitabilty which not only is reduced due to increased cost for snow making, but also the fact that it is coupled with shorter average operating seasons.

An alternative to snow production early in the season when temperatures for conventinal snow making are not low enough is snow storage. Snow storage means that snow is stored in insulted piles during the summer and used the following winter. Current knowledge on snow storage and parameters influencing the melt rate of an insulated snow depot is presented in **Paper E**.

Indoor skiing is further an alternative which is totally independent of the climate and enables skiing all the year round. Indoor skiing is a growing industry in Europe. There are a number of indoor skiing arenas for both alpine and cross-country skiing.

6.2 Environmental impact of snow production

Most ski resorts use machine-made snow in their slopes and pistes, both due to lack of natural snow but also to improve the quality and durability. There are drawbacks with snow production though, mainly linked to increaing water demand and energy consumption. Ecological concerns are according to Steiger (2012) still largely unconsidered, though the increased use of resources contradicts both climate change migration goals and sustainable tourism development. Many ski areas have built reservoirs to supply their snow making needs while some ski areas draw water from lakes and streams (Scott et al., 2006). The withdrawal of water is according to Scott et al. (2006) of concern in some areas since it has a potential impact on fish and other aquatic habitat.

The production capacity for a big snow system is according to SLAO (2012) about 1500 m^3/h, which corresponds to a water consumption of approximately 10 000 l/min. It is hence a considerable amount of water and energy which is consumed during snow production. In Davos for example, an annual volume of about 600 000 m^3 of water is consumed for snow production which corresponds to about 21.5% of the entire water consumption in this region (SLF, 2012). Assuming free access of water, the cost for producing 1 m^3 of snow is between 1-5 SEK (SLAO, 2012). The technology for snow production is expected to be improved and further development of tools and improved techniques could reduce the energy consumption.

It is not only the production of snow that affects the environment, but also the transportation of snow to pistes and tracks. In addition, ground work to prepare for slopes and tracks may destroy vegetation and soil stability, which also needs to be taken into consideration when evaluating the environmental impact. Still quite few investigations have been done on the environmental impacts of snowmaking. A study on how the heat balance in the soils is changed by using machine-made snow instead of natural snow shows that the machine-made snow will generate a prolonged snow cover which may influence the vegetation (Rixen et al., 2004). Soil frost will also occur less frequently on pistes with machine-made snow since the insulation is greater due to the more compact snow and higher snow depth (Rixen et al., 2004). The nucleating agents used as seeding may also have a harmful effect on the environment. A detailed study on environmental impacts of snow producion is of interest for future studies.

6.3 Snow storage

Storage of snow is an old technique which was common for food storage applications before the refrigerators were developed in the beginning of the 20th century (Skogsberg, 2005). Skogsberg and Nordell (2001) mention for instance himuros and yukimoros, which are houses or rooms where vegetables are stored together with ice or snow in order to keep the quality. Skogsberg (2005) studied seasonal snow storage for process cooling, which is presented in the doctoral thesis *"Seasonal Snow Storage for Space and Process Cooling"*.

During the last years, storage of snow has become of greater interest for ski resorts as both an alternative and a complement to snow production. Using stored snow enables ski resorts to have a snow guarantee early in the season, even if there is no natural snow and if warm temperatures does not enable traditional snow production. Summer ski events where stored snow is used are also becoming more popular. Some Swedish ski resorts that store snow are Bruksvallarna, Högbo Bruk, Idre Fjäll, Orsa Grönklitt, Åre and Östersund. In **Paper E** a summary of current knowledges and experiences of snow storage is presented.

Snow can be stored indoors in thermally insulated buildings, underground in caverns in which case no insulation is necessary or on the ground in open ponds or pits covered with some kind of thermal insulation material (Nordell and Skogsberg, 2007). The thermal insulation material can either be natural materials or fabricated materials. Most common is to store snow on the ground.

Mikko Martikainen is a pioneer within snow storage. He was responsible for the first snow stored for skiing purposes, which was in Ruka, Finland in 2000. Martikainen (2016) distinguishes between three different methods to insulate snow stored on the ground. Firstly a breathable method, which means an insulating material that enables evaporation. Secondly, a non-breathable method, which is an insulating layer that only insulates the snow. The third method is a combination between these two. Most common in Scandinavia is to use a breathable method and a natural insulating material. Natural insulating materials are for example bark, crop residues, mineral particles or debris and different types of wood chips, such as cutter shavings of different size, sawdust and wood powder. Fabricated materials are generally different kinds of loose sheets, such as plastic sheets, filled tarpaulins e.g. with straw, geo textile sheets, aluminum folio, felts and sometimes thermal foam in between (Skogsberg, 2005; Martikainen, 2016).

A pile of snow insulated with sawdust is shown in Figure 6.2 and a pile insulated with textile sheets is shown in Figure 6.3. Textile sheets were also used to insulated snow which was scraped together in an alpine ski slope in Idre, Sweden, in the end of the season in 2016. The insulated snow was placed in the slope where it was supposed to be used as shown in Figure 6.4.

According to Martikainen (2016) a snow depot should be associated both with low emissions and snow to a low cost. Therefore many local factors at the place where the snow is supposed to be stored needs to be taken into account in order to create the most optimal snow storage. The size for a snow depot is typically 5000 - 30 000 m^3, although they may also be larger (Martikainen, 2016). Both natural snow and machine-made snow can be stored, although machine-made snow is most common since it is considered more durable and weather resistant than natural snow (ICEHOTEL, 2012).

There are many different factors affecting the melt rate of an insulated snow depot. Skogsberg (2005) denotes snowmelting in warm surroundings natural melt, and divides it into ground

Figure 6.2: Stored snow in Vuokatti, Finland, 2013.

Figure 6.3: Stored snow in Idre, Sweden, 2016.

Figure 6.4: Stored snow in an alpine slope in Idre, Sweden, 2016.

melt, surface melt and rain melt as illustrated in Figure 6.5.

Ground melt is the heat transfer through the bottom of a pile which is placed on the ground. Surface melt occurs by heat transfer through from the air, sun and sky. Rain melt occurs through rain which seep through the insulating layer to the snow. Surface melt is the major factor influencing the total melt rate (Skogsberg, 2005). The snow melt occurs by heat exchange between the snow pile and the environment (Nordell and Skogsberg, 2002). The climate, the choice of thermal insulation and the geometry of the pile are therefore also factors affecting the melt rate.

6.4 Studies on snow storage

Information from places where snow has been stored was collected and summarized in order to compare experiences and methods. The volume of snow depots, the insulating material used and the approximate melted volume, where this was known, are shown in Table 6.1. The approximate period of storage was from late spring until the end of October or early November. In Sochi, Russia, snow was stored to be used in February for the Olympic Games. The pile in Arjeplog consisted of natural snow and the piles in Piteå were a mix of natural snow and machine made snow, which was scraped together from a nearby ski slope when it closed for the season. All other piles consisted of machine-made snow.

Further information about each place are given in **Paper E**.

The total melted volume as a percentage of the initial volume for the piles of stored snow at different locations is shown in Figure 6.6. The trend is that larger initial volumes result in relatively lower snow melt.

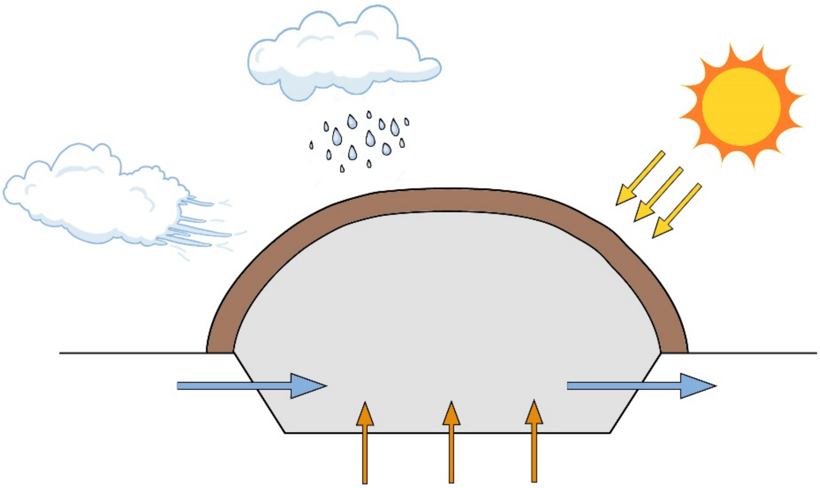

Figure 6.5: Factors affecting the melting rate are heat from the air, sun and sky, rain and heat from the ground (Figure from: Skogsberg (2005)).

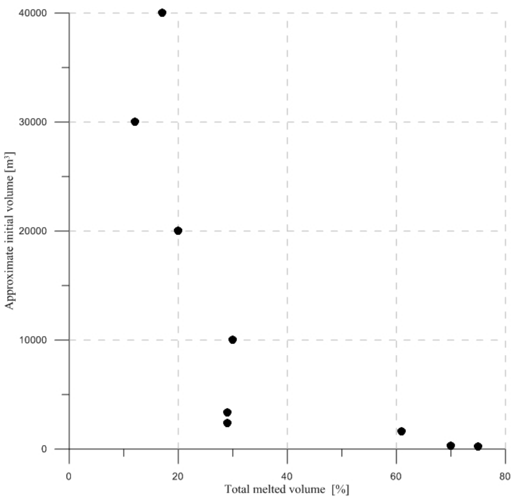

Figure 6.6: The total melted volume as a percentage of the initial volume for piles of stored snow.

Table 6.1: Places where snow has been stored, the approximate volume, insulating materials used and estimated volumes of snow melt (Ädel (2013), Pelkonen (2013), Hedlund (2016), Martikainen (2016), Rindahl (2016), Rommedahl (2016), Skoglund (2016))

Place	Volume [m^3]	Cover material	Estimated total snow melt [%]
Vuokatti, Finland	20 000 - 25 000	Tarpaulin and sawdust, 30-40 cm	20
Östersund, Sweden, 2006	2 piles á 10 000	Sawdust, 70-80 cm	30
Östersund, Sweden	20 000	Sawdust, 50 cm	20
Östersund, Sweden, 2015	30 000	Sawdust, 40 cm	12
Orsa, Sweden	5000	Bark, 40-50 cm	-
Högbo Bruk, Sweden	8000	Sawdust	-
Piteå, Sweden (2012)	2400	Geotextile and 50-60 cm of bark	29
Piteå, Sweden (2013)	3400	Geotextile and 50-60 cm of bark	29
Arjeplog, Sweden (2013)	1600	Geotextile and 40-50 cm of bark	61
Birkebeiner Ski Stadium, Norway	40 000	Wood chips, 30-50 cm	17
Sochi, Russia (2013)	800 000 (several piles)	Geotextile in several layers, foamed plastics, aluminum folio	20-50

Method

An experiment was designed to compare the efficiency of wood chips and bark as thermal insulation on snow. This experiment is presented in **Paper E**. Three piles, each with a volume of approximately 200 m^3 were studied. The piles were shaped as chopped cones with base diameter 12 m, top diamter 6 m and height 3 m. The experient was carried out in Arjeplog, Sweden, in 2013.

Pile 1 was covered with an approximately 40 cm thick layer of bark. Pile 2 was covered with a 30 - 40 cm thick layer of sawdust. Pile 3 was uncovered.

The melted volume of snow was recorded during the study period. The results were compared to theoretical calculations of the total melted volume, V_{TOT}, which consists of contributions from ground melt, V_{ground}, surface melt, $V_{surface}$ and melt from rain, V_{rain}. The theoretical model for the calcualtions is presented in **Paper E**.

Results from studies on snow storage

The results from the study is shown in Figure 6.7 where the volumes of snow are shown at the beginning of the study period, in mid April and in the beginning of October, when the last measurements were performed. These results are further discussed in **Paper E**.

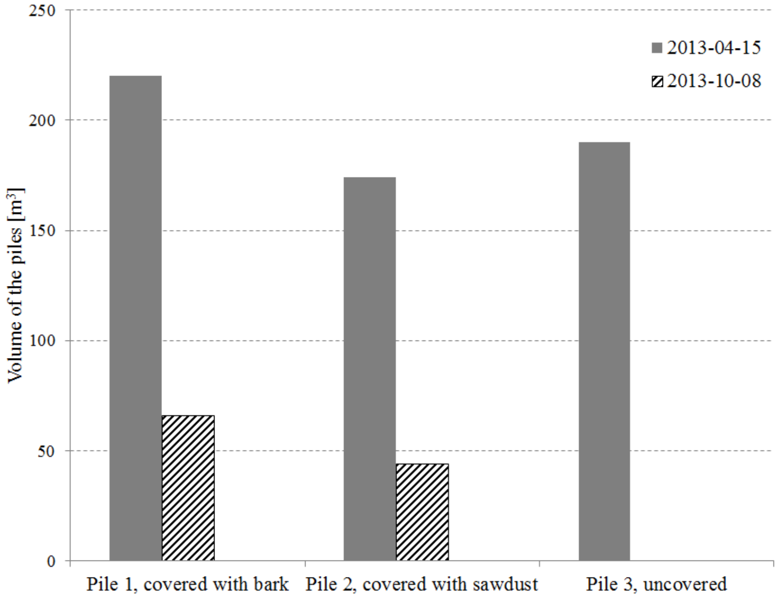

Figure 6.7: Volumes of snow in piles 1-3 at the start and end of the study period.

The results from the calculated and measured values of snow melt for Pile 1 and Pile 2 are summarized in Table 6.2. All snow in Pile 3 melted during the first month of storage. The results for Pile 1 and Pile 2 show that the percentage of melted snow was larger for Pile 2 than Pile 1. The insulating layer was slightly thinner on this pile. The initial volume was also smaller, see Table 6.2. The results from the theoretical calculations agree well with the experimental results.

Table 6.2: Results from theoretical calculations and measured values of melt rate for Pile 1 and Pile 2.

	Pile 1		Pile 2	
Initial volume	220 m^3	174 m^3		
Ground melt, (calculated)	8 m^3	6% of V_{TOT}	8 m^3	5% of V_{TOT}
Surface melt (calculated)	100 m^3	79% of V_{TOT}	119 m^3	82% of V_{TOT}
Rain melt, (calculated)	19 m^3	15% of V_{TOT}	19 m^3	13% of V_{TOT}
Total calculated snow melt	127 m^3		146 m^3	
Total snow melt in % based on calculated values:		64%		73%
Measured volume of melted snow	154 m^3		130 m^3	
Total snow melt in % based on measured values:		70%		75%

6.5 Indoor skiing

Indoor skiing in ski tunnels and ski domes is the most technical climate change adaption making it possible to ski independently of the climate Määttä (2010); Söderström (2016). Today there are at least eight indoor facilities for cross-country skiing in the world, all of them located in northern Europe (Fröjd, 2014). The first ski tunnel in the world opened in 1997 in Vuokatti, Finland. The walls in the tunnel is built of concrete and it is partly built under ground. The track is 1.2 km long and the skiers come to a turning point and skis the same way back. One loop is consequently 2.4 km. As shown in Figure 6.8, there are tracks both for classic style and skating.

In Sweden there are currently three indoor arenas for cross-country skiing, located in Torsby, Gothenburg and Piteå. The arena in Piteå is also used for automotive testing.

There are also indoor facilities for alpine skiing. The first one opened in 1986 and today there are more than 50 downhill ski halls in the world, one of them located in Dubai (Söderström, 2016). The largest indoor skiing arena for alpine skiing in Europe is SnowWorld, located in Landgraaf in the Netherlands. There are two pistes which are 520 m long, see Figure 6.9, and also a snow park with rails and jumps. A compilation of information from indoor ski facilities in Europe were put together and presented in a Swedish report: "Inomhus skidanläggningar i Europa" (Lintzén, 2013). The report was made as part of a feasibility study for the construction of a new indoor ski and automotive testing arena in Piteå, Sweden. Information on indoor skiing is also presented for instance in the theses "Energieffektiv produktion och lagring av snö för skidtunnel" (Fröjd, 2014) and "Climate Change sensitivity and adaption of cross-country skiing in Northern Europe" (Söderström, 2016).

Figure 6.8: Indoor cross-country skiing in Vuokatti, Finland.

Figure 6.9: Indoor alpine skiing at SnowWorld in Landgraaf, the Netherlands.

Chapter 7

Discussion

7.1 Mechanical properties of snow

Researchers has for a long time called attention to the fact that no standardized methods exist to establish material data on snow (Mellor, 1977). Mellor (1977) reported that there is a lack of theories for evaluating material properties and that a variety of test methods are used since no common methods and theories exist. This often result in difficulties in comparing mechanical data from different studies. As researchers use different methods it is of even greater importance to carefully document experimental test procedures and to classify the type of snow used for tests. The test methods used for the present tests are to a large extent the same as standardized methods for ice presented by Schwarz et al. (1981).

Backlight projection was used to study the structure of the fine grained and coarse grained snowtypes used in these studies as shown in Chapter 3 and **Paper B**. It gave good images of the structures although the magnification was not high enough for any detailed studies of grains or bonds between grains.

Density is one key property when characterizing snow. It establishes a relationship between snow and its water content and it is also correlated to the strength (Judson and Doesken, 2015). Mechanical properties of snow and snow strength are therefore often related to density (Mellor, 1963; Brown, 1977). However, several researchers report that snow structure and bondings between grains are more useful measures in combination with mechancical applications (Bader (1962); Shapiro et al. (1997); Kinosita (1967); Yong and Fukue (1977); Painter et al. (2007) and others). In these studies it is suggested not to use density alone as a parameter to which mechanical properties are evaluated. As a complement it is recommended to classify the snow and relate grain size, grain size distribution and other intergranular properties to the strength and mechanical properties.

The results from the investigations in this thesis, presented in Chapter 3 and **Paper B**, and the results from previous investigations presented in **Paper A** show that the density of machine-made snow used for constructions commonly range between 500-650 kg/m^3. These values are higher than values presented for natural snow on the ground (Mellor, 1974; Bader, 1962). Scattered values were observed especially for the coarse grained snow. These variations are assumed to be related to pore spaces and ice clusters in the snow (Vikström and Bernspång, 2002). Temperature variations, melting and refreezing are processes that will increase the ice content in snow and consequently the density. This was observed for the snow from different walls of ICEHOTEL as discussed in **Paper A** and **Paper B**, where samples from the outside walls which were more exposed to these processes, in general had higher density and larger grain size. The density of machine-made snow is also dependent on the conditions during snow production, as was observed for the coarse grained and fine grained machine-made snow used in the present investigations.

Earlier it was beleived that coarse grained machine-made snow with clusters of ice was advantageous as a material for constructions. The results in **Paper A** and Figure 3.16 showed that the compressive strength increased with increasing density. The same clear trend was not observed for the investigated samples of fine grained and coarse grained machine-made snow (see **Paper B**). Glenne (1987) observed a linear increase in compressive strength with increasing density for natural snow with densities $> 400\text{kg/m}^3$. The performed tests (Chapter 3 and **Paper B**) indicate that the coarse grained snow quality was rather unpredictable to failure. The clusters of ice may act as initiation points where cracks can be formed, in which case high density not implies high strength. The specimens taken out for compressive tests at ICEHOTEL were quite wet during specimen preparation but were let to freeze in the cold storage hall before the tests were performed. The refreezing of the specimens resulted in some cases in an icy and brittle structure. A sudden brittle failure occured for some of the specimens. Such an example is shown in Figure 7.1.

Figure 7.1: Brittle failure of test specimen during compressive test at ICEHOTEL.

According to Mellor (1977), the bonds between grains play an important role in determining mechancial properties of snow. The average number of bonds per grain increases with increasing density (Mellor, 1977). The relation between grain bonds and mechanical properities are of importance for the understanding of snow behavior (Kry, 1975). As the density increases, the average number of grains within a unit volume often increase which thus cause the mobility of grains to decrease since there are less pore space. When no longer mobility of grains can take place, the only possible deformation mechanism is by grain deformation which for natural snow usually occurs at densities above 500 kg/m^3 (Kry, 1975; Mellor, 1977). This is one reason why low and high density snow behave differently. In the present investigations, only high density snow were used, which means snow with densities higher than 400 kg/m^3 (Kinosita, 1967).

The creep behavior for beams of machine-made snow from two different walls of ICEHOTEL were investigated as shown in **Paper A**. It was clearly observed that beams of snow from the shady side, which had an average density of 520 kg/m^3 had a higher initial deformation rate than beams of snow from the wall exposed to sunshine with average density 610 kg/m^3. The snow on the shady side had a more fine grained structure than the snow from the wall exposed to sunshine, which was coarse grained. A similar deformation behavior was observed for the beams of fine grained snow, with an average density of about 530 kg/m^3 compared to the beams of coarse grained snow with an average density of 640 kg/m^3 as shown in Figures 3.21 and 3.22. The initial deformation rate was much higher for beams of fine grained snow. These results agree with results for natural snow where a lower creep rate generally is observed with increasing density (Bader, 1962). The reason for the lower creep rate for higher densities is assumed to be related to porosity, morphology and rearrangement and deformation of grains.

Young's modulus for snow is dependent on snow density, bond characteristics and temperature according to Mellor (1963). Moreover, (Mellor, 1963) found that the value of Young's modulus was very low for low density snow but increased almost linearly for densities above about 500 kg/m^3. The results from the investigations in this thesis showed a similar trend for samples from different walls of ICEHOTEL, i.e. increasing values of Young's modulus with increasing density, as shown in Figure 3.18. The same trend was not observed for the fine grained and coarse grained samples of snow as shown in **Paper B**. However, samples of fine grained snow had more similar values whereas results for coarse grained snow were more scattered. Highest values were in general observed with fine grained snow and with snow from the inside walls and walls in the shade, which also had a finer grain structure. This indicates a correlation between Young's modulus, grain size and intergranular properties. No correlation between Young's modulus and strain rate was obeserved.

Both the compressive strength and the residual strength, E_{res}, increased with strain rate for samples of fine grained machine-made snow up to a critical value of about 0.003 s^{-1} as shown in Figure 3.12 and in **Paper B**.

Kinosita (1957) and Kinosita (1967) performed compressive tests on cylindrical specimens of snow to study the relation between deformation velocity of the snow specimen and deformation behavior. The deformation behavior was found to be either plastic or destructive. The stress-strain relation was also studied and the stress for the same strain became larger as the deformation rate increased. When the deformation rate exceeded a certain critical value brittle fracture occurred and the stress dropped instantly from a maximum value to a very small value.

The same behavior was observed during the compressive tests performed with samples of fine grained machine-made snow as shown in Figure 3.17 and in **Paper B**. It was observed both in these studies and in Kinosita's experiments that the compression progressed further after a fracture. The stress increased again with a slope almost parallel to the one prior to the fracture, and fracture occored again at a similar stress level.

The critical deformation rate constitutes the transition from plasticity to brittleness and was by Kinosita (1967) found to increase with decreasing temperature and with increasing density. Kinosita performed compression tests with specimens of various lengths which imply that the deformation rate is more suitable than the strain rate to define the critical speed since the deformation rate only changes slightly but the strain rate largely with the length of the specimens. The conclusions from Kinosita's studies were that mechanical behavior and deformation behavior as well as critical rates of deformation depend on the internal structure of the snow, network connections and geometry of ice grains.

Kinosita (1967) presented an expression based on experimental results where the critical deformation rate, v_c, taking the temperature and density into account was suggested to be roughly estimated as

$$v_c = 0.4T + 20\rho + 3, \tag{7.1.1}$$

where T is the temperature in $°C$ and ρ the density in g/cm^3. The test temperature for the performed laboratory tests, -10°C, and densities between 500-700 kg/m^3 would, according to the Equation 7.1.1, give critical deformation rates between 13-17 mm/min. These values are lower than the critical deformation rate observed during the experiments, which was about 27 mm/min.

All compressive tests performed at ICEHOTEL were carried out at such a low deformation rate (up to max 5 mm/min) that only plastic deformation behavior took place. The maximum possible deformation rate for the compressive test machine used was not high enough for any brittle or destructive fracture to occur.

The strain rate affect the strenght of machine-made snow, which is in agreement with results of strenght of natural snow, where density, strain rate, strain history, snow type and temperature have been reported to affect the strenght (Mellor, 1963; Brown, 1977).

The effective modulus evaluated from four point load tests on beams were in general higher for fine grained machine-made snow compared to coarse grained machine-made snow. The bending strength and ultimate load were also in general higher and the results were more uniform for the fine grained snow. The maximum recorded value was about the same for the two snow qualities though, but the coarse grained snow had more scattered results. The load application rate was important during the beam tests. Applying the load slowly in the initial phase resulted in higher maximum ultimate loads before failure.

The test methods used to evaluate mechanical properties can be further improved, for example when it comes to the beam tests. An advantage with four point loading when evaluating mechanical properties for snow beams is that it is rather simple. A disadvantage with the method and other flexural test methods is that they are indirect. Applying elastic theory on snow which is an inhomogeneous, anisotropic and viscoelastic material gives incorrect numerical values. However, the elastic theory is assumed to give acceptable approximations for determining index values of strength properties, which can be used to compare equally evaluated mechanical properties from similar tests (Schwarz et al., 1981).

Values of snow strength must be applied with caution since failure of objects with different size and shape under different stress conditions give different results, which thus might not be comparable to each other (Mellor, 1963; Brown, 1977).

Strength of snow can according to Salm (1982) be explained as a chain where a series of elements are connected and the weakest link cause fracture of the entire body. Fracture of one element can also lead to re-distribution of stresses and eventually, after a sufficiently high increase in load, result in failure. For a satisfactory description of the structure which ultimately determines the strength of snow Bader (1962) suggests that the grains and the surrounding matrix have to be considered rather than separate grains alone. Mellor (1963) showed that the highest strength is achieved with snow having a wide range of particle sizes if density, temperature, specimen size and loading rate remain constant.

Snow has highest strength in compression (Mellor, 1963). In Mellor's (1963) study, the tensile strength for natural snow with similar density as the investigated machine-made snow was about half that of the compressive strength. Shear strength is according to Bader (1962) and Kuroiwa and Lachapelle (1973) similar to tensile strength. Shear strength were in Mellor's (1963) study found to be different for coarse grained and fine grained snow.

The strength of natural snow has in addition to grain texture and structure also been found to be dependent on density, strain rate, strain history, snow type and temperature (Mellor, 1963; Brown, 1977).

To conclude, it is always the bonds between grains that constitute both the strength and the hardness of snow (Shapiro et al., 1997). This should be kept in mind when machine-made snow for structures is produced. By controlling the snow making conditions the desired quality of snow can be produced. Although the results presented in **Paper A** and **Paper B** indicate that fine grained homogeneous snow give more predictable test results, it also gave rise to large plastic deformations although they did not lead to failure. Large deformations may not be desired for buildings like ICEHOTEL where structures like walls, roofs etc. should be kept intact during the whole season which corresponds to a period of almost six months.

As shown in **Paper A**, the deformation was much smaller for snow structures with wooden reinforcement. Most structures at ICEHOTEL today are reinforced and thus deformations are not a problem.

Future investigations of mechanical properties of machine-made snow should include testing different pre-determined snow qualities. Moreover, differences between machine-made snow and processed natural snow are of interest for future investigations.

