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Characterisation of liquid water content and snow density in a cross-country race ski track

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Abstract

Various snow parameters have been registered during measurement campaigns in cross-country race ski tracks in Norway (1995–98), Hakuba/Japan (1996–98) and Sundance/USA (1999). Specific attention has been paid to snow hardness, LWC (liquid water content), snow density, snow grain structure and electrolytic conductivity. The present paper focuses on LWC, snow density and to some extent snow grain structure.

The mean density of the upper 5 cm in ski tracks (0.50 g cm^{-3}) is considerably higher than typical densities of seasonal snow covers (0.26–0.38 g cm^{-3}) and higher for transformed snow types (0.51–0.59 g cm^{-3}) than new snow types (0.39–0.43 g cm^{-3}). The LWC of the upper 5 cm in a ski track typically ranges between 0 and 12.5% per volume. It is typically less than 2% for snow temperatures (2 cm depth) below −2℃ and less than 1% for snow temperatures below −7℃. LWC exceeding 4% have only been registered at air temperatures above +1℃. The typical grain size of the snow surface in a ski track ranges from 0.26 to 1.89 mm for transformed snow types and from 0.08 to 0.38 mm for new snow types. *In-situ* microscope imaging of ski tracks is very difficult for new snow types with snow surface grains below 0.2 mm.

1. Introduction

Characterisation of the sliding surface, *i.e.* the snow surface of the cross-country ski track, is necessary in order to understand ski base sliding friction and results from ski base sliding friction tests. It is therefore important to register essential snow parameters when performing accurate ski base sliding friction tests *in-situ*. In our research we have registered and characterised the following snow parameters:

- Snow temperature at depths −5, −2 and 0 cm relative to the snow surface
- Snow hardness of the snow surface
- LWC (liquid water content) and snow density of the upper 5 cm of the ski track.
- Snow type and snow grain structure of the snow surface
- Electrolytic conductivity and water chemistry of melted snow samples from the upper 5 cm of the ski track.

In addition the following weather parameters have been registered:

- Air temperature (0.5 m above the snow surface)
- Relative air humidity (0.5 m)
- Net radiation (0.5 m)

The present paper, which focuses on measurements of LWC, snow density and to some extent snow grain structure, is extracted from the dr. thesis of Moldestad (1999).

Several measurement methods can be used for determining the LWC in a snowpack:

- Melting (hot) calorimetry, see *e.g.* Yosida (1940; 1960), and Hansen and Jellenik (1957).
- Freezing (cold) calorimetry, see *e.g.* Jones *et al.* (1983).
- Alcohol calorimetry, see *e.g.* Fisk (1986).
- Dilution measurements, see *e.g.* Davis *et al.* (1985).
- Centrifugal measurements, see *e.g.* Kuroda and Hurukawa (1954), and Kuroiwa (1954).
- Dielectric measurements, see *e.g.* Ambach and Denoth (1975), Aebischer and Mätzler (1983), Denoth *et al.* (1984), Sihvola and Tiuri (1986), Bergman (1986; 1987), Kendra *et al.* (1994), Denoth (1997) and Stein *et al.* (1997).

Calorimetry, dilution and centrifugal measurements are destructive methods. Freezing calorimetry is accepted as a standard field measurement method and is used to calibrate non-destructive methods

(Stein *et al.*, 1997). Dielectric measurements are faster to perform than the other measurement methods (Boyne and Fisk, 1987) and suitable for *in-situ* non-destructive measurements. The *Snow Fork* instrument (Sihvola and Tiuri, 1986) has been used for measuring LWC and density in this work.

Measurements of the LWC have not been made systematically to a great extent in *in-situ* ski studies. Spring (1988) presented kinetic friction coefficients for skis gliding with speeds up to 10 ms^{-1} on old grainy snow with 0 and 20% per volume LWC. Slotfeldt-Ellingsen and Torgersen (1983) published laboratory friction tests on crushed ice with various LWC, but these tests were performed with too low slider speed (0.3 ms^{-1}) to be of great relevance for typical ski base sliding friction situations. Non-destructive *in-situ* measurements of LWC in snow have been presented by *e.g.* Sihvola and Tiuri (1986), Toikka (1992), Kendra *et al.* (1994), Denoth (1997) and Stein *et al.* (1997).

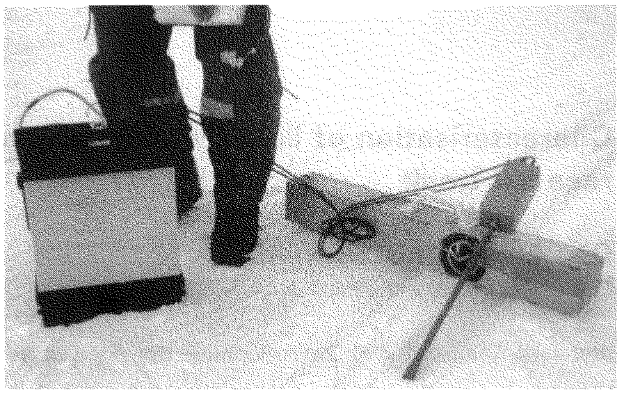

Fig. 1. Setup for snow surface measurements with the *Snow Fork*.