7.2 Classification of snow

Classification of snow is of importance in all fields of snow research. The International Classification for Seasonal Snow on the Ground is generally used as a base for snow classification and it is accepted by most researchers and practitioners. The main focus in this thesis was to classify snow in ski tracks and pistes.

Classification of snow in ski tracks is of interest especially in competitive skiing since the properties of the snow decide both the character of the skis, the topography of the ski-base surface and the ski wax which should be used to optimize the sliding properties. As pointed out by Kuzmin (2010), it is also important to remember that a groomed ski track is a complicated medium which changes every minute. This complicates the process of adjusting parameters to optimize the overall performance and it also demonstrates the need for a fast and reliable method for snow classification in ski tracks and pistes.

Skiers and ski technicians generally talk about cold and warm snow conditions and soft and hard tracks, but there are no clear definition of what these terms actually mean. Terms such as grain size, hardness, liquid water content etc. would be more accurate and essential for the choise of skis, structures and wax. Table 4.2 is a common base for snow classification in cross-country ski tracks. The definitions are not very specific though. Characteristics of the ski track shall for example be classified as "clean", "partly clean", "partly dirty" and "dirty", but there are no guidelines on how these terms should be distinguished.

There has been a demand for a more detailed snow classificaion to determine ski track properties. One property that should be carefully measured is the hardness of the ski track, which likely will have an influence on the dominating friction mechanisms and accordingly the choice of skis for optimum performance. According to Colbeck (1993), there are a number of independent investigations showing that the highest friction occurs between the ski base and fresh snow, the second highest when the snow is wet while the lowest friction occur for old and dense snow. If the track is hard, the ski-snow interaction is limited to the top layer of the snow (Theile et al., 2009). During sintering, the snow settles and the bonds between grains become stronger, resulting in a harder track. Hard tracks are usually desirable for cross-country skiing since they are more durable, but of significant importance in alpine pistes used for competitions.

After grooming the piste must be given enough time to harden before it is used (Fauve et al., 2002). Guidlines for piste preparation and maintenance are presented in a handbook for practitioners written by Fauve et al. (2002). By classifying the snow prior to preparation, the most favourable strategy can be adapted to achieve the required pistes.

The results from the snow classification measurements in ski tracks using the optical sensor Road Eye, as discussed in Section 4 and **Paper C**, showed that different types of snow can be clearly distinguishable. However, additional measurements are needed and also studies to correlate the reflectance to known snow characteristics. This new method enables a completly new classification strategy for ski tracks and pistes. Furthermore, it enables a fast classification of a complete track, not just measurements at one or a few locations which is common practice today. Differences in snow quality along the track can be detected. The information from such measurement runs can be very useful for competitive skiers. The choice of skis can be further optimized according to snow properties at the most critical parts of the track. Attaching an IR-sensor to the measurement system would enable snow temperature to be registered which would add additional valuable information. One way to perform the measurements could be to attach the measurement system to the grooming machine. Then the information could easily be distributed through the web and thus accessible for all skiers, ski technicians and other people with an interest.

Some of the data from the measurements using the sensor Road Eye in ski tracks were correlated to the spectral reflectance measurements of snow samples with different liquid water content by calculating the NDWI index as further described in **Paper C**. The results showed that the method can be used to capture different water contents in snow, however, by only using this method it was not possible to derive whether the water was in solid or liquid phase, i.e. ice or water.

Optical methods for snow classification are very sensitive to grain size. Adding just a small amount of liquid water results in a dramatically increased crystal growth rate and larger grains (Davis et al., 1987). This was observed when the samples for the laboratory experiments. Moreover, the solution also form liquid clusters (Wåhlin et al., 2014). Aging of snow and melting and refrezing processes also increase the crystal growth rate (Warren, 1982).

As shown in the presented study in **Paper C** and in Figure 4.6, increased amount of liquid water in the snow resulted in higher absorption. This can be related to the increased grain size, grain clusters and liquid clusters which absorb more light and consequently less is scattered.

The comparison between the reflectance for the spectrometer and the Road Eye sensor (see Figure 4.6), showed that the reflectance was comparable from the measurements, although the Road Eye showed higher values of reflectance. Both sensors captured the linearity between decreased reflectance with increased water content.

It is a common practice to find optimal wavelength bands where specific properties can be estimated. In Figure 4.5 it was shown that the snow samples were well separated at the wavelength bands 980 nm, 1310 nm and 1550 nm. Therefore these were selected as optimum wavelengths in the presented study and considered in the further investigations as detailed in **Paper C**.

The NDWI has been videly used in many applications, for example for remote sensing of vegetation (Gao, 1995) and snow-vegetation interactions and to study snow melt in the spring (Delbart et al., 2006). The NDWI is easily implemented and sensitive to small water contents. An approximately linear correlation between the NDWI and water content was observed using both the spectrometer and the Road Eye. The NDWI index increased as the water in the snow increased. As for the reflectance, the values are higher for the Road Eye measurements compared to the spectrometer measurements, but captures the effect of water in a similar way.

7.3 Sliding friction during skiing

The ski base sliding friction depend on several different factors, of which all contribute to the total friction coefficient to a different extent depending on the snow and ski properties.

Since the properties of the skis are believed to be more important than the ski base structure and the ski wax, it is decisive to measure the span curve properly. The span curve and the stiffness curve correspond to the identity of the ski and show much of the mechanical properties.

Using Skiselector enabled span curves and stiffness curves to be measured, but only along a line from the ski tip to the ski tail. The pressure distribution across the ski could not be estimated. The pressure distribution is of interest for future investigations since it is assumed to be one of the most crucial parameters for the sliding properties. Moreover, the methods available for span curve measurements only deal with static analysis. The span curve changes during dynamic loading and is a field for future investigation.

Analyzing skis aimed for "cold" and "warm" snow conditions, so called cold skis and plus skis, resulted in some common characteristics for the respective group of skis. Common for cold skis are that both the front and rear glide zones are longer than for skis recommend for warm or wet snow conditions. According to Equation (5.2.17), longer glide zones imply a lower friction force due to compaction since the load is distributed on a larger area. This is advantageous especially during sogt snow conditions.

For classic style skis, the peak camber is higher for plus skis, enabling a thicker layer of grip wax or klister which is commonly used during wet conditions. Other differences observed are the very front and rear parts of the span curves, which for plus skis have larger angles or steeper slopes as seen in Figure 5.5. This shape of the span curve and the shorter glide zones are believed to be favourable when the thickness of the water film increases, so that there is a risk for capillary drag. Moreover, skis aimed for wet conditions sometimes have "gaps" in the glide zones, see the circled areas in Figure 7.2, which further is supposed to be favourable to avoid a too thick and widespread water film. The wet friction force is given by Equation (5.2.16). If the area of the water film gets to wide spread, the friction force will increase. One way to minimize this risk is to shorten the glide zones and to introduce such "gaps" in the glide zones.

Field tests showed that skis aimed for wet conditions often are good also during cold conditions, but not always vice versa. Koptyug and Kuzmin (2011) asserted that skis with an optimal pressure distribution always have good sliding properties, even if the ski base surface is not perfect. The definition of an optimum pressure distribution still needs to be investigated,

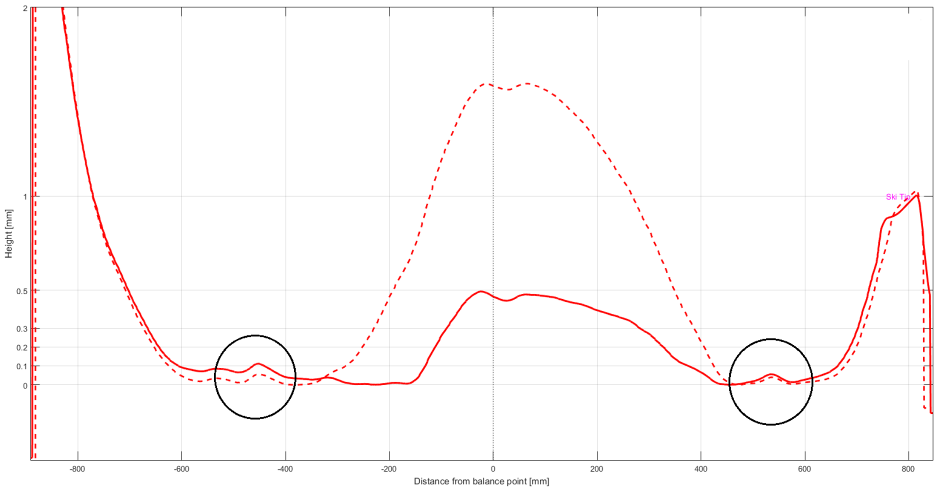

Figure 7.2: Gaps in a span curve for a ski recommended for wet snow conditions.

as well as a method to determine the pressure distribution, also under dynamic conditions.

The temperature dependence of span curve characteristics and properties of classic style cross-country skis are presented in **Paper D**. Changes in stiffness and glide zone lengths were observed which illustrate the importance of measuring ski properties at a temperature relevant for skiing. Moreover, quite large differences in length of glide zones, peak camber height and stiffness were observed during measurements of skis within the same pair, both at room temperature and at -15°C. Not all instruments can capture the significant ski characteristics and may therefore result in such differences.

In published studies on sliding friction, the span curve and pressure distribution of skis are rarely described in detail. Since the span curve is assumed to influence the sliding friction to a greater extent than the ski base structure and the wax, it is essential to know the span curve and the pressure distribution. If different skis are used for example during glide wax tests it seems impossible to know if the results are to be attributed to the ski, the structure or the wax.

In addition to the pressure distribution, also the real contact area is by many researchers assumed to be one of the most important parameters for the sliding friction. The real contact area is the sum of all infinitely small contact spots. Furthermore, the size of the contact spots are essential for the water film thickness and thus directly connected to the sliding friction. The real contact area is defined as the ratio of the normal force to the hardness, according to Equation (5.2.7), where the hardness is the hardness of the softer material at the prevailing temperature.

Both the real contact area and the contact spots can be adjusted using rilling tools and thus affect the thickness of the water film and the sliding properties. There are rilling tools where a structure is pushed down into the ski base, creating an elastic deformation, i.e. a non-permanent structure Breitschädel et al. (2010) and tools where an additional pattern permanently is cut into the ski base. Several studies are made where different structures are tested in different snow conditions, see for instance Moldestad (1999), where it was concluded that the optimum ski base structure roughness increased with snow humidity or with water film thickness.

The results from the field tests of skis with different ski base surface topography showed that longitudinal rilling patterns created with rolling tools had a poorer influence on the sliding properties compared to broken structures both during wet and cold snow conditions. A deeper structure were more beneficial during wet conditions. The longitudinal cutting tools, used on ski pairs 4 and 5, were among the top five ski pairs, both during cold and wet conditions. The deeper of these two structures was more favourable during wet conditions. According to Colbeck (1994) transverse structures are beneficial at low temperatures and longitudinal structures at high temperatures. The results in this study does not completely agree with this conclusion and presumably there are more than one factor which must be taken into account to explain the significance of surface topography in different snow conditions. The real contact area is one of the significant parameters that should be further investigated for the ski pairs tested. The reason why the fine broken structures were advantageous during cold conditions is assumed to be related to the real contact area. According to Equation (5.2.13) the dry friction force is reduced with an increased real contact area. Structuring the skis with the broken structures may increase the real contact area. The real contact area is difficult to measure though, and as seen in the presented studies in Chapter 5.3, different methods seem to give different results.

Moreover, the roughness and surface finish, which commonly is determined in connection to topography studies, do not provide all necessary information about the surface. As pointed out by Hasler et al. (2016), R_a only gives information about variation in height, but does not provide any information about the slopes, shapes and sizes of asperities.

One additional question is what temperatures that should be considered "low" and "high". According to Rogowski et al. (2005), warm snow was considered as snow with temperatures above -5°C, whereas in most studies warm temperatures are regarded as close to 0°C. Temperature is a parameter often measured during sliding tests but it is assumed that the snow grain size, the structure and other intergranular parameters are of even higher significance. This further highlight the importance of a detailed and satisfactory snow classification.

The effect of using glide wax on cross-country skis were not investigated in this study. It seems like noone so far exactly understands what actually happens in the ski base surface when skis are waxed. Researchers disagree on the exact use and benefits with glide wax. Karlöf et al. (2005) mention "stored wax in the base" which touch upon the assertion of pores in the ski base which is a questioned statement without any scientific base. According to Moldestad (1999) and other researchers the effect of waxing might be changed electric conductivity, electrical charging and decreased dirt adhesion, which lead to improved sliding properties. Koptyug and Kuzmin (2011) state that both waxed and unwaxed skis pick up dirt. Other benefits with waxed are by some researchers assumed to be increased hardness of the ski base surface. However, Koptyug and Kuzmin (2011) state that ski wax make the ski base surface softer than it initially was and that the only possibility for wax to increase the hardness of the surface if it has been waxed before. Different ski waxes are said to generate different thicknesses of the water film (Moldestad, 1999; Rogowski et al., 2005). Thus the use of different wax could be beneficial during different snow conditions. The effect of glide wax is a field of research for future investigations.

The development of cross-country skis are continuously advancing. There are an abundance of different skis on the market aimed for different styles of skiing, different snow conditions and different levels of skiers. Within long distance cross-country skiing it has during the last few years become increasingly more common to ski without grip wax and thus only practice double poling. This technique does not require any grip wax and thus the grip wax zone can be excluded. Part of the work on span curve analysis in this thesis concerned optimizing span curves for a new type of ski aimed only for double poling. The preliminary results of these investigations seem to be promising, but further research and tests are necessary to draw some clear conclusions.

7.4 Snow and climate change

The climate change will according to Scott et al. (2006) and Breiling (1998) create winners and loosers in the ski industry. Breiling (1998) addressed the issue based on ski resorts in Austria. Resorts located at a low altitude are expected to loose customers wheras on the other hand resorts at higher altitudes might be favoured and experience a comparative advantage. A similar scenario is likely to be expected throughout the European alp region. Scott et al. (2003) introduced snowmaking as an adaption strategy to climate change, which thus substantially lower the climate impact on the ski industry. However, large quantities of water are required for the snow production. Ski areas with large water reservoirs to supply water or areas where water can be withdrawn from lakes and streams are therefore winners (Scott et al., 2006). Resorts without snowmaking possibilites or with limited resources are disfavoured.

Increased snow production is currently the common way to handle lack of natural snow but also a method to ensure the desired amount of snow at the right time for stakeholders in the winter business industry. More efficient snow production methods are developed and there are also methods to produce snow at temperatures above 0°C. This require some kind of refrigeration though and is thus more costly. An increased environmental awareness is observed among companies in the winter business industry. There is a demand for new methods and techniques to gurantee snow which not only shall be cost effective.

As regards snow and climate change, the most important questions are whether or not it will be possible to produce enough snow at an acceptable cost and if winter tourism can remain a sustainable economy if global warming and climate change continue (Breiling and Charamza, 1999; Scott et al., 2003; Steiger, 2012). Most researchers seem to agree upon the fact that adaption strategies are associated with costs, but the proportions and time frame seem to be more uncertain. Scott et al. (2006) estimate a doubling of the water requirements by the year 2050. A question for future research is what environmetal impact that will have. The impact on animals, plants and the ecosystem needs to be investigated. Furthermore, it is important to include transports of snow to pistes and tracks, snow processing and grooming, in addition to the energy and water consumption, in an environmetal consequence analysis.

Snow storage seems to become a method of increasing interest. The snow which shall be stored can be produced during the most favourable conditions during the winter. As seen in some places, also natural snow has been used for snow storage, as further discussed in **Paper E**. Snow from alpine ski slopes has in some places been stored and re-used. The possibility of using natural snow for snow storage needs to be further investigated, both with respect to the quality of the snow after the period of storage, but also concerning collection of natural snow and what rules and regulations there are regarding contamination and pollution. Using snow from roads in urban areas are associated with environmental issues. In Sweden, the normal snow handling practice is to transport the snow to special snow deposits since the snow are more or less polluted (Viklander, 1996). However, Viklander (1999) reported a clear difference in concentration of contamination between snow from areas with heavy traffic compared to areas with less trafic or activities connected with traffic. The question whether "clean" snow could be collected from areas with low amounts of pollution has been raised since many areas where snow storage is of interest are sparsely populated. Thus those areas might be places where natural snow could be collected. This need further investigation though. If natural snow could be used, one question to adress is a criteria for acceptable amounts of pollution.

The calculated values of snow melt for Pile 1 and Pile 2 in the experiment performed in Arjeplog in northern Sweden showed that experimental values of volumes of melted snow correspond well to calculated values, using the theoretical model presented in **Paper E**. The area reduction was not taken into consideration in the calculations though. These results indicate that the melt rate can be estimated with theoretical calculations, if the geometry of the pile is known and relevant data for climate and material properties are used. By calculating the snow melt, it is possible to estimate the efficiency of different insulating materials and also the thickness required to sufficiently insulate the snow from melting. This gives an opportunity to make economic optimizations based on the amount of snow that melts and additional costs for insulation and placement.

As discussed in **Paper E** and shown in Figure 6.6, larger piles of snow loose as a percentage less snow than piles with a smaller volume. This is supposed to be related to the surface melt rate. In **Paper E** results where shown were the snow melt for two piles of snow with the same thermal insulation but different volume and geometry were measured. It was observed that piles with a larger surface to volume ratio have a higher melt rate. A theoretical explanation of this fact was also included.

An increase in air humidity impairs the evaporation in the insulating layer. Skogsberg and Lundberg (2005) found that the evaporative cooling effect had a significant influence on the melt rate which is supported in the studies in this thesis. A porous material in humid air with constant relative humidity and constant temperature will eventually reach its hygroscopic equilibrium moisture content (Skogsberg, 2005). Increasing hygroscopic moisture content is called absorption, whereas decreasing is called desorption. Sorption isotherms for cutter shavings with a dry density of 90 kg/m^3 based on spruce with a dry density of 430 kg/m^3 are shown in Figure 7.3. The moisture content, w, is shown as a function of relative air humidity, RH. The moisture content during absorption is denoted w_{abs} and the moisture content during desorption is denoted w_{des}. The moisture content increases rapidly as the relative humidity exceed approximately 85-90%. An increase in relative humidity is hence a reason to increased melt rate. A substantially increased melt rate is likely to be observed for insulating layers without or with poor evaporation. Therefore it is suggested to use an insulating material with good evaporation properties.

Natural insulating materials has a decay rate which explains why these are replaced after a certain time. The exact decay rate of different commonly used insulating materials has not been studied but is suggested to be investigated in future studies. The moisture in porous materials is transferred as vapor and as water. Most of the water in an insulating layer is transported downwards through the snow, but some of it is transported upwards through the insulating layer due to capillary forces and evaporation. The rate at which moisture is transferred in the insulating layer decreases with time and with capillary height, resulting in an increased melt rate (Skogsberg, 2005). A wet porous material being drained will attain a new moisture gradient

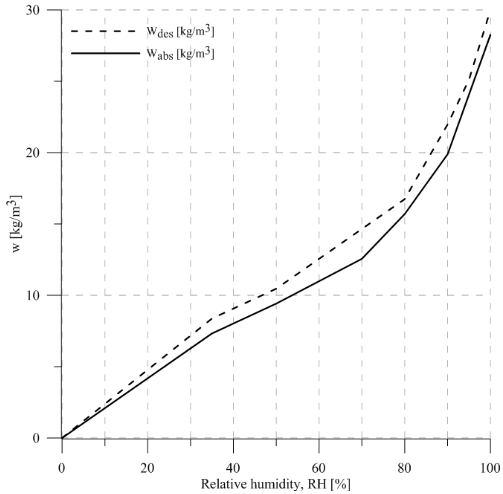

Figure 7.3: Sorption isotherms for cutter shavings with dry density $90kg/m^3$ *based on Swedish spruce with dry density* $40kg/m^3$ *(after Hedenblad (1996) and Skogsberg (2005)).*

through the material, called the passive capillary moisture content, where both total moisture content and capillary height are greater than before soaking (Nevander and Elmarsson, 1994). The capillary moisture transfer, m_{cap}, can according to Skogsberg (2005) be written as:

$$m_{cap} = \frac{A}{2\sqrt{t}}, \tag{7.4.1}$$

where A is the water sorption coefficient and t the time the material has been in contact with water. The sorption coefficient, A, decreases towards zero with time. The decay rate with time is visualized in Figure 7.4. Factors influencing the decay rate of an insulating material should be taken into account in order to insulate the snow sufficiently. Adding some new material or increasing the layer thickness might be alternatives to replacing all material.

The thermal resistance, R, can be calculated as the ratio between the thickness of the insulating layer and the thermal conductivity, λ_{ins}, i.e.

$$R = \frac{d}{\lambda_{ins}}. \tag{7.4.2}$$

The thermal conductivity is not very sensitive to the porosity if the degree of water saturation is high. However, the thickness of the insulating layer is of high importance for the melt rate. The mouldering of bark, saw dust or any other natural insulating material results in a decreased porosity and hence a reduced thickness of the insulating layer. Moreover, a reduced porosity impair the evaporation which in turn will lead to poorer cooling of the pile.

The relation between the volume, V, of insulating material and the porosity, n, is:

$$V = V_s(\frac{1}{1-n}). \tag{7.4.3}$$

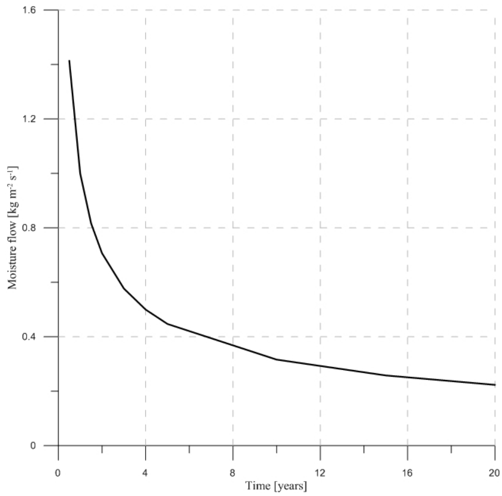

Figure 7.4: Moisture flow into a porous material in contact with water.

Thus, the volume of the insulating layer decreases with decreasing porosity. The thermal resistance as a function of porosity, n, is shown in Figure 7.5. The porosity for bark and saw dust was not investigated, so values of porosity in the figure are based on peat (Vesterberg et al., 2016). The thermal resistance decreases with decreasing porosity. Furthermore, the porosity decreases as a consequence of aging and mouldering which thus lead to deteriorating insulating properties.

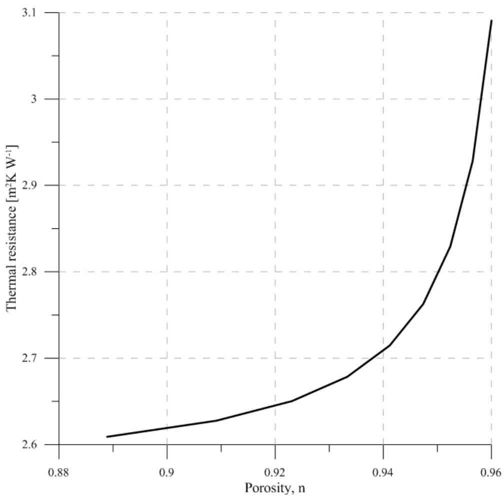

Figure 7.5: Thermal insulance as a function of porosity for an insulating layer.

To create an optimal snow depot, the most important is to minimize the surface melt rate, since this constitutes the largest part of the total melt rate. Thus the geometry should be designed to minimize the surface area. Cost and properties of different insulating material should be taken into consideration. Depending on the local conditions different alternatives may be preferred. Skogsberg and Lundberg (2005) conclude that enough thermal insulation only is a matter of layer thickness, which also can be seen in Equation (7.4.2). An insulating layer with poor porosity or with weaker insulating properties, can be compensated by increasing the thickness instead.

The snow storage should be placed at a location which is protected from wind and solar radiation with good drainage. It has been observed that snow in large snow depots has turned into ice near the ground surface (Hedlund, 2016). This has been assumed to be a result of poor drainage but also because of too large compressive stress due to the total load (Hedlund, 2016). As discussed in Chapter 2 and in the previous section on mechanical properties of snow, the self weight stress, pressure and time are factors which increase the density of snow. Kinosita (1957) found that slow enough deformation can turn snow into ice, which is what happens for a high self weight load. The self weight load causes bondings between snow grains to collapse which in turn implies an increase in density. Therefore, there might be an upper limit for the recommended height of a pile, which should be further investigated in future studies.

The efficiency of different thermal insulating materials need to be further investigated, both when it comes to natural materials and fabricated materials. Fabricated materials can be new types of textiles, which both serve as insulation on the snow but also enable evaporation to minimize the snow melt. Moreover, the long-term profitability should be taken into account. Materials with a decay rate needs to be replaced after some years whereas others have a longer life time. In addition, some materials are more environmentally harmful than others. The decay rate of different insulating materials is further a field of research for future investigations.

An on-going laboratory study is performed to investigate the efficiency as thermal insulation on snow of some different new textile materials. In addition to the new materials, experiments are also carried out with the commonly used natural materials sawdust and wood chips so that the results can be compared. Other parameters that are studied in this experiments are thicknesses of insulating layers and saw dust of different age, i.e. different grade of mouldering.

Chapter 8

Conclusions and future research

8.1 Conclusions

Based on the research presented in this thesis the following conclusions have been drawn:

Mechanical properties of snow

- Machine-made snow has in general higher density than natural snow. Strength of snow often increase with increasing density. Thus, strenght of machine-made snow is most often higher compared to natural snow.
- Snow structure, including grain size, bondings between grains and other intergranular properties are parameters of importance for the mechanical properties of snow.
- The strength and deformation behavior differ for coarse grained and fine grained machine-made snow. The compressive strength and bending strength of fine grained machine-made snow were higher than for coarse grained machine-made snow. However, the creep deformations were also higher. Coarse grained machine-made snow with clusters of ice may be stiff but brittle.
- During uniaxial compressive tests there exists a critical deformation rate where the deformation behavior changes from plasticity and strain hardening to brittleness or failure.
- The compressive strength increased with increasing density for specimens of machine-made snow tested during uniaxial compression at equal deformation rate.
- The load application rate is of importance for the deformation process. If the load initially is applied slowly, structures may resist high loads without failure.
- Structures of snow may undergo large plastic deformations without failure.
- When designing buildings and constructions of machine-made snow, deformation behavior should be taken into account in addition to strength properties since the structures should be kept intact for the entire winter season.

Snow classification

- Spectral reflectance measurements can be used to estimate physical properties of snow, such as grain size, water content, age and roughness.
- Water content in snow can be estimated by spectral reflectance measurements, both using a traditional spectrometer and the optical sensor Road Eye.
- Wavelength bands 980 nm, 1310 nm and 1550 nm were considered optimal for classification of snow with different water contents.
- The NDWI is sensitive to water content and an approximately linear correlation between NDWI and water content in snow was observed.
- The optical sensor Road Eye can be used to classify different types of snow in ski tracks and pistes.

Cross-country skiing

- The major mechanical properties of cross-country skis can be determined by measuring the span curve.
- The span curve demonstrate the characteristics of cross-country skis. From the span curve measurements, glide zone lengths, peak camber height could be calculated.
- Different features of the span curve are advantageous during different snow and track conditions. For example, shorter glide zone lengths were found to be beneficial in wet and hard tracks.
- Thermo-related changes in mechanical properties of classic style cross-country skis were observed. This implies that it is significant to measure skis at a temperature relevant for skiing in order to accuratelly determine the span curves and stiffness curves.
- The ski base topography has an influnce on the sliding properties. A coarse structure is favourable during wet snow conditions.

Snow and climate change

- Winter business industry is highly affected by climate change. The most common method to handle lack of natural snow is to increase the snow production. In addition, snow storage is a method of increasing interest. Indoor skiing is also a growing business.
- Natural materials used as thermal insulation on stored snow, such as bark and different types of cutter shavings, are efficient if the layer thickness is large enough.
- The surface melt constitute the most significant part of the total snow melt in an insulated snow depot. Thus, the surface area should be minimized.
- Theoretical calculations with chopped cones showed that approximately 80% of the total melted volume was due to surface melt, 15% was due to rain melt and 5% was due to ground melt.

- Higher relative humidity and higher moisture content in the insulating layer increase the melt rate of stored snow.
- The thermal resistance will decrease with time when sawdust and bark are used as insulating materials. This is due to due to aging and mouldering, which imply a decreased porosity.
- Decreased evaporation implies increased melt rate for insulated snow depots. An insulating layer without or with poor evaporation will thus lead to a substantially increased melt rate. It is thus advantageous to choose a thermal insulating material with good evaporation properties.
- Simplified theoretical calculations can be used to estimate volumes of melted snow in snow depots, if the geometry of the pile, climate data and type of thermal insulation is known. Theoretical calculations agree well with measured values of melted snow, at least for the experiment performed in northern Sweden.

8.2 Future research

Scientists have conducted snow and ice research for many years, but the climate change, new requirements on snow and snow quality and new fields of applications has brought new questions of research. Some topics for future research, based on the work in this thesis are:

- To further investigate how to prepare snow as a material to be used for constructions.
- Determine mechanical properties of different pre-determined snow qualities.
- Correlate mechanical properties of snow to carefully determined snow characteristics.
- Continue the development of the new method for snow classification in ski tracks and pistes using spectral reflectance measurements and in particular the sensor Road Eye.
- Develop a method for measuring the pressure distribution of a cross-country ski, also during dynamic loading.
- Correlate results from sliding tests of skis with different ski base surface topography to accurately determined snow conditions.
- Correlate microscopy studies of the surface topography to results from sliding tests.
- Determine the real contact area of cross-country skis.
- Investigate the effect ski wax has on the ski base material and what actually occurs in the ski base surface during waxing.
- Develop a method for ski tests in the field where the human factor is eliminated.
- Study the environmetal consequences of the increased snow production and increased use of machine-made snow.
- Investigate the possibility to use natural snow for snow storage, both out of an environmetal perspective but also in terms of snow quality.

- Analyze the results from the laboratory study where different textiles were used as thermal insulation on snow.

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Part II

Paper A

Study on basic material properties of artificial snow

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Study on basic material properties of artificial snow

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ABSTRACT

For buildings and constructions made by snow, like for example the ICEHOTEL in Jukkasjärvi, generally artificial snow is used. Both for safety reasons and for design purposes it is hence of importance to understand the material behaviour of artificial snow. Many buildings and structures made by snow and ice are constructed using knowledge obtained by experience.

When subjected to a load snow undergoes an immediate elastic deformation and a time-dependent irreversible deformation, known as snow creep, which constitutes the considerably highest part of the total deformation. The magnitude of the snow creep deformation is the dominating deformation mechanism for snow structures but it is poorly investigated and not well understood.

To study material parameters and mechanical behaviour of artificial snow unconfined compression test and deformation tests to observe the creep behaviour have been performed. Results from experimental tests have been analyzed and compared with theoretical calculations and finite element simulations. The density and viscosity have shown to be important parameters for the deformation behaviour and will have a direct influence on the creep rate. The investigation indicates that the artificial snow used for the tests have higher density, compression strength and creep strength compared to natural snow used in other studies.

Keywords: Creep, Deformation, Laboratory tests, Snow ice and frost, Strength and testing of materials

1 INTRODUCTION

Snow has been used for several years as a material for constructions. The Inuit igloos may be the most well-known buildings made by snow and ice. Experiences with bigger constructions have been popular during the last decades (Selzer, 2001). Today the ICEHOTEL in Jukkasjärvi is one of the biggest and most well-known snow buildings in the world. In addition to the hotel building, also a church and an ice bar is built each year. Buildings constructed by snow and ice must be designed with care in order to ensure safety and durability. For construction purposes artificial snow is generally used. Artificial snow is here referred to as snow manufactured by e.g. snow cannons. Knowledge about the material properties and the behaviour of artificial snow is important in order to design the building properly, using the right amount of snow and ice.

The properties of snow and ice are strongly dependent on the climate conditions prevailing during formation of the crystal structure (Finnish Safety and Chemical Agency, 2011). Different mechanical properties are hence likely to be found in artificially produced snow compared to natural snow as well as in artificial snow manufactured under different weather conditions. Time dependent transitions and parameters such as temperature and humidity have a great influence on the material's properties.

Several investigations are made on the deformation behaviour and strength of snow but those are generally based on natural snow on the ground (Bader, 1962, Mellor, 1974, Salm, 1982, Shapiro et al., 1997). The only studies which have been found regarding mechanical properties of artificial snow for construction purposes are made at Luleå University of Technology (Vikström, 2002, Selzer, 2001). Thus there is a need to evaluate and understand the difference between natural snow and artificial snow.

Some of the most important properties when studying snow are density, porosity, compressibility, creep and shear strength (Cassel, 1950, Chandel et al., 2007). The properties are of course related to each other.

The density of snow is dependent on external conditions, for example the rate of compaction and liquid water content. The density of freshly deposited natural snow is generally less than 100 kg m^{-3} (Mellor, 1977). High density snow in natural snow packs has a density of > 500 kg m^{-3} (Salm, 1982). Snow is considered to have become ice at a density of about 800 kg m $^{-3}$ (Mellor, 1977).

Unconfined compression tests are a common way to measure the compression strength. The influence of different strain rates are also often studied (Mellor, 1975, Mellor and Smith, 1966). It is proposed that there is a critical strain rate which varies with temperature and density (Mellor and Smith, 1966). Samples tested below the critical strain rate have been observed to creep whereas samples tested above that strain rate will undergo a brittle fracture.

Creep is an important parameter which results in the settlement of natural snow in a snowpack under the action of pressure and metamorphism (Chandel et al.,2007). Snow creep is provoked by deformation or rearrangement of grains and results in densification of the snow (Selzer, 2001). Snow creep in natural snow packs has been studied by several researchers (Bader, 1962, McClung, 1982 and others). Studies of creep behaviour of constructions made by natural and artificial snow are rare. The experiments made by Vikström (2002) may be the first creep studies on artificial snow manufactured for construction purposes. The viscosity of snow is an important parameter for the creep behaviour (Yosida, 1956). The viscosity is highly temperature dependent and has a direct influence on the creep strain rate. The value of the viscosity decreases as the snow becomes softer, which allows larger deformations of the snow.

This review summarizes research performed by Luleå University of Technology to study the deformation behaviour of artificial snow manufactured in Jukkasjärvi for the ice hotel.

2 LABORATORY AND FIELD TESTS

Studies to measure the deformation properties were made on snow and snow structures that formed the ICEHOTEL and its ice church during the winter 2000-2001 (Vikström, 2002). In 2010 new experiments were made aiming to further investigate the deformation properties and to study the influence of sun exposure during the season on artificial snow constructions. Both laboratory tests and field tests on site have been performed.

2.1 Compression tests

Unconfined compression tests were performed on cylindrical test samples which were drilled out from blocks of snow from the ice church and the ice hotel (table 1). Snow samples from the ice church were taken out in December 2000 (Vikström, 2002) (table 1). Samples from the ICEHOTEL were taken out in April 2010. In order to investigate the influence of sunshine on the snow in the walls samples were taken out both from the side of the building exposed to sunshine (Comp2) and from the shady side (Comp3). The tests were conducted at a constant deformation rate. The samples were loaded to failure. The origins of the samples, dimension, temperature and deformation rate are compiled in table 1 along with the number of tests performed for each case.

Table 1 Unconfined compression tests. Samples taken out from the ice church in December 2000 and from the ICEHOTEL in April 2010. Samples both from the side exposed to sunshine (Comp2) and the shady side (Comp3) were analyzed.

Origin of sample	**Ice church, Comp1**	**Ice hotel, Comp2**	**Ice hotel, Comp3**
Dimension [mm]	Ø = 50 h = 100	Ø = 70 h = 120	Ø = 70 h = 120
Temperature [°C]	-5, -10, -11	-10	-10
Deformation rate [mm s^{-1}]	0.025	0.1	0.1
Number of tests	5*	8	10

*Two tests at -5°C, two tests at -10°C and one test at -11°C.

2.2 Creep tests

Creep tests have been performed both in the laboratory and on site. Table 2 summarizes the performed tests.

Table 2 Summary of creep tests

Origin of test samples	**Test**
Ice church (cylinders)	Cr1
New blocks of artificial snow (7 beams)	Cr2
ICEHOTEL, wall exposed to sunshine (2 beams)	Cr3
ICEHOTEL, wall on the shady side (2 beams)	Cr4
Wooden reinforced arc of snow (1 prefabricated construction)	Cr5
Field tests inside the ice church	Cr 6

Cylindrical samples of artificial snow from the walls of the ice church were used to study the creep behaviour (Vikström, 2002). The diameter and length of the samples were 40 mm. The samples were created by compacting snow into small moulds. Creep tests (Cr1) were performed at -5°C, -10°C and -11°C. The samples were loaded with a constant stress applied by a dead load and allowed to deform vertically. The stress levels were 0.06 MPa for the tests at -5°C, 0.07 MPa for the tests at -10°C and 0.10 MPa for the tests at -11°C. For each temperature two samples were deformed under confined conditions and two samples under unconfined conditions. The vertical deformation as a function of time was recorded.

In 2001 creep tests (Cr 2) were performed in a cold storage hall in Jukkasjärvi using beams of artificial snow (Vikström, 2002). Seven beams were sawed out from bigger blocks of snow using a power driven saw in order to get as fine surfaces as possible. The dimension of the beams was 0.4x0.2x1.8 m. The beams were simply supported and a constant dead load was applied through a cantilever at two load points, each at one third of the length, figure 1. The temperature when performing the creep tests was about -5°C. The load and deflection were recorded using linear variable differential transformers.

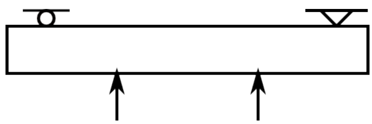

Figure 1; Outline of the creep tests (Cr 2).

Simply supported beams of artificial snow were used for creep tests in the laboratory in 2010 (Cr3 and Cr4). The beams were taken out from the walls of the ice hotel in April 2010. Two beams of snow were taken out from the side of the building exposed to sunshine and two from the shady side. The dimension was 0.2x0.4x1.6 m. 0.3 m of each end of the beam was used as supports making the free length in between 1 m. One beam from each side of the building was loaded with a circular dead load of about 200 N. The other beam from each side was unloaded. The vertical deflection at each side of the central part was measured by hand. The temperature in the laboratory was set to -10°C but was fluctuating between

-10°C and 0°C due to problems with the cooling system.
One wooden reinforced pre-fabricated arc of snow was placed in a cold storage room in Jukkasjärvi in 2010 where the temperature was around -5°C (Cr5). The kind of arc used for the measurements were the same as generally is used when building hallways etc. in the ice hotel, see figure 2. The arc is manufactured using two sections which are created by compacting snow into steel moulds. The sections are then put together and the internal dimension of the finished arc is 5.6 m wide and 3 m in height. The thickness of the arc is 1 m in the bottom part and about 0.5 m in the upper section. The creep behaviour was observed during a period of 77 days. Linear variable differential transformers were attached at two positions on the inner side of the upper central part of the arc and at one position about 45° to the side from the centre. Those were used to record the vertical deflection every 10 minutes using a data logger.

Figure 2 Pre fabricated wooden reinforced arc of snow manufactured using steel moulds. The height of the arc is approximately 2 m and the width 4 m. Photo: Mikael Bergman.

3 EVALUATION OF MATERIAL PROPERTIES

During the unconfined compression tests at constant deformation rate, the peak force, F, was recorded and used as failure criterion. The unconfined compression strength, σ_{UCC}, was calculated by dividing the maximum value of the force, F, by the cross section area of each test sample.

The strain rate at different times during the creep tests was determined during the experiment with the cylindrical test samples (Vikström, 2002). The viscosity was calculated as the vertical stress divided by the strain rate. For unconfined creep tests the viscosity is denoted axial viscosity η_E. For confined creep tests the viscosity is denoted compactive viscosity η_C.

For the creep tests on beams general beam theory was used to evaluate the results. The maximum and minimum value of tensile stresses were calculated.

4 RESULTS

4.1 Density

The density was measured for all types of snow used in the study. Average values from density measurements are given in table 3.

Table 3 Density measurements on artificial snow, manufactured in Jukkasjärvi from different parts of the building and investigated at different times during the season. The given month is when the samples were taken out.

Origin of snow sample	Test	No. of tests	Average density [kg m^{-3}]
Blocks of new manufactured snow	Cr2	14	510
Walls in the ice church, December	Comp1	12	500
Walls in the ice church, December	-	17	520
Walls in the ice church, April	-	6	600
Walls in the ICEHOTEL exposed to sunshine	Comp2	8	610
Walls in the ICEHOTEL shady side	Comp3	4	520

4.2 Compression strength

The results with snow from the ice church tested at different temperatures indicated that the compression strength increases with decreasing temperature. The values measured were in the range 0.5–0.9 MPa. The densities of the measured samples were between 530-560 kg m^{-3}.

The snow samples from the wall exposed to sunshine had compression strength in the range 0.8-2 MPa. The compression strength from samples from the shady side was in the range 0.2-1.2 MPa. Figure 3 shows the compression strength as a function of density for samples from the ice hotel.

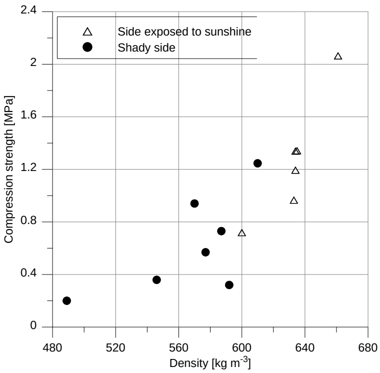

Figure 3 Compression strength vs. density

4.3 Creep deformation

Calculating the viscosity based on results from the creep tests with cylindrical tests samples gave values of the axial viscosity, η_E in the range between $2 \cdot 10^6$-$3 \cdot 10^6$ MPa-s. The values of the compactive viscosity, η_C were around $1.5 \cdot 10^6$-$4 \cdot 10^6$ MPa-s. The results indicated an increase in viscosity with increasing temperature.

For the creep tests on beams from new manufactured blocks of snow the creep rate for the second stage of the creep curve was studied. The deflection for the central part of the beam as a function of maximum tensile- and compression stress for the present load is shown in figure 4(Vikström, 2002). The increase in deformation rate is ten times larger when maximum tensile or compression stress increases from approximately 50 to 75% of the failure stress compared to an increase from approximately 25 to 50%.

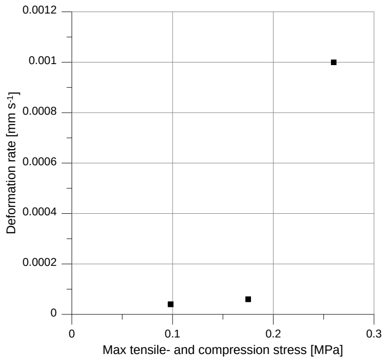

Figure 4 Defomation rate as afunction of max. tensile and compression stress (Vikström, 2002)

The results from the creep tests on beams from the sunny side of the building and the shady side after a test period of 77 days is shown in figure 5. The average deformation has been recorded as a function of time.

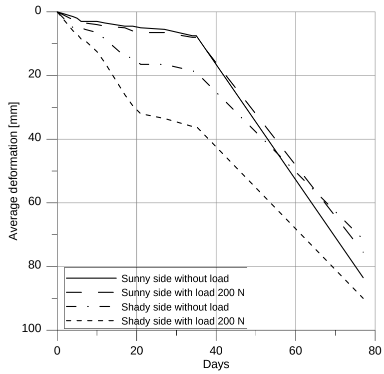

Figure 5 Average deformations for the four beams during the creep test. The deformation was measured once a week during the first 35 days and then only at the end of test after 77 days.

The average deformation for the unloaded beam from the sunny side of the building was 0.21 mm/day while the deformation rate with the circular dead load of 200 N was 0.23 mm/day. The values for the beams from the shady of the building were in average 0.54 mm/day for the unloaded beam and 1.03 mm/day for the beam with the dead load of 200 N. The total deformation after 77 days varied quite a lot between the measuring points on the left and the right side of each beam. The average value of total deformation was 72 mm for the unloaded beam from the shady side and 96 mm for the loaded beam. Corresponding values for the beams from the sunny side were 90 mm and 84 mm respectively.

Studying the creep deformation as a function of time for the creep test on the prefabricated snow arc showed a constant deformation behaviour from the start of the test until the observations were terminated after 77 days. The average deformation rate was 0.4 mm/day. The total recorded vertical deflections at the end of the measurements were 28.7 mm and 2.1 mm respectively for the linear variable differential transformers which were placed in the centre of the arc. The recording of the transformer placed at the side of the centre was 28 mm.

5 FINITE ELEMENT SIMULATIONS

Finite element simulations concerning creep on snow beams and on the ice church in Jukkasjärvi was performed in order to see if results from such analyze correspond to observed results during laboratory tests and field tests.

The finite element analyses were based on simplified models. Material properties were based on values from literature which not exactly correspond to the actual values of the snow produced in Jukkasjärvi, since the values in the literature are based on natural snow and not artificial snow. Creep deformation was integrated to the finite element program by means of a power law which was set equal to the creep strain rate (Selzer, 2001). Only influence on structural behaviour of dead load was considered in the study. Influence of parameters like metamorphism, wind and temperature changes were not taken into consideration in the analysis.

The results from the analysis with snow beams indicate that the values of the deformation achieved seem to be realistic (Seltzer, 2001). Comparing results from two-dimensional and three-dimensional models of the arcs in the ice church showed that the three-dimensional models gave results with better correspondence to the field observations.

6 DISCUSSION

6.1 Density

The densities for the samples are generally higher than values presented for natural snow on the ground (Mellor, 1975, Salm 1982). Both pressure and time will increase the density of snow (Salm, 1982). Variations in density for samples of snow of the same origin can be explained by pore spaces between the ice clusters (Vikström, 2002). Variations in density between different snow samples can be explained by differences in construction technique used for manufacturing different parts. Temperature variations and different stress conditions are other parameters affecting the density.

The higher density of snow samples taken out in April is a result of densification and higher ice content. Weather changes and melting and refreezing will increase the ice content in the snow and consequently the density.

The measured values have not been compared to other measurements of artificially produced snow since there are no available data from other studies with artificial snow.

6.2 Compression strength

During the unconfined compression tests with artificial snow from the ice church a peak value of the force was reached followed by a stress drop and then a slow recover, which is interpreted as a hardening process where the snow increases in strength after the first collapse (Vikström, 2002). The measured values of the compression strength are in general lower than results presented by for example Bader (1962) and Shaphiro et al. (1997) but similar to values presented by Mellor (1975). A similar behaviour was observed during the unconfined compression tests with the samples of artificial snow from the ice hotel. The higher value of the compression strength for the samples from the side of the building exposed to sunshine is in accordance with other test results which show that the compression strength increases with increasing density.

The increase in compression strength with increasing density for the samples tested is assumed to be a result of larger ice content in the snow and plastic deformation of the snow.

6.3 Creep deformation

The creep rate for snow is highly dependent on density and viscosity (Bader, 1962). The creep rate is usually lower for high-density snow since the porosity and hence space for rearrangement of grains is smaller. For seasonal snow under the action of gravity and metamorphism the creep is to about 90% a result of rearrangement of grains and about 10% is attributed to mechanical effects such as deformation of ice grains (Mc Clung, Schaerer, 1993). As the snow densifies the deformation rate decreases. As for other materials, high creep rates may not lead to failure. Instead failure is often a result of collapse of the structure independently of the creep behaviour.

Vikström (2002) compared results from the creep tests (Cr1) with artificial snow from the ice church with results from other tests. The axial viscosity at -10°C and -11°C showed similar values while the values at -5°C were higher. This indicates that the viscosity increases by increasing temperature. The compactive viscosity was higher compared to tests by Shapiro et al. (1997) where snow from different locations was studied. At all temperatures the values of both the axial and the compactive viscosity were higher than result reported by Chandel et al. (2007). This indicates that the tested artificial snow is more resistant to deformation than other investigated snow samples of similar density.

The different creep behaviour for beams from the shady side of the ice hotel was different from then obtained from the side of the building exposed to sunshine (Cr4 and Cr3). This is assumed to be a result of different degrees of densification and different porosity. The initially higher creep rate of beams from the shady side (Cr4) is assumed to be a result of larger pore spaces and lower degree of densification for the snow. The result is in accordance with the theory where a lower creep rate generally is observed with increasing density (Bader, 1962). The difference in deformation rates between the loaded and unloaded beam from the shady side is much larger than the difference between the beams from the side exposed to sunshine. This also indicates higher deformation resistance with increasing degree of densification and higher density.

Sources to scattered results in the creep test measurements are large grains and pore spaces in the snow. Sublimation during the tests is a parameter which influences the creep rate (Vikström, 2002). It leads to a reduction in mass and a decrease in diameter of the samples. This in turn leads to an increase of the normal stress and hence an increase of the creep rate.

Problems with the recording of values for one of the transformers resulted in failed values for one transformer during the deformation measurement on the wooden reinforced arc of snow. This is the reason to the big difference between the obtained values. The average deformation rate of 0.4 mm/day corresponds to about 12 mm/month.

Assuming the deformation rate to be constant during the season (October – April) when the ice hotel is open the total deformation would be 84 mm for the wooden reinforced arc of snow. This is considered to be small as compared to similar arcs of snow without wooden reinforcement where observations by staff at the ice hotel have shown deformations of about 500 mm.

To get a better understanding of the creep strength for artificial snow it is advisable to make further tests analyzing the creep behaviour with respect to important parameters such as temperature, density and viscosity.

6.4 Finite element simulations

In order to improve results from finite element simulations, material parameters valid for the snow being analyzed should be used. The viscosity is a critical parameter since it has a direct influence on the stresses and strains. Using such an exact value as possible for the viscosity parameter is therefore of importance. Other input parameters also need to be adjusted, like the creep law which as a simplified power law not distinguish between primary and secondary creep. The failure criteria could be improved by practical studies concerning failure dependence on tensile strain (Selzer, 2001). The boundary conditions will also influence the analysis result and can in future simulations be adjusted for good correspondence to reality.

7 CONCLUSION

Artificial snow has generally higher density, compression strength and creep strength than natural snow.

Density of snow and humidity in air has a great influence on structural parameters in snow, like compression strength and creep strength. Sizes of test samples and boundary conditions will also affect the test results. It is therefore of importance to find proper and repeatable test methods for evaluating material parameters. Existing methods for testing snow need to be improved and new methods need to be developed in order to get a better understanding of the behaviour of snow as a material for constructions.

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Paper B

Uniaxial Strength and Deformation Properties of Machine-made Snow

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Uniaxial Strength and Deformation Properties of Machine-Made Snow

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Abstract: Snow as a construction material has been used for centuries, with igloos among the first examples. Each winter, snow and ice villages, buildings, and artwork are built in many places around the world. Machine-made snow manufactured by snow guns is commonly used for constructions made of snow. However, only a few basic studies on machine-made snow have been published. Knowledge based on experience and studies on natural snow constitute the basis for constructions made using snow and ice. Through material tests on machine-made snow used for construction, data on important physical and mechanical properties have been established that aim to improve and optimize safe constructions made from snow. Strength tests have been performed using two different qualities of machine-made snow. Specimens used for testing were cut out from one block of snow that had a coarse-grained structure with clusters of ice in the snow and from one block of snow with a fine-grained and homogeneous structure. The density for each tested snow sample was measured and strength tests were performed at different deformation rates to investigate the relationship between mechanical properties and deformation rate or strain rate. The load response curves achieved from the strength tests were used to evaluate compressive strength, Young's modulus, and the residual modulus. The results show that compressive strength increases with increasing density. Increasing compressive strength with an increasing strain rate was also observed for fine-grained snow quality specimens, whereas no similar tendency was observed for coarse-grained snow. The residual modulus increased with an increasing strain rate up to a certain critical value for the fine-grained machine-made snow specimens. Regression analysis was used to investigate whether any dependence was observed between the calculated mechanical properties; no further relationship between the mechanical and the physical properties was noticed. **DOI: 10.1061/(ASCE)CR.1943-5495.0000090.**

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Introduction

During the past few decades, the recreational-based snow industry has grown. In addition to use in sports activities, snow and ice have been used in buildings and construction. Each year, villages, hotels, and artwork made with snow and ice are built in several places around the world. The construction is generally done using knowledge based on experience. Current knowledge on the mechanical properties of snow is based on research on natural snow from the mid-twentieth-century (e.g., Bader 1962; Mellor 1974; Kinosita 1967). Machine-made snow—snow produced by snow guns—is commonly used to construct snow buildings. In many respects, the properties of machine-made snow are different from those of natural snow. Natural snow initially consists of crystals with infinitely many different structures and shapes, whereas machine-made snow consists of frozen water droplets, or round grains. The small round grains of machine-made snow result in a more closely packed structure and a higher density compared with fresh natural snow. The shape of these grains also makes machine-made snow more stable and more durable in warm temperatures, precipitation, and wind (ICEHOTEL 2011).

Only two minor scientific studies have been conducted on machine-made snow as a material used in construction. These studies addressed field and laboratory measurements at ICEHOTEL, Jukkasjärvi, Sweden, which were retrieved during the 2000–2001 season (Vikström and Bernspång 2002) and the 2010 season (Lintzén and Edeskär 2012). Unconfined compression tests, confined and unconfined creep tests, and deformation studies were performed on machine-made snow and snow structures from ICEHOTEL (2011) in Jukkasjärvi, Sweden. The obtained results imply that machine-made snow has different mechanical properties compared with natural snow of the same density. Further research is necessary to establish material data for machine-made snow.

In this study, unconfined compression tests on machine-made snow were performed to investigate basic material properties and to relate compression test data to outer parameters. Previous studies showed that natural snow under compression behaves differently depending on the deformation rate (Kinosita 1958, 1967). These studies also showed that snow is a viscoelastic material for which slow deformation results in a continuous deformation process and an elastic-plastic behavior. Fast deformation results in a discontinuous deformation process or brittle failure. The critical deformation rate between plasticity and brittleness is important to the load response of snow and—in addition to the speed of deformation—depends on the density, temperature, and structure of the snow tested.