2. Measurement methods and procedures

2.1. *Snow temperature*

Snow temperature has been measured using a STAR HD 8901 Hygrometer-Thermometer with a snow probe with a small temperature sensor in the tip. The instrument has an accuracy of ±0.1% of registered value ±0.2℃ (STAR, 1995). Snow temperature measurements have been taken at three different levels in the race ski track: 5 cm below the surface of the track, 2 cm below the surface of the track, and in the surface of the track.

It can be difficult to perform qualitatively good measurements of snow surface temperature due to potential influence from air temperature, precipitation and solar radiation on the snow temperature sensor. Direct sunlight on the sensor has been avoided by using the body of the person that holds the probe, to shade for the sun when necessary.

Different measurement levels have been chosen in order to get consistent snow temperature measurements and obtain information about the temperature gradient in the snow. Throughout this paper the snow temperature 2 cm below the surface of the track is referred to as the snow temperature T_s.

2.2. *LWC (liquid water content) and snow density*

LWC (liquid water content) and snow density have been measured with the *Snow Fork* instrument (Sihvola and Tiuri, 1986). The *Snow Fork* is a steel fork used as microwave resonator which operates in the frequency range 500 to 1000 MHz and measures the resonance frequency, attenuation and 3-dB bandwidth of a snow volume. From these electrical parameters the complex dielectric permittivity of the snow can be calculated as well as the density and LWC of the snow (Toikka, 1998). The *Snow Fork* is designed for measuring LWC between 0 and 10% with an accuracy of ± 0.3% (Toikka, 1996). The measurement of snow density has an accuracy of $\pm 0.005\,g\,cm^{-3}$. The *Snow Fork* is primarily designed for measuring snow density below $0.6\,g\,cm^{-3}$, but is also possible to use for measuring higher snow densities.

Normally when measuring the LWC and snow density, the *Snow Fork* is pushed horizontally into the snow pack. In order to measure the LWC and snow density as close as possible to the snow surface, the *Snow Fork* has been put into the snow surface with an angle of approximately 30° relative to the snow surface. This corresponds to measuring the LWC and snow density of the upper 5 cm of the ski track. Figure 1 shows the measurement setup. When the *Snow Fork* measurements are performed at an angle of 30° to the snow surface, a small part of the measurement volume will contain air instead of snow. It is important to adjust the LWC and density results accordingly. This can be performed quite simply by using the fact that the spikes of the *Snow Fork* are 75 mm long, and the width is 20 mm. Assuming that the *Snow Fork* measurement volume consists of a 75 mm long cylinder with 10 mm radius, it can be found that 6% of the measurement volume is air when the *Snow Fork* is put into the snow at a 30° angle relative to the snow surface. The calculated density and snow humidity must therefore be multiplied by the factor:

$$\frac{75}{\left(75-\frac{\sqrt{300}}{4}\right)}=1.0612726 \approx 1.06.$$

If a 45° angle to the snow surface is used in the measurements instead of a 30° angle, the multiplication factor will be approximately 1.034. Half-space measurements (Sihvola and Tiuri, 1986) where the *Snow Fork* lies at the snow surface have also been tested in my research. This setup has not given reliable results, probably due to measurement noise from the air above the snow surface, solar radiation and precipitation.

Table 1. Classification of LWC of snow according to Colbeck *et al.* (1990).

Term	$W_{vol.\%}$ (%)
Dry	0
Moist	<3
Wet	3-8
Very wet	8-15
Slush	>15

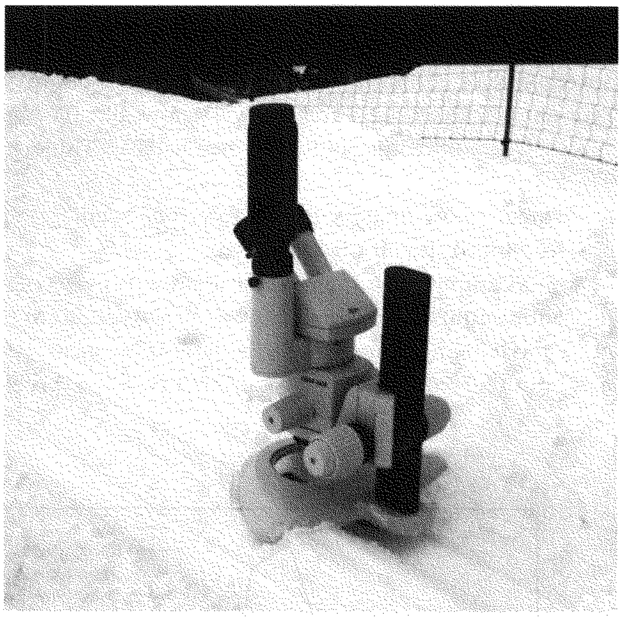

Fig. 2. Snow microscopy setup without camera connected to the phototube. The camera is used to take the setup picture.