Unconfined compression tests were performed at different deformation rates but constant temperature to get an idea of how the deformation rate affects the mechanical behavior. Two different types of machine-made snow were used for the strength tests, one with a coarse-grained structure and one with a fine-grained structure. The air–water mixture in the snow gun, the pressure, and the outer climate conditions are important to the quality of the machine-made snow being produced (Chen and Kevkorian 1971). In this study, coarse-grained snow was created with a relatively higher amount of water, creating snow of high density and clusters of ice in the snow. Fine-grained snow was produced using relatively less water that, in combination with other parameters being optimized, resulted in a homogeneous and fine-grained structure of machine-made snow.

The results show that mechanical properties depend on the structure of the snow. Coarse-grained snow showed scattered results, whereas fine-grained snow provided consistent values for tests performed in controlled conditions. Compressive strength is similar to values obtained in previous studies on machine-made snow (Lintzén and Edeskär 2012). Young's modulus values are difficult to compare with values obtained in other tests because the methods used to evaluate this property generally vary, which seems to have a significant effect on the results.

Method

Material

The machine-made snow used in this investigation was produced with snow guns and was then mixed twice with a snow blower before being cast in a rectangular mold and allowed to freeze to form a block of snow. In this study, specimens from two different blocks of machine-made snow were used for the strength tests. One of the blocks had a coarse-grained structure with clusters of ice in the snow. This block was produced in November 2011 and stored in a freezing room at approximately −10°C for 1 year before test specimens were cut out and compression tests were performed. This machine-made snow is denoted as old snow. The other block of snow had a homogeneous and fine-grained structure. This block was produced in March 2013 and specimens were cut out and tested within 2 weeks of production. This type of snow is denoted as new snow. Both blocks of snow were stored under diffusion-proof plastic covers in freezing rooms to protect them from sublimation and to retain the structure of the snow. Backlight projection and image analysis were used to study the structure of the snow, which are shown in Figs. 4 and 5.

Test Procedure

Sample Preparation

Cylindrical test specimens were drilled out from the blocks of snow and then were cut to the desired length using a miter box to ensure that the end surfaces were flat and that all specimens were exactly the same length. The initial size of the test specimens used for the strength tests had a diameter of 65 mm and a length of 150 mm. A linear pattern was drawn on the specimens' surface to study the longitudinal deformation behavior (Fig. 1). Each individual sample was weighed to determine its density.

Strength Tests

The cylindrical specimens were tested during uniaxial compression at different constant deformation rates. Paper sheets were put between the test specimen and the load plates at the ends to prevent the test specimen from freezing into the load plate surfaces, which may cause undesired end effects with these specimens. During each test, the resisting force was recorded with a load cell and the longitudinal compression was measured as the displacement of the load platens using strain gauges with

Fig. 1. Specimen used for compressive test

an accuracy of ± 0.001 mm. Strength tests were carried out at deformation rates from 0.5 up to 40 mm/min. The temperature during the performed tests was approximately $-10°C$. Between three and five tests were performed at each deformation rate. The Appendix shows the experimental layout with the number of test samples at each deformation rate for the two different types of machine-made snow tested.

Evaluation

The compressive strength, Young's modulus, and the residual modulus were evaluated using the results from the uniaxial strength tests.

Fig. 2 shows a typical force versus time curve from a compressive test using new machine-made snow. The compressive strength of each snow sample was calculated by dividing the registered peak load during the loading procedure at a constant rate of strain by the initial cross-sectional area of the test body, according to Eq. (1)

$$\sigma = \frac{F_{\max}}{A} \tag{1}$$

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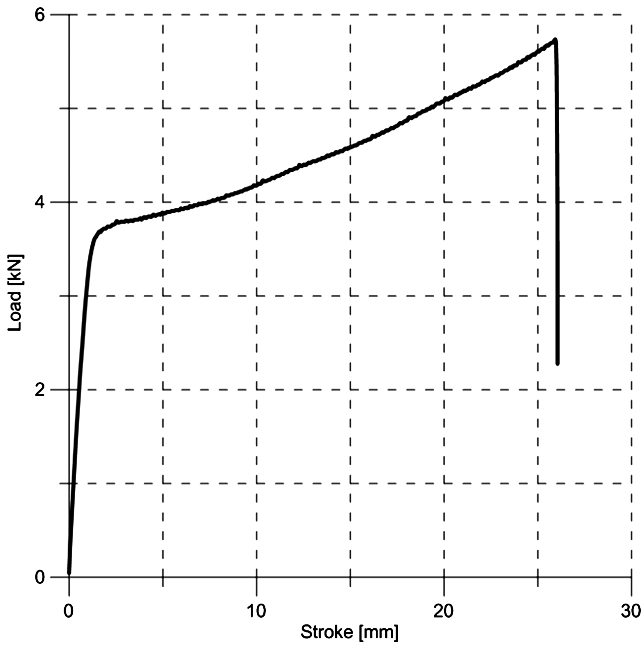

Fig. 2. Typical force versus displacement curve from a uniaxial compressive test with new machine-made snow for which no brittle failure occurred during an early stage of the load process; the deformation rate was 12.5 mm/min

where σ = compressive strength; F_{max} = maximum registered force; and A = initial cross-sectional area. Young's modulus, E_{tan}, was evaluated as the tangent modulus to the stress-strain curve during the initial phase of the load test, in other words, before the peak point or ultimate load was reached, as shown in Fig. 3. The difference in stress was divided by the difference in strain, according to Eq. (2)

$$E_{tan} = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2}$$

In this study, the stage after the load peak is reached is defined as the postload process and corresponds to the residual strength. As is shown in Fig. 3, an almost linear relationship between $\Delta\sigma$ and $\Delta\varepsilon$ is observed unless the test specimen cracks or fails. The residual value, E_{res}, is evaluated as the quotient between $\Delta\sigma$ and $\Delta\varepsilon$ according to Eq. (3)

$$E_{res} = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{3}$$

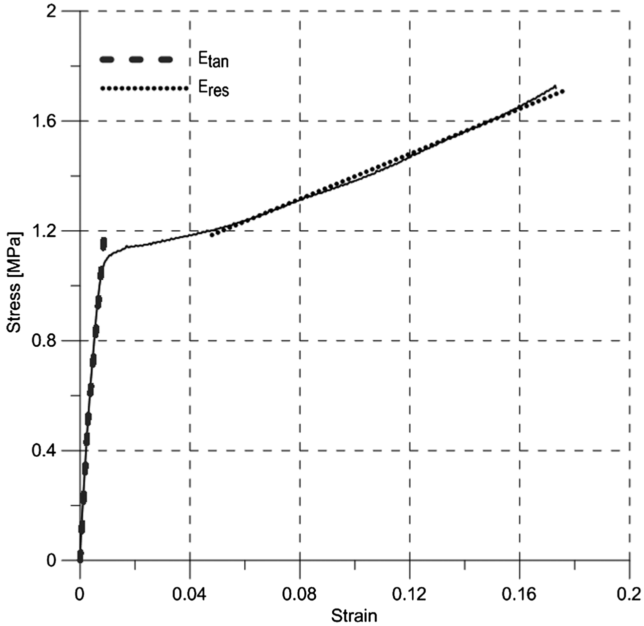

Fig. 3. Typical stress-strain curve from a load test for which no brittle failure occurred during an early stage of the load process; the deformation rate was 12.5 mm/min

Results

Fig. 4 shows the structure of the old snow and Fig. 5 shows the structure of the new snow. The individual grains for the old machine-made snow were observed to be coarse, were a broad range of sizes, and were unevenly distributed throughout the cross section. Some ice clusters also existed in the structure. The individual grains from the sample of new machine-made snow were fine grained, equal in size, and evenly distributed without any clusters of ice.

Fig. 6 shows the variance in the density for the two different snow qualities. The densities for the old snow specimens varied between 550 and 710 kg/m^3. The densities for the new snow specimens were more analogous and varied from 510 to 560 kg/m^3. In general, the new snow had lower density that the old snow. The density was lower for the specimens of new machine-made snow, and the density variance was higher for the old machine-made snow.

Fig. 7 shows the compressive strength versus the density for old and new machine-made snow samples. The tests were performed at deformation rates between 5 and 40 mm/min. The results showed the tendency for compressive strength to increase as density increased for both the new and old machine-made snow samples. However, the mean value of the compressive strength was higher for the new snow

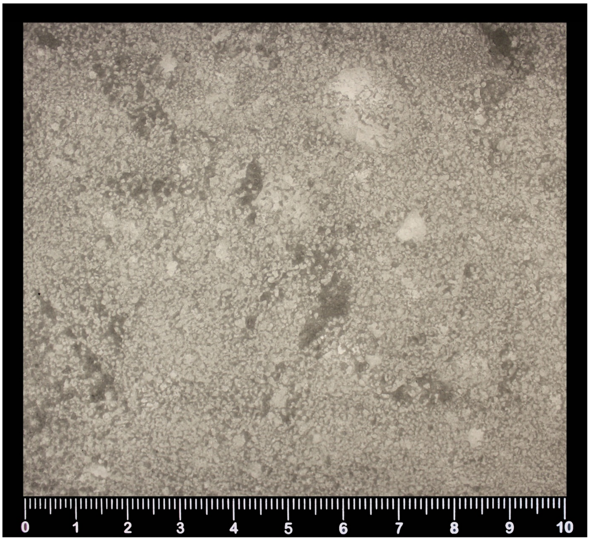

Fig. 4. Structure of the old snow

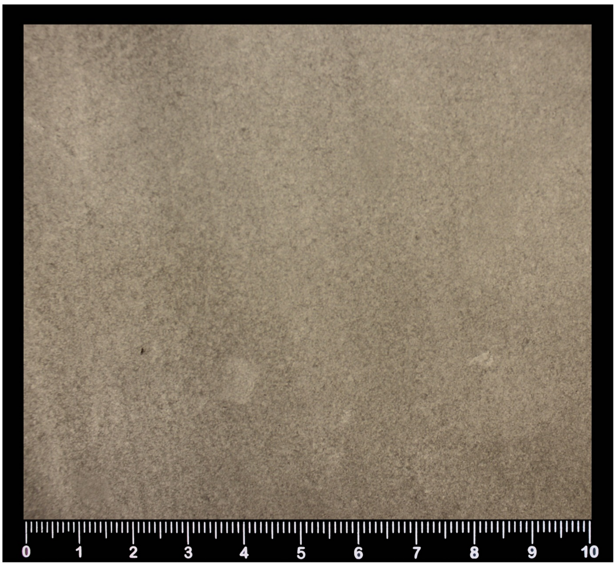

Fig. 5. Structure of the new snow

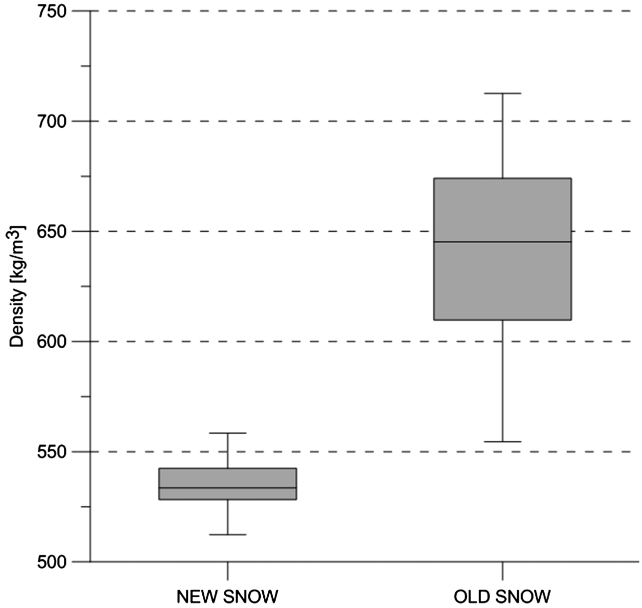

Fig. 6. Density of the new and old snow specimens

than for the old snow, although the density of the new snow was lower than the density for the old snow.

Young's modulus is defined as the tangent modulus up to the registered peak stress. Fig. 8 shows Young's modulus versus the density of the old and new machine-made snow samples. The Young's modulus values were much more scattered for the old snow samples than for the new snow samples; however, the results for both snow types showed no clear tendency for dependence between these two properties.

Fig. 9, which indicates the compressive strength versus the strain rate, shows that the compressive strength was more scattered for the old snow than for the new snow. The compressive strength of new machine-made snow increased as the strain rate increased. Given the scattered data values, no similar clear dependency was observed for old machine-made snow.

Fig. 10 compares Young's modulus versus the strain rate for the old and new artificial snow samples. The average value of Young's modulus, E_{tan}, was 115 MPa for the tested specimens of old machine-made snow and 162 MPa for the tested specimens of new machine-made snow. The results were more scattered for the old machine-made snow.

Fig. 11 shows the residual modulus, E_{res}, versus the strain rate for the tests performed on new machine-made snow. The values increased as the strain rate increased and varied between approximately 3 and 9 MPa.

Most of the tests on the old machine-made snow specimen were either interrupted after the peak point was reached or after the samples cracked, yielding a

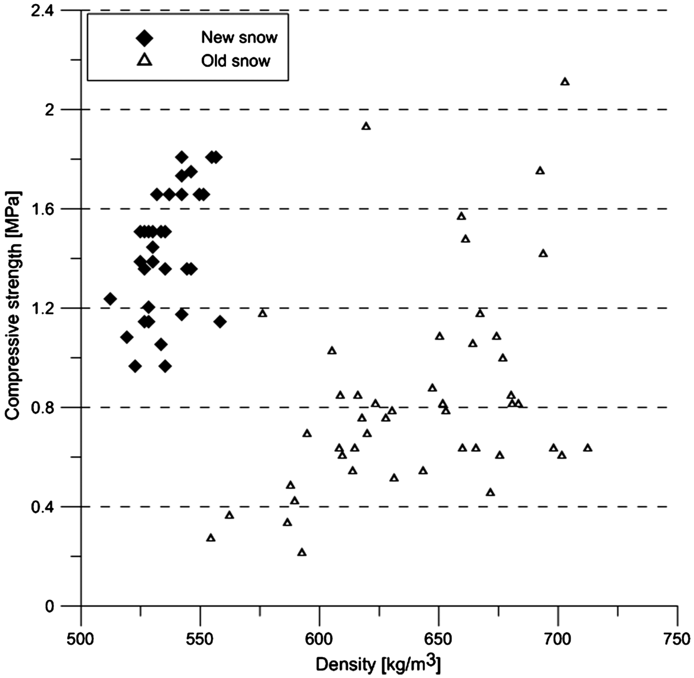

Fig. 7. Compressive strength versus density of all specimens and deformation rates

saw-tooth curve instead of a linearly increasing line, as shown in Fig. 2. For a few tests in which calculating the residual modulus using old machine-made snow was possible, the values varied between 3 and 7 MPa. In other words, values in the same range were observed for the new machine-made snow.

Discussion

The different qualities of the two machine-made snow blocks were the result of both different snow production conditions and aging through sintering of the snow—increased growth of individual ice particles in the matrix. As Fig. 4 shows, the old snow was hard and brittle, with clusters of ice and cavities in the snow block. The inhomogeneous snow made specimen preparation difficult. Some specimens cracked during sample preparation and were not used for testing. The new machine-made snow had a homogeneous and fine-grained structure and did not crack during sample preparation.

As Figs. 4 and 5 show, grain size is larger for the old machine-made snow. This characteristic agrees with previous studies that showed that aging results in increased and varying distribution of grain size (Yong and Fukue 1977). Changes in the internal structure influence the mechanical properties of the snow.

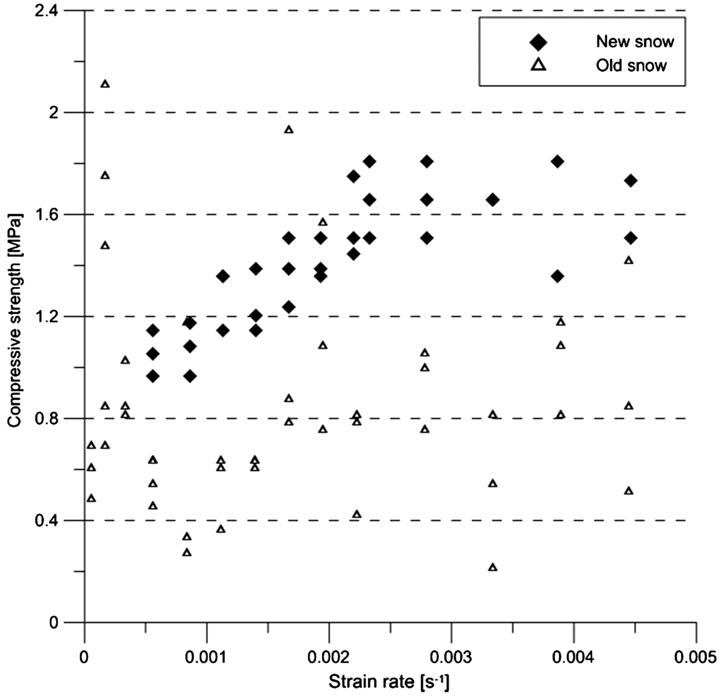

Fig. 8. Young's modulus versus density of all specimens at all deformation rates

The network connections and bonding between ice grains are important for both mechanical properties and the critical deformation rate during compression. This compression separates the elastoplastic behavior observed at low deformation rates that occurs from the brittle failure at higher deformation rates (e.g., Gold 1956; Wakahama 1968; Kinosita 1958, 1967). Wakahama (1968) observed that compression of snow results in several different processes that occur in the ice grains that compose the snow, such as slips at grain boundaries, separation or fracture of ice grains, and migration of grain boundaries. For future studies on machine-made snow, further investigation of grain size and grain size distribution and observation of the structure and deformation behavior at a microscopic level would be interesting to gain additional knowledge on the parameters of importance for the mechanical behavior.

High density variance existed for the old snow test specimens, whereas the density variances for the new snow test specimens were lower. The inhomogeneous structure of the old snow, through which some specimens had high ice content in the snow, resulted in certain specimens with high density and others with less ice having a lower density. Previous studies on machine-made snow from ICEHOTEL showed that the compressive strength increased as density increased

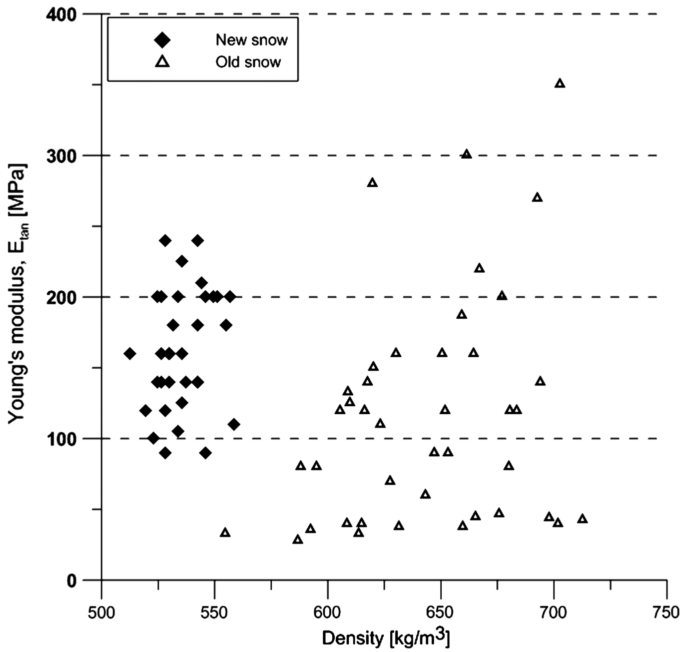

Fig. 9. Compressive strength versus strain rate of all specimens at all deformation rates

(Lintzén and Edeskär 2012). The same tendency was observed from the tests performed in this study; however, snow samples with a high density attributable to high ice content were viewed as not always having higher compressive strength because the ice clusters may also act as initiation points for crack propagation. Density is a common parameter to use as a variable to which mechanical properties are related; however, results from numerous experiments concluded that the response of snow to different loading conditions is better determined by the structure of the snow and the bonding between snow grains rather than its density (e.g., Shapiro et al. 1977; Kinosita 1967; Yong and Fukue 1977). This finding supports the conclusion that investigating and classifying the snow structure on a microscopic scale is of interest for future studies on machine-made snow to correlate grain sizes, grain size distributions, and such parameters to strength and other mechanical properties.

During the compression tests, the initial deformation of the samples was noticed as being uniform along the length axis of the specimen; in other words, the entire specimen was evenly compressed to a shorter and wider shape but still maintained a straight cylindrical form (Fig. 12). The same behavior—a uniform contraction along its entire length—was observed in tests by Kinosita (1967), who concluded that plastic contraction led to hardening of the snow structure as a result of restructuring of ice grains and bonds between grains.

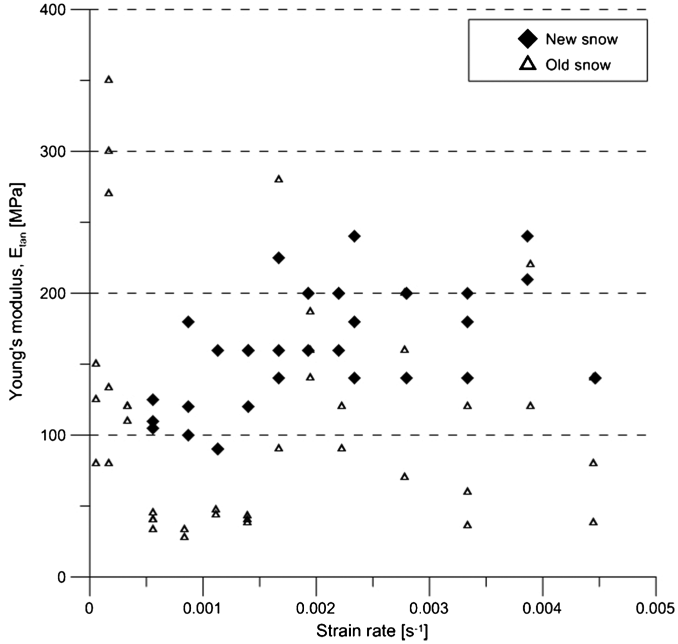

Fig. 10. Young's modulus versus strain rate for all specimens and all deformation rates

The resistive force, which was recorded and used to evaluate the compressive strength and Young's modulus, was initially linear and rapidly increased, as seen in Fig. 2. The interpretation of this initial stage is that a hardening of the structure occurred. If a crack forms during the compression of a specimen without completely breaking, the recorded resistive force may suddenly drop as the crack arises. If the compression is allowed to continue, the resistive force again increases and the slope of the line is approximately the same as before the crack was formed. After reaching the peak value, the resistive force either flattened out or slowly increased unless the test sample cracked or failed, which occurred at high deformation rates. The fractures in the samples were different. Most common was that small cracks occurred before the entire specimen collapsed; however, sometimes a sudden crack occurred throughout the entire specimen, as shown in Fig. 13.

A comparison of the numerical results of the unconfined compressive strength to the results achieved by the strength tests on snow samples taken out from the walls of ICEHOTEL in 2010 shows that the results are in the same range (Lintzén and Edeskär 2012). The compressive strength achieved by Vikström and Bernspång (2002) on samples of machine-made snow at a deformation rate of 1.5 mm/min is lower than the compressive strength of the old machine-made snow achieved in this study at the same test temperature and deformation rate. In this study, the new machine-made snow is not tested at this deformation rate. The compressive strength

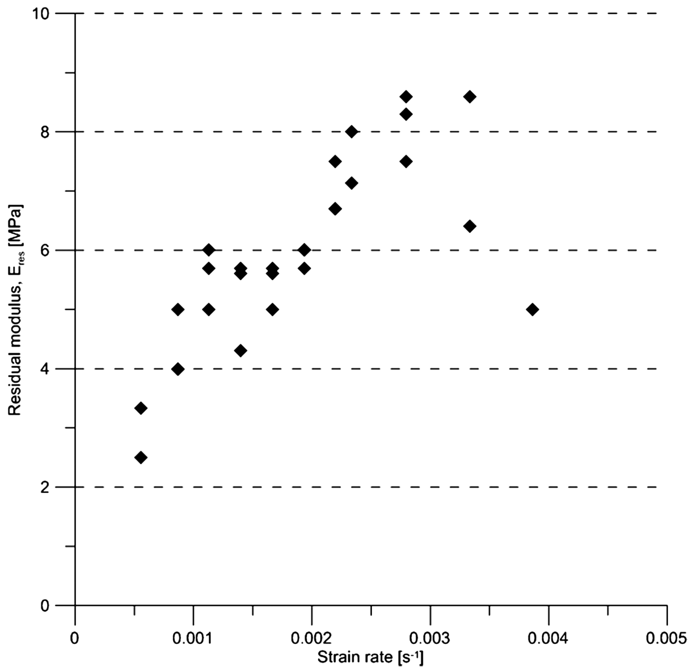

Fig. 11. Residual modulus versus strain rate for all specimens at all deformation rates

is in the same range as the values for natural compact snow with a similar density that was deposited in Hokkaido, Japan, and tested at uniaxial compression at −13°C (Kinosita 1967). Kinosita found that, generally, the compressive strength increases as the density increases. However, this study found that the mean value of the compressive strength for the new machine-made snow was higher than for the old machine-made snow, although the density was generally lower for the new machine-made snow. The densities for all tested samples in this study are higher than for natural snow. This result indicates that the relationship between compressive strength and density might be different for high-density snow than for snow with lower density, a situation that requires further investigation.

The relationship between compressive strength and strain rate indicates an increase in compressive strength as the strain rate increases up to certain critical value. Kinosita (1967) showed that a critical deformation rate exists for natural snow at which the behavior changes from plastic deformation to brittle failure. This breakpoint between plasticity and brittleness is observed in strength tests with new machine-made snow, whereas the scattered data and irregular deformation behavior for the strength tests using old machine-made snow do not allow for any similar observation of a specific critical break point in this study. The critical strain rate for new machine-made snow was noticed to be approximately 0.003 s^{-1}. The corresponding deformation rate was approximately 25–30 mm/min. Because many of

Fig. 12. Test specimen evenly compressed to a shorter and wider shape but still with a straight cylindrical form

the old machine-made snow specimens were brittle, quite a few of them resisted deformation rates higher than 15 mm/min; however, the results were also scattered at lower deformation rates.

Kinosita (1967) presented an expression that took into account the temperature and density and for which the critical deformation rate was suggested to be approximately estimated as

$$v_c = 0.4T + 20\rho + 3 \tag{4}$$

where v_c, T, and ρ should be given in units of millimeters per minute, degrees Celsius, and grams per cubic centimeter, respectively. Eq. (4) applied to the machine-made snow and temperature conditions in this study predicts critical deformation rates of 9–13 mm/min. These estimated critical deformation rates are lower than the observed rates in this study. Kinosita's study was based on strength tests using natural snow with, in general, much lower densities than the machine-made snow used in this study, which may provide a reason for the deviating results.

Linear regression analysis was used to approximately quantify whether relations existed between Young's modulus and the resistive modulus rate; however,

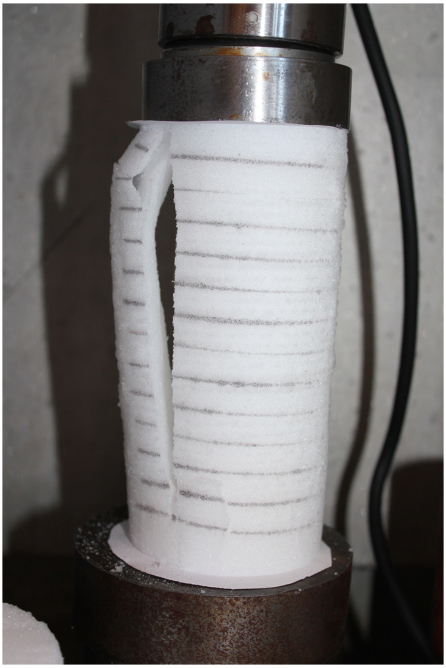

Fig. 13. Specimen that cracked during an early stage of the deformation process during loading at a high deformation rate

no tendency for dependence was observed. Dependence of the moduli toward strain rate was also not observed.

The achieved values of Young's modulus, E_{tan}, were scattered between approximately 50 and 350 MPa for the old machine-made snow samples, and the values were between 100 and 250 MPa for the new machine-made snow samples. Regarding the results of Young's modulus shown in Fig. 9, the significant point is that the values were evaluated from strength tests performed at different deformation rates.

In this study, the results of Young's modulus are in the same range as the values from Mellor (1974) in which tests of uniaxial compression and tension at test temperatures between -12 and -25°C and strain rates between 8×10^6 and $4 \times 10^4\ s^{-1}$ were used to calculate Young's modulus. However, those tests were performed on natural snow with a density between 150 and 350 kg/m^3. The values of Young's modulus achieved by Bader (1962) were much higher at 1,000 MPa; however, those tests were based on the resonance vibration of bars. Vikström and Bernspång (2002) used tests on machine-made snow beams to estimate Young's modulus value at an average of 335 MPa. The experimental method and procedure used to evaluate material parameters is obviously of high importance and affects the results. The various methods used to evaluate the results of the same mechanical property seem to give widely spread data values, indicating difficulties and uncertainties in comparing values from different methods. Standardized test methods for evaluating the mechanical properties of snow make it easier to compare snow used in different investigations.

The residual strength, E_{res}, is linearly increasing with a strain rate that increases up to its critical value, or 0.003 s^{-1} for new machine-made snow. The residual strength, E_{res}, is lower than the values achieved by Vikström and Bernspång (2002) on machine-made snow at the same test temperature and is evaluated in the same way, that is, from compressive test curves. These results varied between 9 and 164 MPa. The increase in stress after the peak point is reach can be explained by the increase in the cross-sectional area of the specimen as the deformation proceeds. Another explanation is sintering or rearrangement of grains to form a more compact and stable structure. Eventually, compression converts the snow specimen into ice.

Conclusion

The major findings in this study are as follows:

- Unconfined strength tests on machine-made snow of different structures show that structure influences mechanical properties;
- Old and coarse-grained machine-made snow is more brittle than new and fine-grained machine-made snow;
- During uniaxial compression, a critical deformation rate exists at which the behavior changes from plasticity and strain hardening to brittleness or failure;
- Density is weakly correlated with compressive strength and Young's modulus, which may depend on the internal structure and high density of the machine-made snow; and
- In general, the uniaxial strength of machine-made snow is similar to natural snow of equal density.

Appendix. Number of Test Samples for the Two Different Types of Machine-Made Snow

Deformation rate (mm/min)	Old snownumber of samples	New snownumber of samples
0.5	3	
1.5	5	
3	3	
5	5	3
7.5	3	3
10	3	3
12.5	3	3
15	3	3
17.5	3	3
20	3	5
25	3	3
30	3	3
35	3	3
40	3	3

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The authors want to thank Ulf Stenman and Mats Pettersson, Luleå University of Technology (LTU), for support with the strength tests and ICEHOTEL for its support and for providing the material studied. Part of the tests was funded by the EU regional fund through the project SNOW AND ICE.

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Paper C

Liquid water content in snow measured by spectral reflectance

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Reformatted version of paper
Submitted

Liquid content in snow estimated by spectral reflectance

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Abstract

The spectral reflectance for snow with different liquid water content (LWC) within the range 920 nm - 1650 nm was measured using a near-infrared (NIR) spectrometer in a climate chamber. A Road Eye sensor, which was used in our previous research to characterise snow samples was also used to measure the reflectance from the same snow samples. It was observed that the spectral reflectance for snow decreases with increasing LWC. A linear correlation between the spectral reflectance and the LWC was observed for both the sensors. Based on the distinct absorptive characteristics, three optimum wavelength bands were selected where the snow with different LWC is clearly distinguishable. The observations showed that the Road Eye sensor properly captured the effect of LWC in snow similar to the traditional NIR spectrometer. A widely used remote sensing index known as the normalised difference water index (NDWI), was used to develop a method to detect and relatively quantify the effect of water content in a given snow sample. The calculated NDWI values from both the sensors showed a positive linear correlation with respect to the introduced liquid water. The results suggests that the proposed method can be used to relatively estimate the water content in snow for example on a ski track and for winter roads.

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1. Introduction

Investigation of physical properties of snow is essential in the fields of avalanche research [1], climatology [2], hydrology [3], skiing [4] and winter road maintanace [5] among many others. Most of these focus on determining the effect of grain size [6], specific surface area (SSA) [7] and liquid water content (LWC) [8] on snow albedo [9]. The LWC describes the amount of water within a snow pack that is in the liquid phase. The LWC has a direct influence on the bonds between grains [10], which in turn determines the strength of snow, the mechanical properties and accordingly much of the behaviour of snow as a material [11].

A technique to detect and/or estimate the LWC in snow should be fast and preferably non-destructive due to the rapid snow metamorphism as snow always exists rather close to its melting temperature [12]. The coarsening is accelerated in the presence of liquid water and any disturbance may lead to rapid changes in the LWC thus a change in texture and structure of the snow occurs. Different dielectric sensors exist for measuring the LWC in snow where a significant difference in dielectric properties for ice and water at radio frequencies. After determining the dielectric constant, the LWC can be estimated using a mathematical model where the density and the porosity of snow must be known and measured separately [12]. Dielectric measurements of LWC in snow might therefore be destructive.

Previous work have shown that snow types can be classified based on their individual distinct absorption properties. The spectral reflectance of snow is a strong function of grain size, grain type and snow age [13, 14, 15]. Among many studies which focus on analytical radiative transfer models, Warren [16] investigated the effect of wavelength, grain size and impurity content on snow albedo. Warren reported that the snow albedo is very sensitive to the grain size in the near-infrared (NIR) region but observed minor influence of the LWC. Snow composed of large grains tends to absorb more light thus a reduction in the snow albedo can be observed.

Wiscombe and Warren [17] observed a slight decrease in the snow albedo for small amounts of liquid water in their measurements. The effect of LWC on the snow albedo depends on where the water is located. Smaller amounts of liquid water is located only at grain boundaries [18], which causes a slight decrease in the albedo. Higher amounts of liquid water causes the grains to form large water-ice clusters, resulting in a large decrease in the snow albedo as these clusters tend to absorb more light [19, 20]. Moreover, the liquid itself might form liquid clusters [21]. A radiative transfer model was developed by Hyvarinen and Lammasniemi [22] to estimate free-water content and grain size using the measured spectral reflectance from several snow types in the wavelength region 600 nm to 2000 nm. They reported that their model estimated the water content and grain size with good accuracy.

The presented study shows the measured spectral reflectance from snow with different LWC using two measurement systems and the measurements were performed in a walk-in climate chamber. A NIR spectrometer and a Road Eye sensor were used to measure the reflected light from the snow samples with different LWC. The NIR spectrometer measurements were recorded from viewing zenith angle 60° while keeping the illumination source at 45° and each spectrum was in the wavelength range of 920 nm - 1650 nm. The Road Eye sensor measured the reflected light at wavelengths 980 nm, 1310 nm and 1550 nm from the same snow samples having both illumination and detector fixed at an angle of 60°. The work presented here describes a relation between the LWC in snow with constant dry density and the reflective properties of the respective snow sample. An optimum band of wavelengths were investigated to better classify snow with varying LWC.

In addition to the experiments in the climate chamber, the Road Eye sensor was also used to measure the reflectance from snow in a cross-country ski track. Based on the correlation between the Road Eye measurements in the climate chamber and in the ski track, a relative estimate of the LWC was investigated. The presented approach is assumed to be used as a fast and simple method for classification of snow in ski tracks and pistes which is of importance especially in competitive skiing. The snow properties constitute the base for choice of skis, ski base topographies and ski wax in order to optimise the overall sliding properties.

The paper is organised as follows; In section 2, the measurement approach including experimental setup and snow samples preparation is detailed. Results of the observations are presented in section 3. In section 4 correlation between snow properties and experimental observations are discussed. The paper ends with conclusions in section 5.

2. Measurement approach

In the following sections experimental setup, measured snow samples and measurement procedure are detailed.

2.1. Experimental setup

Three different experimental setups are detailed. Experimental setups using both the NIR spectrometer and the Road Eye sensor in the climate chamber are presented. The Road Eye sensor was also used to measure the reflectance from snow in a cross-country ski track, which is also presented in this section.

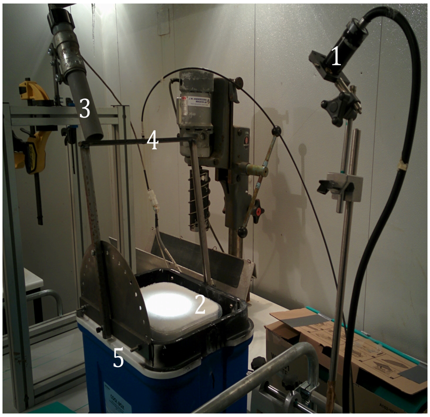
2.1.1. The NIR spectrometer

The experimental arrangement shown in Figure 1(b) consists of the NIR spectrometer, an insulated box, a snow sample, an illumination source and the Road Eye sensor. The NIR InGaAs spectrometer (STE-DWARF-Star NIR) with an extra aperture (field of view 3°, ∅5 mm) was used to measure the reflectance in the wavelength region 920 nm to 1650 nm with spectral resolution of 1.75 nm. The illumination source was a 250 W EKE quartz halogen lamp (Dolan-Jenner MI-150 Fiber Optic Illuminator) coupled with a ∅6.35 mm fiber optic light guide and the output was focussed by a focussing assembly (focal length 40 mm, ∅30 mm). The illumination beam was collimated and formed a bright spot of ∅13 cm on the center of the surface of the snow sample. Experiments were performed in the walk-in climate chamber with a temperature of -12 ±1 °C located at Luleå University of Technology, Sweden.

As can be seen in Figure 1(b), a special rig was attached to the insulated box so that the reflected light from the snow surface can be measured at a given viewing zenith angle. The spectrometer probe was mounted on the radial arm of the rig, 33 cm from the snow surface. The spectrometer measured the reflected light within an area of ∅1.73 cm. The height of the snow sample in the insulated box was adjusted so that the snow surface and the center of rotation of the rig were in the same plane. The spectrometer measured reflected light with a solid angle in the same plane as the incidence, which

a. Compacted $BaSo_4$ sample

c. One of the prepared snow



b. Experimental setup in the climate chamber

Fig. 1. Experimental setup consists of an illumination source (1), snow sample (2), the Road Eye sensor (3), the NIR spectrometer probe (4) and an insulated box (5). The volume of plastic box containing snow was 24 x 16 x 13 cm^3 and all snow samples have equal density of 460 kg/m^3. $BaSo_4$ powder was compacted on a matte black painted plexiglass and the compacted $BaSo_4$ has dimension of 13 x 13 x 2 cm^3.

means the incidence direction, global normal of the snow and the detector direction were all in the same plane.

Measured reflectance spectrums for all the snow samples were normalised during the experiments using a reference and dark spectrum. The reference spectrum was recorded from a sample of compacted $BaSo_4$ powder with dimension 13 x 13 x 2 cm^3, which was placed on a matte black painted plexiglass, see Figure 1(a). Angularly resolved reflectance measurements from the compacted $BaSo_4$ sample showed that the reflectance was above 92% and the $BaSo_4$ exhibits an isotropic reflectance. Following the reference measurement, the dark spectrum was also recorded by turning the illumination source off. Integration time of the spectrometer was fixed to 3 seconds for all the measurements.

A measurement run was recorded by taking a reflectance spectrum in the wavelength region 920 nm to 1650 nm from viewing zenith angle 60° while keeping the illumination source fixed at 45°. Note that the nadir was assumed to be at 90° and the measurements were taken in the backward direction, i.e., illumination direction. This procedure was then repeated two more times so that three measurement runs were obtained for snow with given LWC. The time to perform these three measurement runs was approximately 15 minutes.

The reflectance measurement (R) is labelled as,

$$
\begin{aligned}
&\mathrm{R}_k^i(\lambda), \\
&\qquad \lambda = 921.5 \text{ nm}, 902.25 \text{ nm}, \ldots, 1651 \text{ nm}, \\
&\qquad i = 1, 2, 3, \\
&\qquad k = \text{snow with different LWC},
\end{aligned}
\tag{1}
$$

and a mean reflectance measurement (M) was calculated by taking a mean of the three measurement runs for each snow sample, i.e.,

$$\mathrm{M}_k(\lambda) = \sum_{i=1}^{3} \frac{\mathrm{R}_k^i(\lambda)}{3}. \tag{2}$$

The mean reflectance values (M) were obtained this way for all the snow samples are further used in the next sections.

2.1.2. The Road Eye sensor

The Road Eye (patent number: SE 531949C2) is a non-contact sensor developed specially to monitor road surfaces. The sensor has been used in previous studies [14, 23] to classify different phases of water on asphalt. The sensor consists of three laser diodes of wavelengths 980 nm, 1310 nm and 1550 nm and the reflected light is measured with a photo detector for the respective wavelength.

The sensor was mounted at an angle of 60° and at a distance of 0.7 m from the snow surface. The reflected light of specific wavelengths was measured from the center of the snow surface. The laser diodes and the detector were at the same angle, which means that the Road Eye sensor measured in the backward scattering direction. The data from the measurements was collected with a frequency of 20 Hz and were logged using a portable computer. Five reflectance measurements (R) were taken at each wavelength for each snow sample with given LWC,

$$
\begin{aligned}
&R_k^i(\lambda),\\
&\qquad \lambda = 980\text{ nm}, 1310\text{ nm and }1550\text{ nm},\\
&\qquad i = 1, 2, 3, 4, 5,\\
&\qquad k = \text{snow type.}
\end{aligned}
\tag{3}
$$

A mean reflectance value (I) was calculated from the five individual measurements for each of the snow samples,

$$I_k(\lambda) = \sum_{i=1}^{5} \frac{R_k^i(\lambda)}{5}. \tag{4}$$

Normalised mean reflectance values (M) was then calculated by dividing the mean reflectance values (I) by the reference reflectance $B(\lambda)$ from the $BaSo_4$ sample, i.e.

$$M_k(\lambda) = \frac{I_k(\lambda)}{B(\lambda)}. \tag{5}$$

The normalised mean reflectance values (M) for all the snow samples were further used in the next sections.

2.1.3. The Road Eye sensor for ski track measurements

The idea behind using the Road Eye for measurements in ski tracks was to see if the sensor can be used for snow classification as regards estimating parameters such as LWC, grain size and grain structure.

The Road Eye was mounted inside a tube to protect it from dirt and splash. The tube was then mounted on a sledge at an angle of approximately 45° as shown in Figure 2(a). A motor cycle battery was used as a power supply. This was placed inside the sledge together with a portable computer which logged the measured data. In addition, a GPS was attached to the sledge and connected to the computer, registering the exact route for the ski track measurements.

Measurements were performed on the 13$^{\text{th}}$ and 16$^{\text{th}}$ of April, 2016. The measurements on the 13$^{\text{th}}$ were performed in the morning during coarse grained snow conditions as shown in Figure 2(b) and the snow temperature was between -1 and -3°C. The weather on the previous day (12$^{\text{th}}$) was warm and sunny, i.e. the track was very wet,

(a) Road Eye measurements on a cross-country ski track.

(b) One of the measured snow type on ski track

Fig. 2. Measurements performed using the Road Eye sensor on a cross-country ski track. Measurements performed on the snow shown in Figure 2(b) were on 13th of April 2016.

but had refrozen during the night prior to the measurements. The track was groomed in the morning. The measurements on the 16th of April were performed on freshly fallen snow with a temperature of around 0°C and an air temperature of +2 °C. The track had not been groomed and the snow was fine grained. The mean reflectance values (M) from these measurements were also calculated according to Equation 5.

2.2. Snow samples

The snow used for the measurements in the climate chamber was collected from a nearby ice-skating hall and brought to the climate chamber. The snow was initially quite wet, but it froze in the climate chamber later became hard and dry. In order to prepare equal samples, the snow was grinded into fine particles. Five snow samples with constant dry density of 460 kg/m^3 were prepared and each sample was prepared right before the measurements were performed.

In order to have samples with known LWCs, a NaCl solution was added to the snow. The weight percent of NaCl solution for each sample is shown in Table 1. The concentration of the solution was between 16.2 and 16.5% corresponding to the LWC of a NaCl solution at the experiment temperature [24]. In order neither for the snow to melt, nor the solution to freeze, a temperature difference of at most 0.1°C was allowed when the solution was added to the snow. The salt solution and the snow were put in a sealed container which was shaken thoroughly for one minute so that the liquid was uniformly distributed throughout the snow. A stainless steel plate with dimensions 24 x 16 cm^2 was used to compress the snow manually into a plastic box of volume 24 x 16 x 13 cm^3. The same method to prepare snow samples was used by Wåhlin et al [25].

Table 1. Details about the prepared salt solution samples.

Sample number	NaCl solution [wt %]	Absolute amount [g/m^3]
I	0	0
II	5	0.024
III	10	0.051
IV	15	0.081
V	20	0.115

2.3. The NDWI

A remote sensing index based on the measured reflectance at wavelengths 980 nm and 1310 nm was used. This procedure derives the normalised difference water index (NDWI) from the mean reflectance values (M) at two wavelength bands to investigate the relative amount of LWC in a given snow sample. The NDWI is calculated as

$$\mathrm{NDWI} = \frac{\mathrm{M}_k(980) - \mathrm{M}_k(1310)}{\mathrm{M}_k(980) + \mathrm{M}_k(1310)}. \tag{6}$$

The value of NDWI ranges from -1 to 1 and is applied in various applications to detect changes in water content. Gao [26], McFeeters et al [27] and Xu [28] among many others have given broad details on the NDWI and applicability of the index.

3. Results

Results from the experimental observations for both the sensors are presented in this section. The Road Eye measurements in the ski track were also analysed and a correlation to the observations in the climate chamber was investigated.

3.1. Optimum wavelength bands

The mean reflectance values ($\mathrm{M}_k(\lambda)$) at wavelengths from 920 nm to 1650 nm at viewing zenith angle 60° are presented in Figure 3. Part of the reflectance spectrums from 1535 nm to 1565 nm for all the snow samples were zoomed for better perception.

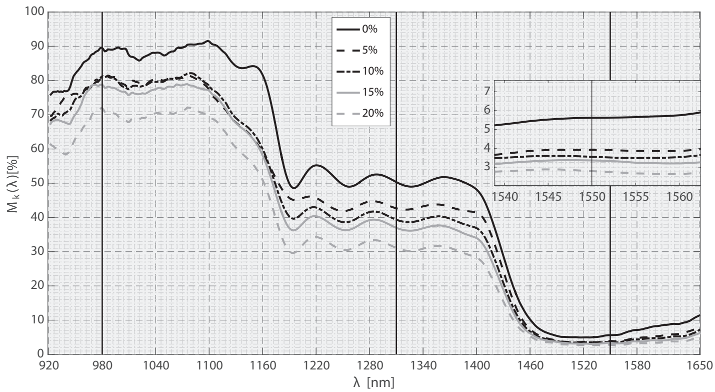


Fig. 3. Measured spectral reflectance data at wavelengths from 920 nm to 1650 nm at viewing zenith angle 60° while keeping the illumination source fixed at 45°. Zoomed window shows the spectral reflectance data at wavelengths from 1535 nm to 1565 nm.

Three regions of several wavelengths can clearly be observed in Figure 3 where reflective properties of snow with different LWC were distinct and significant. These regions of wavelengths were defined as WR1: 960 nm -1100 nm, WR2: 1200 nm - 1400 nm and WR3: 1480 -1600 nm.

All snow samples exhibit similar spectral features but the degree of absorption varied due to the amount of LWC. Moreover the snow samples were well distinguishable as seen in Figure 3 at wavelengths 980 nm from WR1, 1310 nm from WR2 and 1550 nm WR3. It was clearly observed that the snow with different LWC is better distinguishable at 1310 nm than that of at the other two wavelengths. However, 980 nm and 1550 nm can be considered as a reference due to the fact that the snow with different LWC have higher reflective properties and lower reflective properties at these wavelength bands, respectively. The measurements at these three wavelengths are marked with black vertical lines in Figure 3.

Moreover the Road Eye sensor was also equipped with laser diodes of these three wavelengths and measured reflectance in the backward direction. Therefore the reflectance measurements at wavelength bands 980 nm, 1310 nm and 1550 nm are considered further.

3.2. Comparison between the NIR spectrometer and the Road Eye

The mean reflectance values ($M_k(\lambda)$) at wavelengths 980 nm, 1310 nm and 1550 nm at viewing zenith angle 60° using the spectrometer are presented in Figure 4(a). The mean reflectance values ($M_k(\lambda)$) from the Road Eye sensor at 980 nm, 1310 nm and 1550 nm in the backward direction at 60° is presented are Figure 4(b).

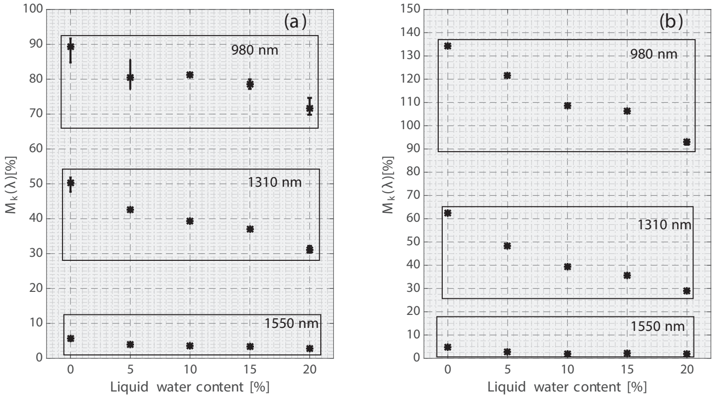


Fig. 4. Comparing the measured reflectance data at wavelengths 980 nm, 1310 nm and 1550 nm using both the spectrometer and the Road Eye. Error bars represent the minimum and the maximum value at the specific data point.

An approximately linear relation between the amount of liquid water and reflective properties of snow at all the three wavelengths can be observed. As the amount of liquid water increases the snow sample tends to have higher absorption, see Figure 4(a). Liquid water in snow causes the grains to form clusters and the grain size increases. Moreover, the solution might also form liquid clusters [21].

Furthermore the observations in Figure 4b also show that the Road Eye sensor captured the linearity between the LWC and the reflective properties of snow. A decrease in the reflectance as the LWC in the snow increased can be seen.

Error bars in Figure 4 represent a minimum and a maximum value at the specific data point. Spectrometer measurements observed to have relatively large variance compare to the measurements from the Road Eye sensor.

3.3. A linear regression equation for the NDWI values

The mean reflectance values at wavelengths 980 nm and 1310 nm were used to calculate the NDWI values for all the snow samples. These two wavelengths are considered in this section as the snow with different LWC was better distinguishable especially at these two wavelengths. Calculated NDWI values with respect to the added LWC are presented in Figure 5. Figure 5(a) shows the data measured using the NIR spectrometer while Figure 5(b) shows the data measured using the Road Eye sensor.

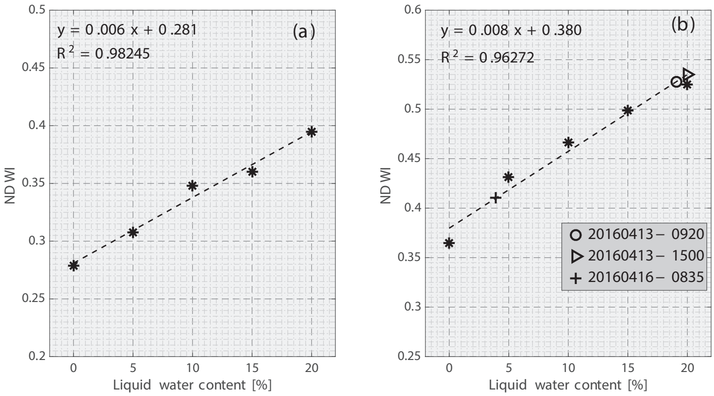


Fig. 5. A linear regression plot for the measured reflectance from both the sensors. Figure 5a shows the calculated NDWI values from the measurements recorded using the spectrometer. Figure 5(b) shows the calculated NDWI values from the measurements recorded using the Road Eye sensor.

It was observed that the NDWI is sensitive to the LWC in snow and the index values increased with increasing water content. There is a strong positive linear correlation between the NDWI values and LWC as shown in Figure 5. A linear regression line was plotted for the NDWI values for the snow samples. The obtained linear regression equations are given in Figure 5 and x in the equation represents the LWC while y represents the estimated NDWI value.

The NDWI values were also calculated for the snow measured in a cross-country ski track on the dates 13th and 16th of April, 2016. Amount of water content was estimated from these NDWI values using the linear regression equation. These data points are also presented in Figure 5(b).

As described in section 2.1.3.1.3 about the measurements in the ski track, the snow on the 13th was refrozen and composed of individual large coarse grains, see Figure 2(b). As shown in Figure 5(b) the estimated water content in snow on the 13th was close to 20%. The snow measured on 16th was a fine grained fresh snow with an estimated water content of just below 5%.

4. Discussions

The crystal growth rate in snow increases rapidly when small amount of liquid water is introduced in snow [29]. Snow aging through melting and refreezing processes further increase the crystal growth rate [16]. In the current study, this behaviour was observed and correlated to the reflectance measurements recorded for snow with different LWC. It is a common practice to find optimal wavelength bands where a specific physical property of a matter is investigated, for example water level in vegetation [30], chlorophyl concentration in a lake snow [31] and size of snow grains [32, 33]. Section 3.1.1 showed that wavelength bands 980 nm, 1310 nm and 1550 nm were selected as an optimal bands. However the wavelength bands 980 nm and 1310 nm were selected where the snow with different LWC was well separated due to the distinct absorption characteristics.

The results in section 3.2.2 showed a correlation between the measured reflectance of a snow sample and the amount of liquid water at the selected wavelength bands. As the amount of water in a snow sample increased, the grain size increased and the snow tend to form clusters, while the liquid itself also is assumed to have formed liquid clusters. These changes in snow structure resulted in more light being absorbed while less was scattered. Fresh dry snow exhibit higher reflectance because of a high degree of scattering.

The measurements from the Road Eye sensor were observed to be sensitive to the LWC in snow. It properly captured the differences between the measured samples of different water content. The reflectance values from the Road Eye sensor appeared to be larger than that of spectrometer especially at 980 nm, even though the reflectance data from both the sensors were normalised by a reflectance measurement from a compacted $BaSo_4$ sample.

The NDWI has been widely used in many applications, including vegetation liquid water [26], live fuel moisture [34] and snow-vegetation interactions [35] from the spectral reflectance measurements. In spite of its easy implementation, the NDWI is sensitive to even smaller water contents which is why the index was used as a scaling factor in this study to investigate the effect of LWC in snow. A linear correlation was observed between the NDWI values and the LWC in snow for the both sensors, see section 3.3.3. The NDWI of a snow sample increased as the amount of liquid water increased. As observed in Figure 5, the NDWI values were slightly higher for the Road Eye measurements compared to the spectrometer measurements, however the Road Eye measurements properly captured the effect of LWC similar to the spectrometer.

The results from the Road Eye measurements in the ski track showed that the NDWI values agree well with the measurements in the climate chamber on snow with different LWC. However, using this measurement procedure only, does not tell whether the water is in solid phase, i.e. ice or in liquid phase, i.e. water. The snow in the ski track on 12^{th} of April was very wet, considered as slush (>15%) according to the International Classification for Seasonal Snow on the Ground [36]. Cold temperatures during the night resulted in refreezing of the snow, creating a hard and icy ski track. The track was groomed in the morning creating a softer track with coarse grains as shown in Figure 2(b). The measurements from the 13^{th} of April performed in the afternoon showed a slight increase in water content. Warm temperatures during the day and sunny weather melted the snow which resulted in a slightly higher water content. The measurements on the 16^{th} of April were performed on a freshly fallen snow on a track which was not groomed. The air temperature was +2° and the snow temperature was close to 0°. The snow was classified as wet according to the International Classification for Seasonal Snow on the Ground [36], which according to these estimations corresponds to a water content between 3% - 8%. According to the performed measurements using Road Eye, the water content in the snow was about 4%, i.e. in well agreement with the observations.

Classification of snow with different LWC in ski tracks and pistes are of outermost importance especially in competitive skiing. Both cross-country skiers and alpine skiers base their choice of skis, ski base topographies and ski wax on the conditions in the ski track. Parameters such as LWC and grain size influence the sliding friction to a large extent and are crucial parameters to determine.

This new method for classifying snow in ski tracks and pistes should be further investigated. By correlating the reflectance measurements to defined snow types and snow classes, the method is believed to enable new opportunities for skiers, ski technicians and other people with an interest in snow classification. The fact that the method is fast and non-destructive further promote it. Common practice today is to classify basic snow properties in ski tracks and pistes at one or a few spots. Additional advantages using Road Eye is that a complete ski track can be classified rather fast. This is a benefit for skiers who are then able to choose skis based on the most critical parts of the track, if the snow conditions around the track varies. The results from this investigation further show that the presented approach provides a reliable estimate on snow classification.

5. Conclusions

The spectral reflective properties of snow with different liquid water content (LWC) within the spectral range 920 nm - 1650 nm were analysed. The spectral reflectance of snow was measured in backward scattering direction using a near-infrared (NIR) spectrometer and a Road Eye sensor in a walk-in climate chamber. The Road Eye sensor was used in previous research for monitoring winter roads to detect different phases of water. Along with the measurements in the climate chamber, the Road Eye was used to measure the reflectance from snow in a cross-country ski track. It was observed from the experimental measurements that the reflectance for snow decreases with increasing LWC and a linear relationship between the spectral reflectance and the LWC was observed. Wavelengths 980 nm, 1310 nm and 1550 nm were selected as an optimum bands where the snow with different LWC was distinguishable.

The observations from the Road Eye sensor showed that the Road Eye properly captured the relation between the reflectance and the LWC in snow. A widely known remote sensing index (normalised difference water index) was used as a scale factor to investigate the effect of LWC in snow based on the reflectance at wavelengths 980 nm and 1310 nm. The observations based on the NDWI suggest that the presented preliminary measurements and method can be used to estimate the LWC in snow by measuring reflectance at three wavelengths. The results suggest that the proposed method can be used to relatively estimate the water content for example in ski tracks and for winter roads maintenance.

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Paper D

Span curve temperature dependence of classic style cross country skis

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Span curve temperature dependence of classic style cross country skis

Abstract

Ski properties such as the span curve, the stiffness curve, the grip zones and the load carrying glide zones are important factors for the overall performance in cross country skiing. The performance of the ski can to some extent be predicted by analyzing the span curve, which is unique for every ski. This means that skis within the same pair also are different from each other.

In this study, cross country skis for classic skiing have been analyzed in a digital span curve measuring device. Usually, span curve measurements are done at room temperature whereas skis are used at temperatures below zero. The stiffness curve and span curve for racing skis of eight different major ski-brands were analyzed both at room temperature and at -15°C. Differences in properties between skis within the same pair could be measured, as well as a difference due to temperature, which was the aim of the study.

The results of our investigation show temperature related changes in mechanical properties for classic style cross- country skis during static load conditions. Glide zone length, grip wax zones, span curves and stiffness curves, which are properties related to the overall performance and characteristics of the ski, changed with temperature. Minor differences were found for some of the brands studied, whereas significant differences were observed for other brands.

Keywords: cross country skis, glide zone, span curve, temperature dependence, ski characteristics

Introduction

Skis have been used for hundreds of years for transportation on snow. Today, the majority of skis is designed for recreation and sport activities and the design criteria is related to optimization of grip and glide performance. The pressure distribution between the ski and the snow and to adjust the friction and gliding surfaces has been devoted special attention (Ekström, 1987). The design of skiing equipment and the materials used have developed a lot during the last decades. The first skis were made of wood but in the 1950s the manufacturing process changed and various new materials were used in order to improve the mechanical properties of the skis and the skiing performance (Sakata, 1987). Steel, glass, carbon, boron and kevlar fibers are examples of materials used in the ski manufacturing process. The change from wood to fiberglass resulted in skis with a higher stiffness and tensile strength and lower weight which improved the glide properties (Ekström, 1987). Today manufacturers use different production methods and different core materials for their skis. Many studies show that the construction method and design influence the final ski characteristics, see e.g. Bäckström et al (2008).

The manufacturing processes as well as the method the manufacturers use for classifying skis are generally considered as business secrets. This complicates the comparison between different ski brands (Sakata, 1987). For skiers it is difficult to get enough information to select suitable skis and also to compare skis made by different manufacturers (Sakata, 1987). In addition, it is difficult to know what kind of ski that is most suitable for a certain type of track- and snow conditions. In order to match different snow conditions and different skier’s weight, technique and range of use, a successful ski design must take numerous design variables into account, i.e., geometry, elastic properties, dynamic behavior etc. (Glenne, 1981). Since there exist a large variety of ski models on the market it is important that the factors affecting the ski-skier compatibility should be well understood.

In cross-country skiing, the overall performance of the skis depends mainly on the track conditions and the snow properties (Glenne, 1981). The glide performance is further believed to be related to the construction of the ski and its stiffness- and span curve, as well as to the ski base material, the ski base texture and the wax used on the skis. According to Bäckström et al (2008), the pressure distribution between the ski and the snow is to a great extent responsible for the overall performance. The texture of the ski base surface and ski wax also influence the performance, but to a smaller extent. The stiffness- and span curve, the ski base surface and the base texture are properties that vary for different skis. Different properties are also desirable in different snow conditions in order to achieve the best glide properties. In addition to this, due to different techniques, different skiers also require skis with different properties.

To achieve sufficient grip when this is required while maintaining as good glide properties as possible, is contradictory, but clearly important while selecting skis for skiers with different technical skills and requests. Hence, the process of selecting skis for elite athletes is generally very time-consuming (Breitschädel, 2012). In addition to the classic technique in country skiing, there is also the skating technique. Skating skis have different geometry and different properties than classic style cross country skis. They are in general shorter in length and stiffer than the classic skis.

The span curve demonstrates both the glide zones and the wax pocket of the ski, i.e. the upward arching in the middle of the ski, see Fig. 2. In warm conditions klister grip wax is used. Klister waxes builds a thicker layer and require a higher camber height than harder grip wax used during colder conditions, to not come into contact with the snow surface while gliding, and lead to increased ski-drag. The span curve can be used to determine the weight the ski is capable of carrying. This carrying capacity is of importance since the skis need to withstand the load from the skier, preferably without having the grip wax in contact with the snow, since this impairs the glide properties. The load required to press the ski down to a certain camber height defines the stiffness of the ski. As the name suggests, the stiffness curve maps the camber height as function of the load required to press the ski down to this height. This is useful information connected to the grip, when using grip wax. Normally, skiers prefer different stiffness of their skis depending on their individual technique and the type of track and terrain. Consequently, the stiffness, the length of the grip wax zones and the length of the glide zones are believed to be of outermost importance for the glide properties. By mechanical analysis of the skis, important properties can be determined. In this way skis can be characterized and classified for different snow conditions.

Ski properties are generally measured at room temperature whereas skis are used at temperatures near or below zero. In a previous study, static- and dynamic ski characteristics for skating skis were performed at temperatures between +20 and -15 °C and was found to change (Breitschädel et al., 2010). Breitschädel et al (2010) pointed out that thermo-dependent changes could be of higher importance for classic-style cross-country skis. The fact that ski producers use different core and cap materials, production methods and shapes for their skis were stated as reasons to the difference in thermal behavior. If thermo related changes in properties exist, it is important to take temperature into account when analyzing results from span curve measurements.

Experimental

The span curves for eight pairs of different brands of cross-country skis were measured. The skis were elite racing skis of major brands. The modes of construction are different for different ski brands as well as the core material. The core materials in the tested skis were wood, foam, hollow tubes and honeycomb. It is very difficult to obtain information about the construction methods since this is treated at business secrets as pointed out by Bäckström et al (2008). The measurements were conducted both at room temperature, i.e., skis were about 23 °C, and when the skis had a temperature of -15 °C. The data from the measurements where analyzed in order to determine e.g. stiffness, length of the grip wax zone, length of glide zones, opening angles and the temperature dependence of these. The difference between skis within the same pair was also studied.

The Skiselector™ measurement device

The digital instrument Skiselector™ was used for the measurements. The instrument consists of a rigid aluminum frame with a completely flat surface of stone, on which the ski was placed during the measurements as shown in Fig. 1. The load was applied through a load unit and controlled by a computer. During the span curve measurements, a sensor traveled underneath the ski from the rear end to the front and back. When the sensor traveled towards the ski tip, the half weight of the given load was applied, and then the full weight of the given load was applied when the sensor traveled back again. Noteworthy is that only longitudinal measurements can be performed with this instrument, i.e. no transverse measurements across the ski can be done. The longitudinal resolution of the measurements was about 0.6 – 0.7 mm.

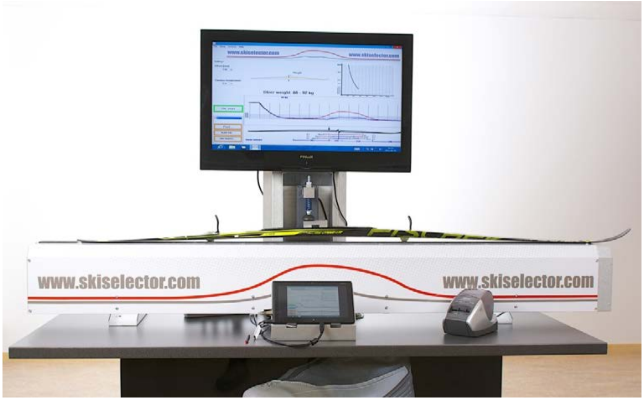

Fig.1 The Skiselector measuring device (Photo: SkiSelector™).

During the span curve measurements the ski was placed so that the load was applied 130 mm behind the balance point, or 130 mm behind the center of mass, which is the position where the skier is assumed to have the mass during double poling. The full weight load applied on the skis was 75 kg, i.e. 735.75 N, for all measurements. The data from the span curve measurements was saved as a text file, which was analyzed using a Matlab script. During the stiffness measurements a load was applied 70 mm behind the balance point, which approximately corresponds to the position where the force is applied during diagonal stride.

Skis tested

The skis were cleaned carefully from ski wax and dirt before the measurements. The lengths of the skis were between 196 cm and 210 cm according to Table 1. The skis within the same pair were called *a* and *b* respectively. The camber height at the balance-point of the ski when unloaded is shown in Table 1.

In order to control the accuracy of measurements, two measurements were done on each ski at both temperatures. The skis were removed from the machine between the measurements. The deviation in glide zone length between the measurements was 0 – 5 mm, which is considered negligible.

Table 1 Length and camber height at midpoint for the skis tested

Ski Brand	Length [cm]	Camber height at balance point when unloaded [mm]	
		Ski a	Ski b
A	207	20.5	25.6
B	202	24.2	24.9
C	202	26.9	26.2
D	210	20.9	19.8
E	203	31.1	29.7
F	196	25.5	24.3
G	201	25.5	25.3
H	198	29.0	28.5

Numerical analysis of data

A MATLAB script was written to analyze properties of the ski from each measurement. For instance, the script was developed to calculate the lengths of the grip and the glide zones and to visualize the half and full weight span curves. Figure 2 depicts the full weight span curve as a continuous line and the half weight span curve as a dashed line. It gives a graphical description of peak camber height and the grip wax zones. For the half weight curve it is assumed that the full load, which in this case is 735.75 N, is equally distributed between the two skis. Moreover, to calculate the length of the glide zones at the front and rear part of the ski, a point with span curve heights lower than 0.05 mm was defined as being in contact with the track.

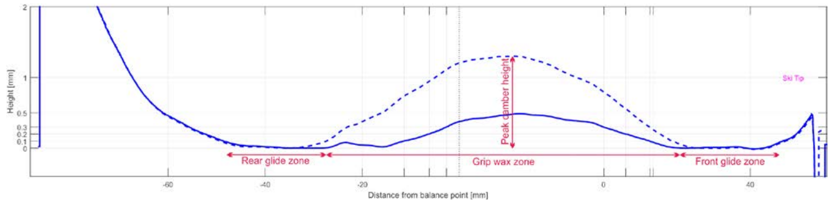

Fig. 2 Half-weight load span curve (dashed), full-weight load span curve (solid), front- and rear glide zones, grip wax zone, peak camber height and angles determined.

Stiffness of skis

The peak camber height as a function of load was determined for all skis in the test, using the Skiselector. Stiffness curves showing the load required to press the ski down to a certain camber height was achieved and the stiffness was calculated as the derivative of the load versus peak camber height. The aim was to identify any differences in stiffness between measurements at room temperature and at -15 °C.

Temperature control and analysis of cold skis

The instrument used for the span curve measurements had to operate at room temperature in order to give reliable test results. In order to perform measurements on cold skis, the skis were put in a freezer, prior to the analysis. The freezer was equipped with a fan to distribute the temperature evenly and maintain an average temperature of -18 °C. Frost or ice formations on the ski base surface were removed with a nylon brush, a common tool used to brush ski base surfaces. The measurements were performed immediately thereafter. The time from when the ski was taken out of the freezer until the measurement was finalized was 120-150 seconds. During this time the temperature of the ski did not markedly change. The temperature of all skis was close to -15 °C during the span curve measurements.

Results

The difference in peak camber height , Δ PCH, at half weight load and the difference in position in relation to the balance point, Δx of PCH at room temperature, RT, compared to -15°C is shown in Table 2. Both skis within each of the eight brands were measured. Negative numbers indicate smaller values at -15°C.

Table 2 Difference in peak camber height (PCH) at half weight load (367.88 N) between the measurements at RT compared to -15°C, and the change in position, Δx, in relation to the BP.

	Ski a		Ski b	
Ski brand	Δ PCH [mm]	Δx of PCH [mm]	Δ PCH [mm]	Δx of PCH [mm]
A	0.09	-1.3	-0.03	-4.1
B	0.2	-23.1	0.28	-6.8
C	0.34	-107.3	0.37	-74.7
D	0.01	-39.5	-0.08	-43.6
E	0.23	-90	0.14	-79.1
F	0.02	-9.3	0.02	-2.3
G	0.1	-5.1	0.09	-3.8
H	-0.08	-78.4	-0.06	-7.8

The difference in front and rear glide zone lengths (GZL) between measurements carried out at RT and at -15°C for the skis with the full load of 735.75 N are shown in Table 3. Negative numbers indicate a smaller GZL at -15°C compared to RT.

Table 3 Difference in front- and rear glide zone length (GZL) between measurements at RT compared to -15°C.

	Ski a		Ski b	
Ski brand	Δ Front GZL [mm]	Δ Rear GZL [mm]	Δ Front GZL [mm]	Δ Rear GZL [mm]
A	3	0	4	9
B	11	-10	4	-49
C	49	-11	48	73
D	18	21	7	16
E	3	-22	81	-9
F	11	-3	87	-15
G	2	2	-3	-10
H	6	-11	85	6

The total glide zone lengths for the skis at room temperature with the applied load of 735.75 N are shown in Table 4.

Table 4 Glide zone lengths with an applied load of 735.75 N for measurements at room temperature. The differences between Ski a and Ski b are highlighted.

Ski Brand	**Difference in front glide zone length between Ski a and Ski b [mm]**	**Difference in rear glide zone length between Ski a and Ski b [mm]**	**Total glide zone length [mm]**	
			Ski a	**Ski b**
A	259	68	420	747
B	30	11	366	347
C	16	107	407	530
D	65	27	475	567
E	37	20	465	448
F	93	12	438	543
G	34	41	396	403
H	12	52	457	497

The peak camber height at half weight load versus ski length for *Ski a*, i.e. one of the skis in the pair, for all the tested ski brands is shown in Fig. 3. There is no clear indication of increasing peak camber height with increasing ski length for the skis tested.

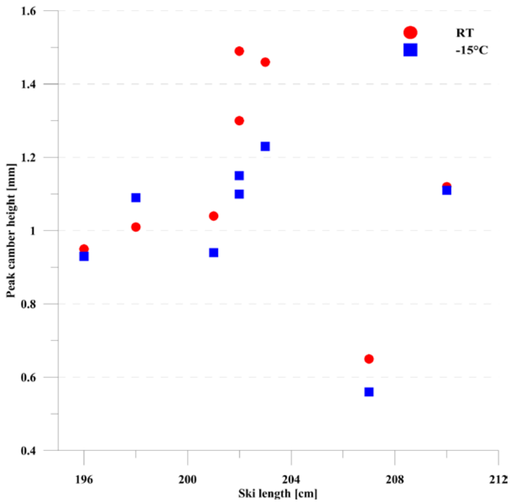

Fig. 3 Peak camber height at half weight load versus ski length at room temperature, RT, and at -15°C.

Span curves for *Ski a*, i.e. one of the skis for all the tested ski pairs are shown in Fig. 4. The continuous blue line corresponds to full weight load, i.e. 735.75 N at -15 °C and the dashed blue line corresponds to half weight load, 367.88 N. The corresponding red lines are for measurements at room temperature. Notice that it for some of the tested skis is a small difference between the curves at room temperature and at -15 °C, whereas a major difference can be observed for other pairs.

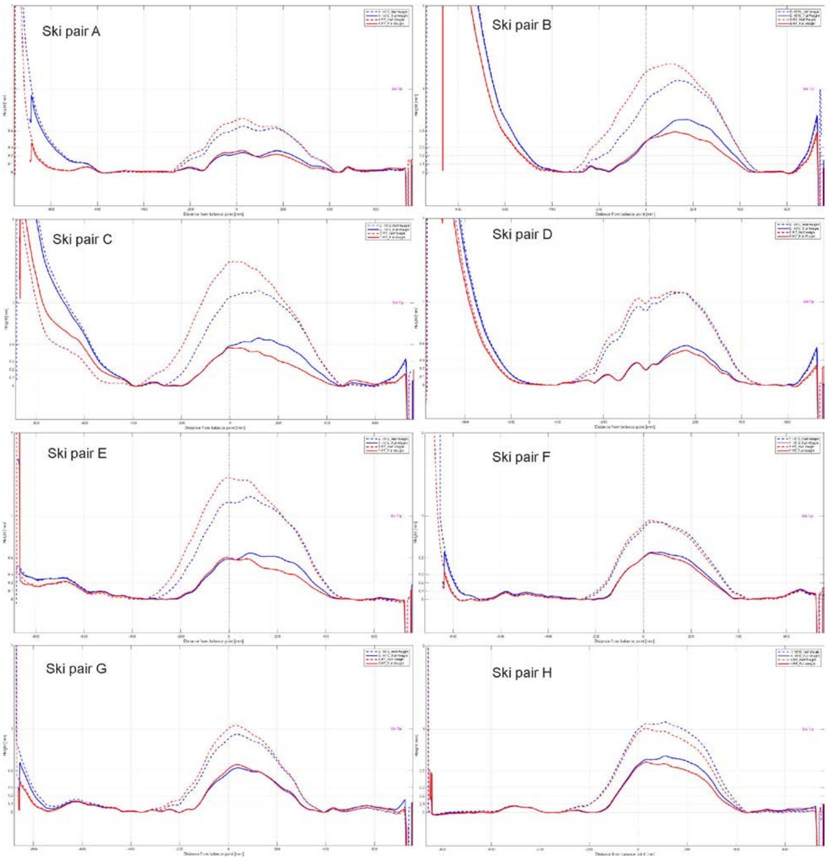

Fig. 4 Overview of the span curves of one of the ski from each tested ski pair. The span height [mm] is plotted against the distance from the balance point [mm]. Red curves correspond to room temperature and blue for -15°C. Dashed lines correspond to half weight load and solid lines to full weight load.

Stiffness curves for the skis tested are shown in Fig. 5. The red curves correspond to room temperature measurements and the blue curves to measurements at -15°C. The continuous curves are measurements for ski *a* and the dashed curves represent ski *b*, with in each pair.

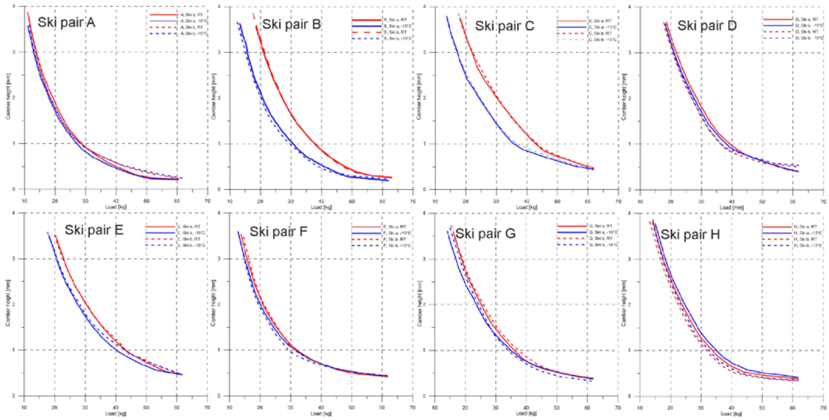

Fig. 5 Stiffness curves corresponding to the span curves in Fig. 4. The camber height [mm] is plotted against the mass [kg]. Red lines correspond to room temperature and blue lines to -15 °C. Solid lines represent Ski a and dashed lines represent Ski b within each pair.

The stiffness of the skis was computed as the derivative of the curves shown in Fig. 5. The values of the stiffness at 50% and 75% of the maximum load are shown in Table 5.

Table 5 Stiffness at 50% and 75% of maximum load for all skis at room temperature, RT, and at -15°C.

	Ski a RT		-15°C		Ski b RT		-15°C	
Ski brand	Stiffness at 50% load [kN/m]	Stiffness at 75% load [kN/m]	Stiffness at 50% load [kN/m]	Stiffness at 75% load [kN/m]	Stiffness at 50% load [kN/m]	Stiffness at 75% load [kN/m]	Stiffness at 50% load [kN/m]	Stiffness at 75% load [kN/m]
A	273,7	531,7	317,8	556,2	317,8	568,0	337,5	585,7
B	123,6	438,5	226,6	554,3	120,7	435,6	295,3	680,8
C	113,8	389,5	209,0	513,1	110,9	362,0	217,8	460,1
D	124,6	423,8	143,2	442,4	173,6	552,3	187,4	541,5
E	114,8	351,2	139,3	445,4	120,7	347,3	156,0	371,8
F	292,3	622,0	328,6	660,2	322,7	672,0	401,2	716,1
G	166,8	550,3	206,0	531,7	150,1	490,5	196,2	525,8
H	212,9	603,3	190,3	574,9	246,2	621,0	224,6	588,6

The stiffness for ski a and ski b of each pair at RT, with 50% and 75% load are also shown in Fig. 6.

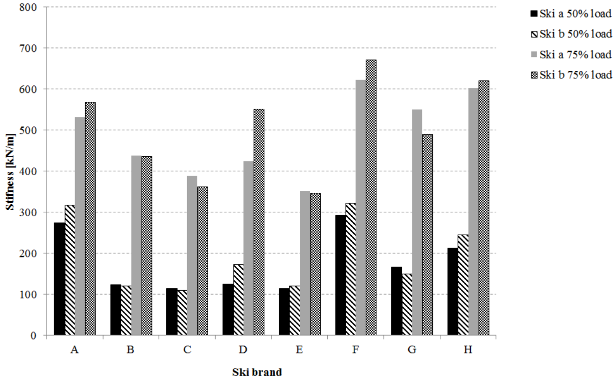

Fig. 6 Stiffness for ski a and ski b of each pair at RT, with 50% and 75 % of the maximum load.

The difference in stiffness between measurements at RT and at -15°C for ski a and ski b within each brand, at 50% load and 75% load, respectively is shown in Fig. 7.

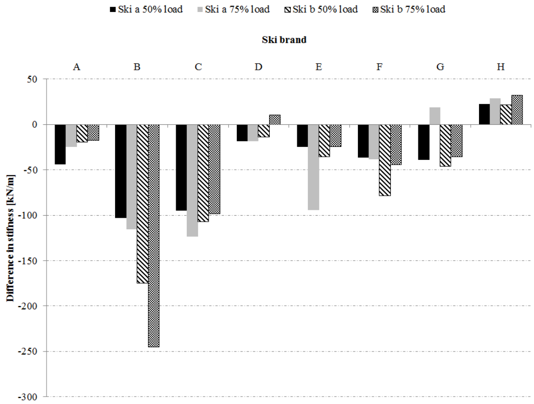

Fig. 7 Difference in stiffness between measurements at RT and at -15°C for ski a and ski b within each pair, at 50% load and 75%load.

Figure 8 shows the stiffness at 50% load for all skis at RT measurements versus the total glide zone length.

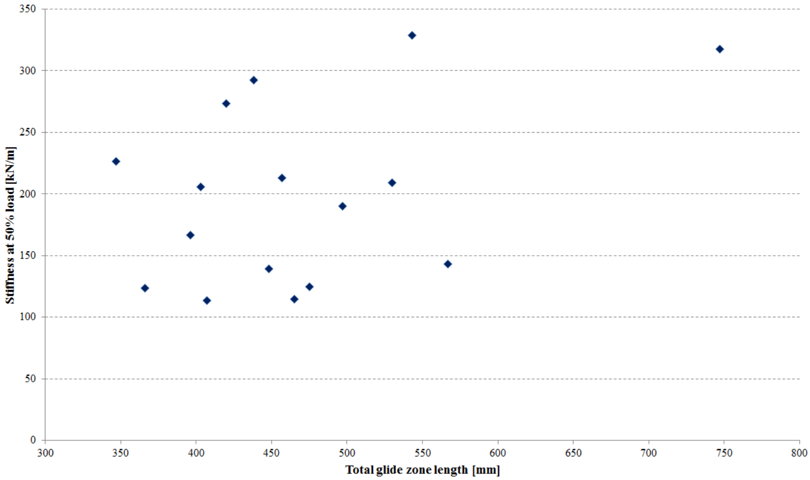

Fig. 8 Stiffness at 50% load for all skis at RT measurements versus the total glide zone length.

Discussion

Comparing results from measurements of skis within the same pair showed that there for some ski pairs is a significant difference between the two skis, both at room temperature and at -15 °C. This means that the behavior for skis within the same pair is likely to be quite different. The grip zone length and grip zone area tells how much grip wax that should be used for optimum grip- and glide properties. It is therefore important that each ski is characterized separately, with respect to the weight and skills of the skier. Moreover, the difference in ski properties with respect to temperature shows the importance of testing skis at a temperature close to that they are going to be used. For some skis the difference in glide zone length was as much as about 30% or 7-8 cm. For the recreational type of skiers, this is likely of minor importance whereas it might be quite significant for an elite skier, where every fraction of a second can be essential.

The peak camber height is sometimes used to estimate the stiffness of skis, where a higher camber height will allow either more load to be applied, i.e. heavier skiers will need a higher peak camber height, or it may indicate that more grip wax can be used. This is for example wanted in snow conditions when klister wax is required to get a sufficient grip. The measurements of peak camber height at room temperature compared to the measurements at -15°C shows in general a decrease in peak camber height at lower temperature. Perhaps even more important is that the position changes, in general towards the front tip of the ski, which changes the grip wax zones and the guidelines for application of grip wax. Different thermal properties for the materials used in the production process for the investigated ski brands could explain the thermally related changes.

The glide zone length is important for the overall ski performance, since it corresponds to the pressure distribution. It was observed that the glide zone length differed both for skis within the same pair and also at the two different temperatures. The longest total glide zone length were observed for ski pair A followed by ski pair D and F. Ski pairs A and D were also the longest skis in the test (207 cm and 210 cm, respectively), but ski pair F was the shortest skis (196 cm). This shows that the total glide zone length not necessarily must be connected to longer skis, which is a common assumption. The total glide zone length is neither connected to the stiffness of the skis as shown in Fig. 8. Ski pair F had the highest stiffness values but did not have the shortest glide zones. Instead the shortest total glide zones were observed for ski pairs B and G.

The curves of load versus peak camber height in this test should not be compared to each other, since all tested skis were of different stiffness and not initially aimed for the same specific weight. The biggest difference between these curves at the two different temperatures was observed for ski pair B and C (see Fig. 5). As shown in Table 5 and in Fig. 6, the stiffness was significantly lower at room temperature than at -15°C, for ski pair B and C. Ski brand H was the only brand with a higher stiffness at room temperature than at -15°C. The stiffness did in general not considerably change for the other brands, although ski a at 75% load for ski brand E and ski b at 50% load for ski brand F have apparent thermo related changes in stiffness. The different core materials used in the skis is likely a reason to the different behavior for the different brands, but needs to be further investigated.

Ski pair E had the highest peak camber height when unloaded, but not the highest stiffness. Thus, peak camber height alone, neither with nor without load, can be used to determine the stiffness of a ski.

Analysis of the measurements of glide zones and camber height can be done in different ways, depending on whether the measured parameter can be expected to have normal distribution or not. Assuming the measurements to be independent samples of some stochastic parameter, a sign test can be done as described for example in Gibbons & Subhhabrata (2011). Table 6 summarizes the confidence intervals and confidence levels in %, obtained for different r. For example for r = 5 there is a 92.3% probability that the “average ski” has a peak camber height at -15°C between 0.89 and 15.38% lower than at room temperature. The position of the peak camber height at -15°C is between 7.74 and 52.85 % closer to the ski tip than at room temperature. Moreover, the front glide zone length at -15°C is between 1.95 and 18.53% shorter than at room temperature.

For each of these parameters, “average ski” means that if repeated measurements for an equal and very large number of skis of brand A-H is performed and the median computed for all relative changes, then asymptotically (as the number of skis grow towards infinity) there is a 92.3 certainty that the computed median will be in the corresponding confidence interval. For example, for r = 5 there is a 92.3% probability that the “average ski” has a peak camber height at -15°C that is somewhere between 0.89% and 15.38% lower than the peak camber height at room temperature. For shorter confidence intervals and/or higher confidence levels, a large number of measurements is needed, but for the mentioned three parameters (peak camber height, peak camber position and front glide zone length) eight pairs of skis was enough to get confidence intervals not containing zero, which gives a clear indication either for an increasing or decreasing parameter value. For the recreational skier, this is likely not of importance, but for elite skiers and especially in the national teams, this gives a clear indication that the ski span changes with temperature. Measurements at expected racing temperatures could help finding the optimal pair of skis for each skier.

Table 6 Sign test results

r	$I_r^{Camber\ peak\,height}$	$I_r^{Camber\ peak\,position}$	$I_r^{Front\,GZL}$	$I_r^{Rear\ GZL}$	$P(m\epsilon I_r)$
1	[-24.34,8.42]	[-2647.06,1012.26]	[-33.33,1.85]	[-26.94,27.07]	99.9969%
2	[-22.82,7.92]	[3.52,553.15]	[-29.79,-1.02]	[-8.5,11.89]	99.9481%
3	[-19.31,6.67]	[4.89,261.33]	[-28.81,-1.07]	[-5.84,7.33]	99.5819%
4	[-15.75,4.05]	[6.04,178.28]	[-20.16,-1.24]	[-2.97,6.71]	97.8729%
5	[-15.38,-0.89]	[7.74,52.85]	[-18.53,-1.95]	[-2.12,5.98]	92.3187%
6	[-13.85,-2.11]	[13.48,39.94]	[-7.89,-2.39]	[-1,5.88]	78.9886%
7	[-9.62,-2.25]	[16.45.32.98]	[-5.61,-2.41]	[0,4.39]	54.5502%
8	[-9.15,-7.96]	[20.28,22.22]	[-5.53,-4.69]	[1.26,4.15]	19.6381%

For the rear glide zone, the 92.3% confidence interval contains zero, as shown in Table 6. For r = 7, zero is avoided in the confidence interval, but then there is only a 54.5% chance that the rear glide zone for the "average ski" gets between 0 and 4.39% longer at -15°C than at room temperature. For a higher confidence level, but still a confidence interval not containing zero, more measurements are needed.

The different span curves and the different behavior both related to temperature and load is hypothesized to depend on the construction of the ski and the material used both for the core and the cap of the ski. The construction methods and material used in the skis varies for different manufacturers. The different behavior for the full- and half weight load curves can be due to the fact that the cap material takes the initial load and that both the cap, but presumably of higher importance, also the core material differs between the different ski brands.

Although differences between the measurements at room temperature and at -15 °C were observed, it should be pointed out that only one pair of skis of each brand was tested. A future more comprehensive study where a number of skis of each brand are tested is therefore suggested.

Static measurements, like those performed in this study, can give some indications on the mechanical properties of the skis. It gives an apprehension of the behavior of the ski and an idea about the conditions and for which body weight the skis most likely are suitable to be used for. However, the behavior of the ski during dynamic loading might be a lot different than during static load conditions. For future research it is therefore of interest to also perform dynamic measurements.

In order to match skis with specific span- and stiffness curves as well as other mechanical properties to different snow and track conditions it is important to characterize the snow to have a clear and standardized definition of different snow types. The skis and the ski base structure have to match the local snow and track conditions to achieve perfect glide (Breitschädel, 2012). Therefore it is of utmost importance to also have a good knowledge about the snow.

Conclusions

Thermo-related changes in mechanical properties were observed for all the ski brands tested.

The front part glide zone length decreased at -15 °C compared to measurements at room temperature for all except one of the tested ski pairs. The decrease was greatest in the front part glide zone while the rear part glide zone for some of the ski brands increased. Also the grip zones changed both with respect to the area in front of and behind the balance point.

The peak camber height and the span curves changed for all skis with the greatest changes for ski pairs B, C and E, where the half weight load span curve became lower at -15 °C while the full weight curve became higher. Ski brand H was the only ski brand where both the half weight and the full weight span curve was higher at -15 °C.

The static measurements performed make it possible to determine mechanical properties of importance for the ski characteristics and also to match properties of skis in order to get as similar characteristics as possible for skis within the same pair.

The results obtained in this paper clearly indicate that temperature is an important parameter when measuring span curve and when analyzing ski characteristics.

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Paper E

Snow storage - modelling, theory and some new research

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Submitted

Snow storage – modeling, theory and some new research

Abstract

Due to the global warming it is nowadays often a later arrival of natural snow. This causes problems for ski resorts and other places where winter activities in different forms take place. Storing snow is one solution for the winter business industry to deal with this problem. However, there is so far very little research concerning this question. In this paper some modeling and theoretical calculations are presented regarding snow storage, which can be important as a background when designing an insulated snow depot. Moreover, present knowledge is reviewed and new results concerning melting losses of stored snow in northern Sweden are presented. These results are compared to theoretical calculations. The results show that the model used for the calculations can be used to estimate melting losses of insulated piles of snow, if the geometry of the pile is known. The model can also be used to compare different insulating materials and to determine properties such as thickness of the insulating layer needed to sufficiently insulate the snow. The surface area of insulated snow depots shall be minimized in order to reduce melting related to heat from the air, sun and sky which constitute the largest part of the total melt. The quality of insulating materials used shall be observed annually. Commonly used insulating materials such as bark, wood chips, cutter shavings and sawdust have a decay rate, which imply deteriorating insulating properties with time.

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1. Introduction

Storage of snow is an old technique which was common for food storage applications before the refrigerators were developed in the beginning of the 20th century (Skogsberg, 2005). Skogsberg and Nordell (2001) mention for instance himuros and yukimoros, which are houses or rooms where vegetables are stored together with ice or snow in order to keep the quality. Nowadays snow and ice are stored for different purposes. Japan, China, Canada, USA and Sweden are some countries where different techniques of snow and ice storage for cooling applications have been performed (Nordell and Skogsberg, 2007). The hospital in Sundsvall, Sweden, is one example where snow has been stored for cooling purposes (Skogsberg, 2001). Utilizing snow and ice for cooling is according to Nordell and Skogsberg (2007) a renewable natural energy without any environmental drawbacks.

An enhanced interest in storing snow for winter activities has been observed during the last decade. Due to the global warming, the arrival of natural snow has become more unpredictable and at the same time higher temperatures imply difficulties with traditional snow making. Storing snow in order to guarantee an early start of the season has become more common for establishing cross country ski tracks, alpine ski slopes and ski jumping areas. A stored snow depot enables resorts and skiing facilities to guarantee a fixed opening date. Stored snow is also used for summer ski events. A typical size for a snow depot is 5000 - 30 000 m^3, although they may also be larger (Martikainen, 2016). According to Martikainen (2016) the first insulated snow storage in the world aimed for skiing was located in Ruka, Finland in 2000. Different kinds of insulating materials were tested, for example sawdust, foamed plastics, aluminum folio and sheets with different properties. Both natural and machine made snow can be stored, although machine-made snow is most common when storing snow for winter activities since it is considered more durable and weather resistant than natural snow (ICEHOTEL, 2011).

Snow can be stored indoors in a thermally insulated building, underground in a cavern in which case no insulation is necessary or on the ground in open ponds or pits covered with some kind of thermal insulating material, which is the most common method (Nordell and Skogsberg, 2007). The thermal insulating material can either be natural materials or fabricated materials. There are different methods to insulate open pond snow storages, i.e. piles of snow which are stored on the ground. Martikainen (2016) distinguishes between three different methods; a breathable method, which means an insulating material which enables evaporation, a non-breathable method, which is an insulating material which only insulates the snow, or a mix between the two methods. Most common in Scandinavia seems to be a breathable method with a natural insulating material. Table 1 shows a compilation of information from some places where snow has been stored together with the insulating materials used. Natural insulating materials are for example bark, crop residues such as rice shells, mineral particles or debris and different types of wood chips, which here include cutter shavings of different size, sawdust and wood powder. Fabricated materials are generally different kinds of loose sheets, such as plastic sheets, filled tarpaulins e.g. with straw, geo textile sheets, aluminum folio, felts and sometimes thermal foam in between (Skogsberg, 2005, Martikainen, 2016). The most commonly used insulating materials on snow storages in Scandinavia are bark and different types of cutter shavings. As an example a pile of stored snow covered with sawdust is shown in Figure 1.

Figure 1 Snow storage insulated with sawdust, Vuokatti, Finland, 2013.

According to Martikkainen (2016) a snow depot should be associated both with low emissions and snow to a low cost. Therefore many local factors at the place where the snow is supposed to be stored need to be taken into account in order to create the most optimal snow storage.
There are many different factors which affect the melting rate of an insulated snow depot. Skogsberg (2005) denotes snow melting in warm surroundings as natural melt and divides it into three parts; ground melt, surface melt and rain melt, see Figure 2. Ground melt is the heat transfer through the bottom of a pile placed on the ground. Surface melt occurs by heat transfer from the air, sun and sky. Rain melt is melting through rain seeping through the insulation to the snow. Surface melt is, according to Skogsberg (2005), the major factor influencing the total melt rate. The climate, the choice of thermal insulation and the geometry of the snow pile are factors affecting the melt rate (Nordell and Skogsberg, 2002).

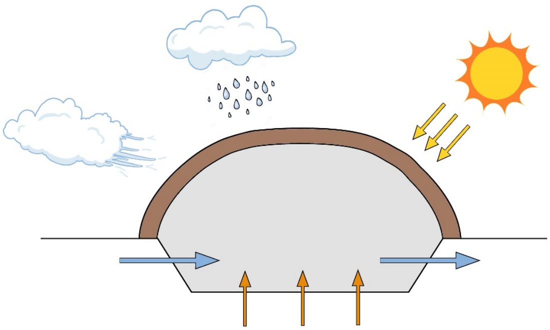

Figure 2 Factors affecting the melting rate of an insulated pile of snow are ground melt which is heat transfer through the ground, surface melt which includes heat transfer from the air, sun and sky and rain melt (From Skogsberg, 2005).

The optimum design of a snow storage is not yet fully understood. The objective with this paper is to summarize current knowledge and experiences from some places where snow has been stored and to present new results from practical experiments of snow storages. The results are compared to theoretical calculations of the melt rate.

2. Knowledge regarding snow storage

2.1 Mass and heat transfer in an insulated snow depot

The mass and heat transfer through a porous material used as thermal insulation on a snow depot placed on the ground, occurs through water transport, heat conduction, heat convection and radiation (Skogsberg and Lundberg, 2005). This is illustrated in Figure 3. The radiation exchange at the surface of the insulating layer includes both short wave radiation from the sun and long wave radiation, i.e. heat. The convective heat and mass transfer is according to Skogsberg and Lundberg (2005) influenced by the temperature, humidity, wind velocity and the properties of the insulating layer such as surface roughness of the material, water transport capacity and compaction. The thermal conductivity depends on the properties of the insulating material, such as structure, compaction and moisture content. The energy conduction rate depends on the temperature difference between the different media.

Moisture is transported as vapor and as water (Skogsberg, 2005). Vapor is transferred by diffusion and by mass convection. Water is transferred by Darcy flow and by suction. Most of the melt water is transported downwards through the snow. In wood chips layers, some of the water is transported upwards, through the insulating layer due to capillary forces and evaporation. Evaporation requires energy and will therefore cool the insulating layer and thereby decrease the melt rate. Evaporation is, according to Skogsberg and Lundberg (2005), a minor part in the mass balance but plays a significant role in the energy balance. This is due to the latent heat. The latent heat of vaporization, i.e. when a liquid goes to gas, is 7.5 times greater than the latent heat of fusion, i.e. when a solid goes to liquid. Thus also minor evaporation will decrease the melt rate significantly.

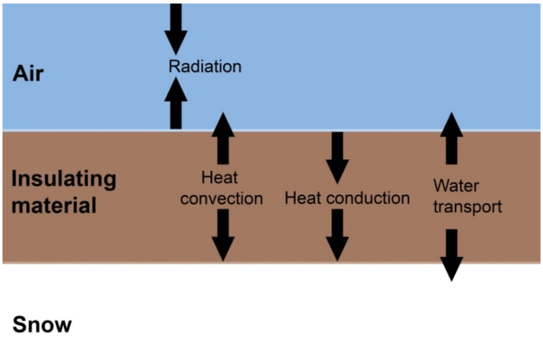

Figure 3 Mass and heat transfer through a porous material (from Skogsberg and Lundberg, 2005).

2.2 Factors affecting the melt rate in an insulated snow depot

The natural melting of an insulated snow depot was by Skogsberg (2005) divided into surface melt, rain melt and ground melt, of which surface melt constitute the largest part of the total melt. Surface melt was therefore investigated by Skogsberg and Lundberg (2005) in a laboratory experiment where cutter shavings were used as thermal insulation. The aim was to study the effect of different factors on the surface melt rate. The influence of five main and two complimentary factors on the melt and evaporation rate was studied. The main factors were the thickness of the insulating layer, the wind velocity, the light intensity, the air temperature and the absolute air humidity. The complimentary factors were cutter shavings moisture content and hindered evaporation. The results from the study showed that the melt rate decreased with thickness of the cutter shavings layer. The melt rate increased with wind velocity, light intensity, air temperature and air humidity. An increase in any of these factors increased the melt rate independently of the value of the other factors. The evaporative cooling effect was found to be important, and the melt rate drastically increased without evaporation. It was also found that the surface melt rate was about the same with dry as with wet cutter shavings, which indicated that the increased evaporation rate balanced the increased thermal conductivity.

The choice of thermal insulating material will affect the melt rate. Studies with cutter shavings, sawdust and wood chips as insulting material are presented by Skogsberg (2002, 2005) and Skogsberg and Lundberg (2005). The thermal insulation quality of wood chips on snow and ice depends on heat conductivity, water transport capacity, evaporation capacity, absorptivity and relative surface area of the insulating material (Skogsberg and Lundberg, 2005). Skogsberg (2002) found in a study that two piles of snow, one insulated with 0.1 m of cutter shavings and the other with 0.2 m of sawdust, melted at about the same rate. This indicated that cutter shavings are more efficient as thermal insulation on snow than sawdust. The advantage with cutter shavings is according to Skogsberg and Lundberg (2005) due to the large surface area and airy structure of the cutter shavings pieces. An advantage with sawdust though, is stated to be the higher compactness, which leads to decreased convective heat transfer.

One drawback with wood chips as thermal insulation material is its decay rate with time (Skogsberg, 2005). Wood chips, cutter shavings and sawdust get wet and darken with age, which together with the deterioration of the water transport affect the insulating quality. Wood chips used as thermal insulation on snow stored for cooling purposes at the hospital in Sundsvall were found to decay fast and it was necessary to add new material every year and to replace all of it after three years (Nordell and Skogsberg, 2007). The same trend has been observed at Birkebeiner Ski Stadium in Norway with a decay of the wood chips. In Östersund, where sawdust is used, no obvious decay of the material has been observed. Bark has not been extensively studied, but has smaller or non-existent capillary transfer and is according to Skogsberg and Lundberg (2005) assumed to be a poorer thermal insulation material than wood chips. Skogsberg and Lundberg (2005) pointed out that the effect of aging is an important factor to take into account when studying cutter shavings as thermal insulation on snow, but presumably this concern also bark and other insulating materials.

3. Practical examples of snow storages

Information from places where snow has been stored was collected in order to summarize information and to compare experiences and methods. The volume of snow depots, the insulating material used and the approximate melted volume, where this was known, are shown in Table 1. The approximate period of storage was from late spring until the end of October/early November. In Sochi, Russia, snow was stored to be used in February for the Olympic Games. The pile in Arjeplog consisted of natural snow and the piles in Piteå were a mix of natural snow and machine made snow, which was scraped together from a nearby ski slope when this closed for the season. All other piles consisted of machine-made snow.

Table 1 Places where snow has been stored, the approximate volume, insulating materials used and estimated volumes of snow melt (Ädel, 2012, Pelkonen, 2013, Hedlund, 2016, Martikainen, 2016, Rindahl, 2016, Rommedahl, 2016).

Place	Volume [m^3]	Cover material	Estimated total snow melt[%]
Vuokatti, Finland	20 000 – 25 000	Tarpaulin and Sawdust, 30-40 cm	20
Östersund, Sweden (2006)	2 piles á 10 000	Sawdust, ≈ 70-80 cm	30
Östersund, Sweden	20 000	Sawdust, ≈ 50 cm	20
Östersund, Sweden (2015)	30 000	Sawdust, ≈ 40 cm	12
Orsa, Sweden	5000	Bark, ≈ 40-50 cm	-
Högbo Bruk, Sweden	8000	Sawdust	-
Piteå, Sweden (2012)	2400	Geotextile, Bark, ≈ 50-70 cm, partly covered with plastics	29
Piteå, Sweden (2013)	3400	Geotextile and Bark, ≈ 50-60 cm	29
Arjeplog, Sweden (2013)	1600	Geotextile and Bark, ≈ 40-50 cm	61
Sochi, Russia (2013)	800 000 (several piles)	Geotextile in several layers, foamed plastics, aluminum folio	20-50
Birkebeiner Ski Stadium, Norway	40 000	Wood chips, ≈ 30-50 cm	ca. 17

In the Finnish city Vuokatti, snow has been stored for more than 10 years to construct cross country ski tracks (Pelkonen, 2013). Each year on the 10th of October the outdoor ski track of stored snow opens, in connection to an indoor track in a ski tunnel. This prolongs the pre-season with 1-2 months and has become a great business since it enables professional athletes to carry out their pre-season training. The estimated melted volume of snow during the period of storage is 20%.

Östersund in Sweden has been storing snow since 2006 (Hedlund, 2016). The stored snow is of importance for the city since they annually host the world cup opening in biathlon. The stored snow is used each year in the beginning of November in order to build a cross country ski track. In 2006 two piles of snow, each with a volume of approximately 10 000 m^3 were stored, insulated with a 70-80 cm thick layer of sawdust as shown in Table 1. Approximately 30% melted and 10% had turn into ice near the ground (Tidig och säker snö, 2007). During the years, larger volumes of snow has been stored and the approximate volume of snow melt for piles with a volume of 20 000 m^3 has been 20% (see Table 1). In 2015, the snow storage was placed beside the place where the previous piles of snow had been located, in order to let the ice layer on the ground melt. During the summer only 12% of the snow melted, which was assumed to be due to better drainage without the ice crust underneath the pile. In 2016, two piles of snow with a volume of 30 000 m^3 in each pile was stored, covered with a 40 cm thick layer of sawdust. Since some sawdust is lost each year during the handling process, some new sawdust has been added each year to the insulating layers on the piles. In 2014, eight years after the first snow was stored, all the old sawdust was replaced with new. No noticeable reduction in melt rate was however observed with the new sawdust compared to the old sawdust (Hedlund, 2016).

Snow has been stored twice in Piteå, Sweden, and used for cross country skiing. In 2012 about 2400 m^3 of snow was stored and in 2013 the volume was about 3400 m^3. The insulating material was geotextile and bark. The total snow melt was 29% for both piles.

Arjeplog in Sweden is an important place for the automotive industry due to testing activities in cold climate and long winter seasons. However, also the automotive industry is affected by the climate change and the later arrival of snow early in the season. Therefore a snow storage experiment was done in 2013 in order to investigate if stored snow can be used for testing of tires early in the season in case of lack of natural snow. The results from the test showed that 61% of the snow melted.

At the Birkebeiner ski stadium in Norway wood chips are used as thermal insulation on snow (Rindal, 2016). In 2015 about 17% of the initial volume melted during the summer. It has been noticed that a larger volume of snow melts when old wood chips are used. The wood chips are therefore replaced every third year.

In 2013, several piles of snow were stored in Sochi in Russia for the Olympic Games in 2014. The piles were covered with geo textile, foamed plastics and some piles were also covered with aluminum folio to reflect the sun (Martikkainen, 2016). The geotextile blankets were made of several layers (Hoffert, 2013). A layer of thermal foam was added followed by a geotextile layer to render evaporation. The melting percentage varied between 20-50 % for these piles.

Orsa Grönklitt and Högbo Bruk, Sweden, also use stored snow for cross country ski tracks, which are used by both amateurs and professional skiers early in the season. In Orsa Grönklitt, approximately 5000 m^3 of snow is stored covered with a 40-50 cm thick layer of bark (Ädel, 2012). In Högbo, 8000 m^3 of snow was stored during the summer 2016, covered with sawdust (Rommedahl, 2016). The volume of melted snow has not been estimated at these two locations.

In Japan a 0.3 m thick layer of rice shells was used as insulation on a snow depot, which was found to decrease the melt rate significantly (Skogsberg, 2005). This shows that different kinds of agricultural waste also may be used as insulation on snow. Other materials like straw and sheep wool are likely also applicable as thermal insulation (Skogsberg and Lundberg, 2005). However, mineral wool and other materials without capillary water transport will benefit from lower thermal conductivity but suffer from omitted evaporative cooling.

The results of debris or mineral particles as a thermal insulation on snow has been observed on glaciers, where the melt rate decreases with thickness of the debris layer (Pelto, 2000, Kayastha et.al, 2000, Takeuchi et.al, 2000). In contrast to wood chips, there is no decay of debris and thus a one-time cost, if chosen as thermal insulation on a snow depot (Skogsberg, 2005).

One advantage with granular materials as thermal insulation is the adjustment to the pile and its geometry as the snow melts. Loose sheets may slide apart as the pile changes in shape, which is one disadvantage with the sheets. Skogsberg (2005) stated other disadvantages with the loose sheets as being considered too small, too difficult to handle, too expensive and too fragile. However, the development has advanced and different kinds of loose sheets have been successfully used as thermal insulation, for example in Sochi, Russia, prior to the 2014 winter Olympics (Sonne, 2013) and in Idre, Sweden during the summer 2016 (Skoglund, 2016).
Polystyrene, commonly known as Styrofoam, has been used as insulting material for snow storage. However, Styrofoam might not be a long lasting thermal insulating material due to poor weatherability (Gray, 2011). The thermal conductivity is similar to that of sawdust and cutter shavings, i.e. around 0.08 $Wm^{-1}K^{-1}$. The water transport capacity of polystyrene is not known but the water absorption is 0.03-1 %. This indicates some water transport capacity and perhaps also evaporation. Irregularly shaped polystyrene pieces allow space for air which is a favorable property of insulating materials.

The total melted volume as a percentage of the initial volume for the piles in Table 1, is shown in Figure 4. The trend is that larger initial volumes result in relatively lower snow melt.

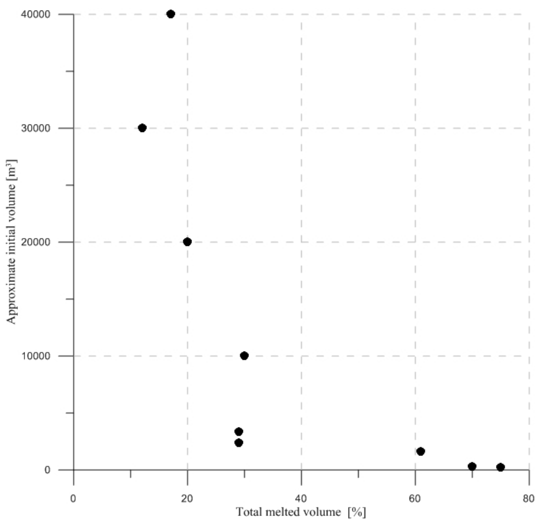

Figure 4; Approximate initial volume versus the melted volume as a percentage for the piles in Table 1 and Table 3.

A practical experiment using saw dust and bark as insulating material
In order to compare the efficiency of wood chips and bark as thermal insulation on snow, an experiment was designed where the melt rate of piles with approximately equal volume were studied.

- Pile 1 was covered with bark (Figure 5).
- Pile 2 was covered with sawdust (Figure 6).
- Pile 3 was left uncovered (Figure 7).

The experiment was carried out in Arjeplog, Sweden, during the summer 2013. Each pile was shaped as a chopped cone with approximate dimensions; base diameter, 12 m, top diameter 6 m and height, 3 m. Thus, the approximate volume of each pile was initially 200 m^3. The piles were made of natural snow. The thickness of the insulating layer of sawdust varied in the range of 30-40 cm and the thickness of the insulating layer of bark was approximately 40 cm. The period of storage was between the 15^{th} of April and the 8^{th} of October, 2013.

Figure 5 Pile 1: Snow covered with bark, Arjeplog, Sweden, 2013.

Figure 6 Pile 2: Snow covered with sawdust, Arjeplog, Sweden, 2013.

Figure 7 Pile 3: Uncovered pile in Arjeplog, Sweden, 2013.

3.1 Observation of melt rate

Surface melt is according to Skogsberg (2005) the major factor influencing the total melt rate. Two piles of snow with different geometry and surface area were observed with respect to the melt rate. The volumes of the piles were different, but the same insulation was used. One pile, called pile 4, see Figure 8, consisted of natural snow collected in the area close to the place of storage. This pile was stored in Arjeplog, Sweden during the summer 2013.

Pile 5, consisted of snow collected from a downhill ski slope and was a mixture of natural snow and machine-made snow. Pile 5 was stored in Piteå, Sweden, during the same period of time as the pile in Arjeplog. The surface of both piles were covered with geotextile and an approximately 50-60 cm thick layer of bark.

Figure 8 Pile of natural snow covered with geotextile and a 50-60 cm thick layer of bark. Arjeplog, Sweden, April, 2013.

The volume of each pile was measured using a position instrument, Topcon GR-S1, a handheld computer with built in receiver and a PG-A1 antenna, a so called network RTK equipment, i.e. a differential GPS. The instrument is used for relative measurements, which means that it will get both positions directly from a satellite and corrections from a base station located at a known position. The base stations belong to the land surveying "Lantmäteriet". The volumes of the piles were measured in the beginning of the storage period, i.e. on the 15th of April, after about six weeks of storage and in the end of the storage period, on the 8th of October. The volume of the piles was measured twice during the period of storage; on the 15th of April and on the 8th of October, at which time also the ground surface area of the piles were measured. The relation between the ground surface area and the total volume was calculated. This gives an indication of the surface area, which was difficult to estimate due to the irregular shape of the piles.
Climate data were collected every fourth hour using weather stations placed close to the piles. The monthly average temperature in Arjeplog and Piteå during the study period is shown in Table 2 and the locations are shown in Figure 9.

Table 2 Monthly average temperature in Arjeplog and Piteå during the study period.

Month	Average temperature [°C] Arjeplog	Average temperature [°C] Piteå
May	8.9	9.0
June	14.0	15.7
July	14.8	15.0
August	14.6	14.4
September	9.7	8.8
October	1.9	2.0

Figure 9 Location of Arjeplog and Piteå, Sweden.

4.Theoretical calculations of melting rate

Theoretical calculations of the snow melt were performed in order to compare calculated results to the practical experiment, piles 1-3. The most physically correct approach to calculate the snow melt is through energy budget and to determine all parameters and processes associated with heat sources from groundwater, rain, sun, sky and radiation (Skogsberg and Nordell, 2001). This is complicated and simplified models can therefore be used. The total melted volume, V_{TOT}, has been calculated as the sum of the contributions from ground melt, V_{ground}, surface melt, $V_{surface}$ and rain melt, V_{rain}, i.e.

$$V_{TOT} = V_{ground} + V_{surface} + V_{rain}. \quad (1)$$

The general heat equation without heat due to phase change can be written as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{c}{\lambda}\frac{\partial T}{\partial t}, \quad (2)$$

where, T is the temperature (°C), λ is the coefficient of thermal conductivity (W m^{-1} °C^{-1}), c is the heat capacity (J kg^{-1} °C^{-1}) and t is the time (h).
This equation constitutes the basis when calculating the loss by leakage to the ground.

Ground melt

The thermal flow from the ground, Q_{ground} (W), can be calculated as

$$Q_{ground} = \lambda_{ground} A_{ground} \frac{\Delta T_g}{l}, \quad (3)$$

where λ_{ground} is the coefficient of thermal conductivity for the ground (W m^{-1} °C^{-1}), A_{ground} the area of the pile towards the ground (m^2), ΔT_g the temperature difference (°C) between the ground surface and a distance, l (m), down in the ground (Johansson and Bäckström, 2009).
The rate of melted snow from ground melt, v_{ground} (m^3 s^{-1}), can thus be calculated as

$$v_{ground} = \frac{Q_{ground}}{L_{snow}\rho_{snow}}, \quad (4)$$

where L_{snow} (J kg^{-1})is the latent heat of fusion for the snow and ρ_{snow} is the density of the snow (kg m^{-3}) (Näslund, 2010).
The total volume of melted snow due to ground melt, V_{ground} (m^3) is then

$$V_{ground} = v_{ground} * t, \quad (5)$$

where t is the time (h) for the period of storage.

Surface melt

The melting rate with respect to the surroundings can be regarded as a stationary problem, with respect to the variations in air temperature (Näslund, 2010). The time derivative and the thermal storage capacity of the insulating material drops out and the heat transport from the surroundings, $Q_{surface}$ (W) is thus reduced to

$$Q_{surface} = A_{surface} * \frac{\lambda_i}{d} (\Delta T_s), \quad (6)$$

where $A_{surface}$ is the surface area (m^2) of the pile of snow, λ_i is the coefficient of thermal conductivity for the insulating material (W m^{-1} °C^{-1}), *d* is the thickness of the insulating material (m) and ΔT_s is the temperature difference (°C) between the air and the snow. Skogsberg (2001) estimated the coefficient of thermal conductivity for the insulating material to be the average value of the thermal conductivity for water and for the thermal conductivity of dry solid material, as the insulating material was assumed to be wet. The same estimation has been made in these calculations. The melt rate with respect to the surroundings, $v_{surface}$ (m^3 s^{-1}), can thus be calculated as

$$v_{surface} = \frac{Q_{surface}}{L_{snow}\rho_{snow}}. \quad (7)$$

The total melted volume due to surface melt, $V_{surface}$ (m^3), is

$$V_{surface} = v_{surface} * t. \quad (8)$$

Rain melt

The volume of snow which melts through rain, V_{rain}, can be calculated as

$$V_{rain} = \frac{PA\rho_{water}c_{water}T_{surroundings}}{L_{snow}\rho_{snow}}, \quad (9)$$

where *P* is the amount of precipitation (m), *A* is the total area of the pile (m^2), ρ_{water} is the density of water (kg m^{-3}), c_{water} is the heat capacity of the water (J kg^{-1} °C^{-1}) and $T_{surroundings}$ is the air temperature (°C) (Näslund, 2010).

5. Results

5.1 Sawdust and bark as insulating material

The volumes of the piles of snow stored in Arjeplog, including the approximately 70 m^3 of bark and 60 m^3 of sawdust are shown in Table 3 and illustrated in Figure 10. Due to technical problems with the instrument during the time for the second measurement, no data was achieved for the pile covered with sawdust.

Table 3 Snow storage experiment in Arjeplog, Sweden, in 2013 using sawdust and bark as insulating materials. The presented volumes include insulating material.

Date	Pile 1: covered with bark		Pile 2: covered with sawdust		Pile 3: Uncovered pile	
	Total volume [m^3]	Total snow melt [%]	Total volume [m^3]	Total snow melt [%]	Total volume [m^3]	Total snow melt [%]
April 15	290 m^3		234 m^3		190 m^3	
May 27	278 m^3	2	-		0	100
October 8	136 m^3	70	104 m^3	75	0	

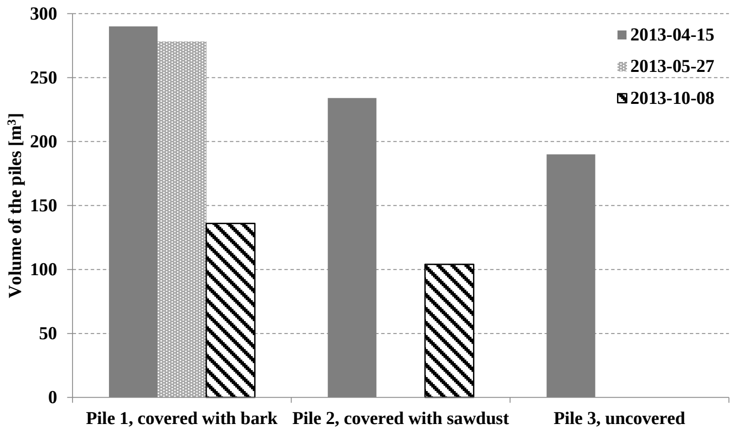

Figure 10 Volume of piles 1-3, covered with bark, sawdust and uncovered respectively.

Pile 1 did not significantly change in volume between the first measurement in mid-April and the second measurement in the end of May, as shown in Figure 9. At the time for the last measurement, 8th of October, 154 m^3 of snow had melted in pile 1, which corresponds to 70%. In pile 2 the melted volume was 130 m^3, corresponding to 75%. The pile of snow without insulation melted away during the first month of storage.

5.2 Melt rate of snow piles of different surface area

The volumes of the piles with different surface area are shown in Table 4. The ground surface area in the end of the storage period, the relation between the ground surface area and the total volume and the total snow melt in percent are also given.

Table 4 Snow storage in Arjeplog and Piteå in 2013. Volume of the piles and relation between the ground surface area and the total volume.

	Volume, April, 15 [m^3]	Volume, October 8, [m^3]	Ground surface area, October 8, [m^2]	Ground surface area / Total volume	Total snow melt [%]
Pile 4	1590	614	803	1.3	61
Pile 5	3409	2406	1284	0.5	29

The relation between the ground surface area and the total volume was much larger for pile 1 than for pile 2, as shown in Table 4. As can be noticed in Figure 5, pile 4 was very widespread with a low height and correspondingly a large ground surface area and a large upper surface area. About 1000 m^3 of snow melted in both piles which correspond to a snow melt of 61% for pile 4 and 29% for pile 5.

5.3 Theoretical calculations of melting rate

The different parts of the total melt rate were calculated according to the Equations (5), (8) and (9), using the values given in Table 5. The air temperature, i.e. the temperature of the surroundings was calculated as the average temperature during the period of snow storage. The temperature difference, ΔT_g, between the ground surface and a distance of 2 m into the ground was estimated to +2°C. Tabulated values of thermal conductivity for the ground, λ_{ground}, are between 0.15–2 $Wm^{-1}K^{-1}$ (Sundberg, 1988). In these calculations the value was estimated to 1 $Wm^{-1}K^{-1}$. Depending on the degree of compaction, the thermal conductivity for sawdust, $\lambda_{sawdust}$, is between 0.08–0.14 $Wm^{-1}K^{-1}$ (Mörstedt and Hellsten, 1999). The value used in the calculations was 0.1 $Wm^{-1}K^{-1}$. The value of the thermal conductivity for bark varies in different literature. The value used for the calculations was 0.074 $Wm^{-1}K^{-1}$ (Bridgwater, 2008). The temperature of the snow was assumed to be 0°C. The precipitation during the period of storage was calculated based on data from SMHI (Swedish Meteorological and Hydrological Institute).

The area of the piles were calculated according to the approximate dimensions of the piles, i.e. base diameter 12 m, top diameter 6 m and height 3 m. The density of the snow was estimated to 650 kg m^{-3} (Viklander, 1994).

Table 5 Values of properties used to calculate the snow melt for test piles stored in Arjeplog during the summer in 2013.

Quantity	Value
T_{snow}	0°C
$T_{surroundings}$	11.9°C
ρ_{snow}	650 kg m^{-3}
ρ_{water}	1000 kg m^{-3}
L_{snow}	92.8 J kg^{-1} K^{-1}
c_{water}	1.16 J kg^{-1} K^{-1}
$\lambda_{sawdust}$	0.1 W m^{-1} K^{-1}
λ_{bark}	0.074 W m^{-1} K^{-1}
λ_{water}	0.58 W m^{-1} K^{-1}
λ_{ground}	1 W m^{-1} K^{-1}
ΔT_g	2°C
ΔT_s	11.9°C
l	2 m
P	316 mm

The results from the calculations of snow melt from the ground, rain and surface are given in Table 6. The calculated total melted volume for pile 1 was 127 m^3 and the total melted volume for the pile 2 was 146 m^3. The reduction of the areas of the piles with time has not been taken into account in the calculations, which should lead to overestimated calculated values.

Table 6 Results from theoretical calculations and measured values of melt rate for pile 1 and pile 2.

	Pile 1: covered with bark		Pile 2: covered with sawdust	
Ground melt, v_{ground}	8 m^3	6% of V_{TOT}	8 m^3	5% of V_{TOT}
Surface melt, $v_{surface}$	100 m^3	79% of V_{TOT}	119 m^3	82% of V_{TOT}
Rain melt, v_{rain}	19 m^3	15% of V_{TOT}	19 m^3	13% of V_{TOT}
Total calculated snow melt, V_{TOT}	127 m^3		146 m^3	
Total snow melt in percent based on calculated values:		64%		73%
Measured volume of melted snow, $V_{measured}$	154 m^3		130 m^3	
Total snow melt in percent based on measured values:		70%		75%

As seen in Table 6, the surface melt was 79% and 82% for pile 1 and 2, respectively. Corresponding values due to ground melt was 6% and 5% for pile 1 and 2. The calculated amount that melted due to rain was 15% for pile 1 and 13% for pile 2. Rain and ground melt was found to contribute to less than 20% of the total natural melt when a 30 000 m^3 pile of snow in Sundsvall, Sweden was covered with a 0.2 m thick layer of wood chips (Skogsberg and Nordell, 2001). The size and of the piles in this study were substantially smaller though and the geometry different than for the pile in Sundsvall, but there is still a good agreement between the results.

6. Discussion

The results showed that the total measured snow melt in percent was slightly larger, 75%, for pile 2 covered with sawdust, compared to 70% for pile 1 covered with bark as shown in Table 6. The initial volumes of snow in Pile 1 and Pile 2 were approximately 220m^3 and 174m^3 respectively.

The calculated values of the snow melt for the pile 1 and pile 2, correspond well to the actual measured melted volumes of snow melt, although the area reduction was not taken into consideration in the calculations. The results indicate that the melt rate can be estimated with theoretical calculations, if the geometry of the pile is known and relevant data for climate and material properties are used. By calculating the snow melt, it is possible to estimate the efficiency of different insulating materials and also the thickness required to sufficiently insulate the snow from melting. This gives an opportunity to make economic optimizations based on the amount of snow that melts and additional costs for insulation and placement.
As observed during the study of melt rate for pile 4 and pile 5, a bigger ratio between ground surface area and total volume results in a larger melt rate. It has been observed for instance in Östersund, that piles of snow with a larger volume loose in percentage less snow than piles with a smaller volume. The same trend was observed in Figure 4, where the initial volumes versus snow melt in percent for the piles in this study are shown. The reason for this can be related to the surface melt rate. We assume that the heat and mass transfer through the surface is proportional to the surface area. For simplicity this fact is illustrated by modeling a pile of snow as a half sphere with radius *r*, the volume, V_r, of the pile will be

$$V_r = \frac{2\pi r^3}{3}, \tag{10}$$

and the surface area, S_r

$$S_r = 2\pi r^2. \tag{11}$$

If also a half sphere with radius, r/2 is modeled, the volume of this pile will be

$$V_{\frac{r}{2}} = \frac{2\pi r^3}{3*8} = \frac{V_r}{8}, \tag{12}$$

and the surface area

$$S_{\frac{r}{2}} = \frac{2\pi r^2}{4} = \frac{S_r}{4}. \tag{13}$$

According to Equation 12, eight half spheres of radius *r/2* is required in order to get the same volume as one half sphere with radius *r*. The total surface area of eight half spheres of radius *r/2* is according to Equation 13 twice as large as the surface area of a half sphere with radius *r*. This means that it is advantageous to store snow in one large pile rather than in several smaller piles. Of course, any other modeling of the pile (e.g. chopped cones etc.) could have been used as well, with a similar clear theoretical explanation of this fact. A minimized surface area implies steeper sides of a cone which should be kept in mind when designing the snow storage. The insulating material may fall off if it is placed on a pile with too steep sides.

Yet another reason for the greater percentage of snow melt for pile 4 might be that this pile consisted of natural snow, which is known to be less weather resistant than machine made snow (ICEHOTEL, 2011). This fact is however not investigated. Storing natural snow is recommended for future studies, as well as the difference in quality of stored natural snow compared to stored machine-made snow after the period of storage.

Hedlund (2016) and others have reported a considerable reduction of the volume of the piles occurring in the summer when the relative humidity increases to above 70-80%. The volume reduction between the first and the second measurement of pile 1 was negligible, as seen in Table 3, which also proves that the melt rate increases during the latter part of the summer. An increase in air humidity impairs the evaporation in the insulating layer. Skogsberg and Lundberg (2005) found that the evaporative cooling effect had a significant influence on the melt rate which is supported in this study. A porous material in humid air with constant relative humidity and constant temperature will eventually reach its hygroscopic equilibrium moisture content (Skogsberg, 2005). Increasing hygroscopic moisture content is called absorption, whereas decreasing is called desorption. Sorption isotherms for cutter shavings with a dry density of 90 kg m^{-3} based on spruce with a dry density of 430 kg m^{-3} are shown in Figure 11. The moisture content, *w*, is shown as a function of relative air humidity, *RH*. The moisture content during absorption is denoted w_{abs} (kg m^{-3}) and the moisture content during desorption is denoted w_{des} (kg m^{-3}). The moisture content increases rapidly as the relative humidity exceed approximately 85-90%. An increase in relative humidity is hence a reason to increased melt rate.

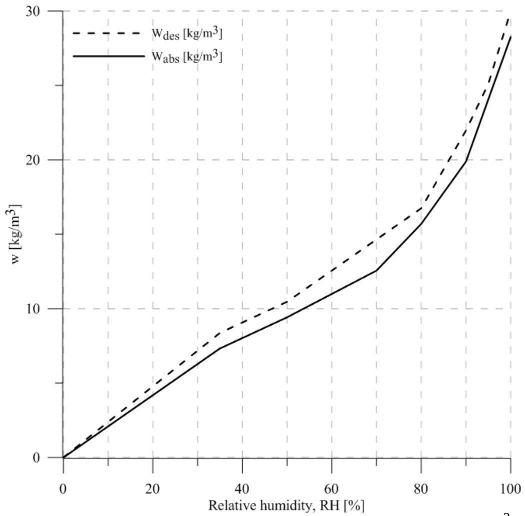

Figure 11 Sorption isotherms for cutter shavings with dry density 90 kg m^{-3} based on Swedish spruce with dry density 430 kg m^{-3} (after Hedenblad, 1993 and Skogsberg, 2005).

An insulating layer without or with poor evaporation will thus lead to a substantially increased melt rate. It is thus advantageous to choose a thermal insulating material with good evaporation properties.

The decay rate of insulating materials is mentioned in previous sections and explains why the material is replaced after a certain time. The exact decay rate of different commonly used insulating materials has not been studied but is suggested to be investigated in future studies. The moisture in porous materials is transferred as vapor and as water. In an insulated snow depot most of the melt water is transported downwards through the snow, but some of it is transported upwards through the insulating layer due to capillary forces and evaporation. The rate at which moisture is transferred in the insulating layer is denoted, $\dot{m}$, and can be calculated using Fick's law and is in one dimension written as the product of a transfer coefficient and a potential gradient (∇v, ∇w, ∇p, ∇T) (Hedenblad, 1996, Skogsberg, 2005). The moisture transfer due to evaporation in the insulating layer can thus be written as:

$$\dot{m}_{diff} = -\delta_{vap}\nabla v = -\frac{D}{\mu_{por}}\frac{dv}{dx}, \qquad (14)$$

where , $\dot{m}_{diff}$ is the diffusive vapor flow rate (kg m^{-2} s^{-1}), δ_{vap} is the vapor permeability coefficient (m^2 s^{-1}), ∇v is the vapor content gradient (g m^{-3} m^{-1}), D is the vapor diffusivity in air (m^2 s^{-1}), μ_{por} is the resistance coefficient, dv the vapor content difference (g m^{-3}) and dx the distance over which the vapor content difference occurs (m). The rate at which moisture is transferred in the insulating layer will decrease with time and with capillary height, resulting in an increased melt rate of the snow. A wet porous material being drained will attain a new moisture gradient through the material, called the passive capillary moisture content, where both total moisture content and capillary height are greater than before soaking (Nevander and Elmarsson, 1994). The capillary moisture transfer rate, $\dot{m}_{cap}$
(kg m^{-2}) can according to Skogsberg (2005) be written as:

$$\dot{m}_{cap} = \frac{A}{2\sqrt{t}}, \qquad (15)$$

where A is the water sorption coefficient (kg m^{-2} s$^{-1/2}$) and t is the time the material has been in contact with water. The coefficient A decreases towards zero with time. The decay rate with time with respect to the capillary moisture transfer is shown in Figure 12, showing that the capillary moisture flow has been reduced to about half the initial value after approximately two years.

The factors influencing the decay rate of the insulating material should be taken into account in order to insulate the snow sufficiently. Adding some new material or increasing the layer thickness might be alternatives to replacing all the insulating material.

Calculations of heat capacity for different insulating materials, λ_{ins}, were done according to a method described in Andersland and Ladanyi (2004). The thermal resistance, R (m^2 K W^{-1}) was then calculated as the the ratio between the thickness of the insulating layer, d (m), and the thermal conductivity, λ_{ins} (W m^{-1}K^{-1}), i.e.

$$R = \frac{d}{\lambda_{ins}}. \qquad (16)$$

The thermal conductivity is not very sensitive to the porosity if the degree of water saturation is high. However, the thickness of the insulating layer is of high importance for the melt rate. The mouldering of bark results in a decreased porosity and hence a reduced thickness of the insulating layer. Moreover, a reduced porosity impair the evaporation which in turn will lead to poorer cooling of the pile.

Assuming a unit volume of insulating material, V consisting of the sum of volume of solid particles, V_s and the volume of the pores, V_p, then the relation between the total volume and the porosity, n, is:

$$V = V_s + V_P = V_s\left(\frac{1}{1-n}\right). \qquad (17)$$

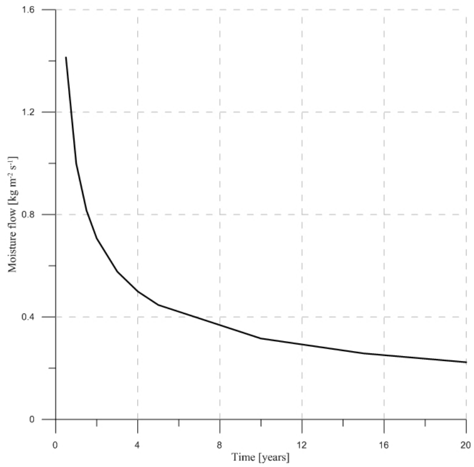

Figure 12 Moisture flow into a porous material in contact with water.

The volume of the insulating layer decreases linearly with decreasing void ratio. The porosity for saw dust and bark has not been investigated, but low mouldered peat has a porosity between 0.91-0.96, intermediate peat has a porosity in the range 0.89-0.94 and high mouldered peat has values in the range 0.88-0.93, according to Vesterberg et al. (2016). A similar trend is expected for bark and sawdust.
The thermal resistance as a function of porosity, *n*, is shown in Figure 13. The thermal resistance decreases with decreasing porosity. The porosity decreases as a consequence of aging and mouldering which thus lead to deteriorating insulating properties.

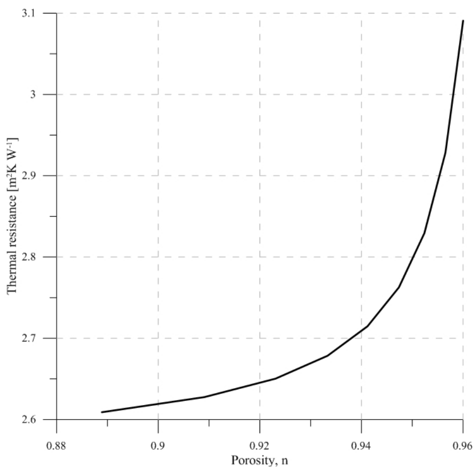

Figure 13 Thermal insulance as a function of porosity for an insulating layer.

To create an optimal snow depot, the most important is to minimize the surface melt rate, since this constitutes the largest part of the total melt rate. The geometry should be designed to minimize the surface area. Cost and properties of different insulating material should be taken into consideration. Depending on the local conditions different alternatives may be preferred. Skogsberg and Lundberg (2005) conclude that enough thermal insulation only is a matter of layer thickness. Thus, an insulating layer with poor porosity can be compensated by increasing the thickness instead. The snow storage should be placed at a location which is protected from wind and solar radiation, with good drainage. It has been observed that snow in large snow depots has turned into ice near the ground surface (Hedlund, 2016). This might be a result of poor drainage but also because of too large compressive stress due to the total load, which causes the bondings between snow grains to collapse and the density to increase. Therefore, there might be an upper limit for the recommended height of a pile, which should be further investigated in future studies.

The efficiency of different thermal insulating materials need to be further investigated, both when it comes to natural materials and fabricated materials. Fabricated materials can be new types of textiles, which both serve as insulation on the snow but also enable evaporation to minimize the snow melt. Moreover, the long-term profitability should be taken into account. Materials with a decay rate needs to be replaced after some years whereas others have a longer life time. In addition, some materials are more environmentally harmful than others. The decay rate of different insulating materials is further a field of research for future investigations.

7. Conclusions

The research findings reported in this paper are that:

- Natural materials such as bark and different types of cutter shavings are efficient thermal insulating materials on snow depots, if the layer thickness is large enough.
- The surface melt constitute the most significant part, around 80%, of the total snow melt in an insulated snow depot. Thus, the surface area should be minimized.
- The modeling and theoretical calculations presented in this paper give a good basis for estimating the melt rate and meted volume of stored snow.
- Higher relative humidity and higher moisture content in the insulating layer will increase the melt rate of stored snow.
- The thermal resistance will decrease with time when sawdust and bark are used as insulating materials. This is due to due to aging and mouldering, which imply a decreased porosity.
- Decreased evaporation implies increased melt rate.
- Theoretical calculations with chopped cones showed that approximately 80% of the total melted volume was due to surface melt, 15% was due to rain melt and 5% was due to ground melt.

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