Classification of LWC of snow according to Colbeck *et al.* (1990) is shown in Table 1. Snow with LWC less than 0.5% per volume has been approximated as dry in our measurements.

2.3. *Snow type and snow grain structure*

To avoid damage of the original structure of the snow surface in the track, we chose to use a measurement procedure that did not involve movement of snow from the track. A LEICA MS5 stereomicroscope (max. 40×magnification) was used to observe the snow surface directly *in-situ* in the track. Microscope images of the snow surface were captured with a Nikkon F70D camera connected to the microscope through a phototube. Figure 2 shows the setup without camera connected to the phototube. At a later stage (indoor) the captured images were converted to digital form by a scanner, and analysed and characterised digitally using the general image processing program Adobe Photoshop 5.0 (Adobe, 1998).

The 2D snow grain surfaces in microscope images have been characterised using the following definitions:

Table 2. Classification of $\bar{d}$ according to the classification of grain size given in Colbeck *et al.* (1990).

Term	$\bar{d}$ (mm)
Very fine	<0.2
Fine	0.2-0.5
Medium	0.5-1.0
Coarse	1.0-2.0
Very coarse	2.0-5.0
Extreme	>5.0

Table 3. Classification of the grain shape of the snow according to Colbeck *et al.* (1990).

Basic classification	Graphic symbol
Precipitation particles	+
Decomposing and fragmented precipitation particles	/
Rounded grains (monocrystals)	●
Faceted crystals	□
Cup-shaped crystals and depth hoar	∧
Wet grains	○
Feathery crystals	∨
Ice masses	□
Surface deposits and crusts	∀

j - snow grain surface number in a microscope image of a snow surface

d_j - length of the largest 2D diagonal for snow grain surface number j in a microscope image of a snow surface, mm

n_g - number of snow grains with distinguishable boundaries in a microscope image of a snow surface

$\bar{d}$ - mean of d_j for the n_g snow grains with distinguishable boundaries in a microscope image of a snow surface, mm

δ_d - standard deviation of d_j for the n_g snow grains with distinguishable boundaries in a microscope image of a snow surface, mm

$\bar{d}$ has also been classified according to the classification of grain size given in Colbeck *et al.* (1990), see Table 2.

Further, the snow type in the track has roughly been classified according to the following snow type categories:

1. "Falling" new snow
2. New snow
3. Combination of new snow and transformed snow, mainly new snow
4. Combination of new snow and transformed snow, mainly transformed snow
5. Transformed snow
6. Artificial snow

The grain shape of the snow has furthermore been classified according to Colbeck *et al.* (1990), see Table 3.

2.4. *Air temperature*

Air temperature, T_a, has been measured by using an air probe on the STAR HD 8901 Hygrometer-Thermometer. The measurement of air temperature has the same precision as the snow temperature measurements (STAR, 1995). The measurements have been performed 0.5 m above the snow surface.

2.5. *Relative air humidity*

Relative air humidity has been registered 0.5 m above the snow surface with the same air probe as in the air temperature measurements. The measurement of relative air humidity has a precision of ±2% for relative air humidities between 5 and 90% and +4/−2.5% for relative air humidities between 90 and 98%. The relative air humidity, *Rh*, is defined as the ratio between the amount of vapour present in the air considered and the amount that air at the same temperature could contain if it was saturated. Air is defined as saturated when it in these determined conditions of temperature, air and pressure, has absorbed the greatest possible amount of vapour.

2.6. *Net radiation and cloudiness*

Net radiation, q_{net}, is the difference between incoming and outgoing radiation at the surface of the earth. Modelling of net short wave and long wave radiation has been performed by *e.g.* Male and Gray (1981), and Løset (1992).

Net radiation has been registered 0.5 m above the snow surface with the Anderaa Instruments net radiation sensor 2811 instrument. This sensor measures both sunlight and infrared radiation. The measurement range of the instrument is ±2000 W m^{-2}, and the accuracy ±1% of full scale.

Cloudiness, *C*, has roughly been characterised in octoparts ($0<C<8$). A complete cloud cover is expressed as $C=8$, while $C=0$ indicates a clear sky.

3. Results

This section presents major results from measurements of LWC and snow density of the upper 5 cm in 117 cross-country race ski tracks. The presented measurement results are based on measurement campaigns in Norway, 1995-98, Hakuba/Japan, 1996-98 and Sundance/USA, 1999.

The snow temperature in the campaigns has ranged from 0 to −22.1℃ (Granåsen, 26.01.1996), while the air temperature has ranged from +14.2 (Hakuba, 14.02.1996) to −14.6℃ (Granåsen, 26.01.1996). The relative humidity of air has varied from 18% in dry sunny Sundance (03.03.1999) to 100% during snow events in Trondheim (winter 1996). A maximum net radiation of 816 W m^{-2} has been registered in Hakuba at 36° N (27.01.1998).

Figure 3 shows histograms for snow density measurements of different snow types in cross-country race ski tracks, while Table 4 gives snow density statistics. The following definitions are used in Table 4:

$\bar{\rho}$ mean snow density for a snow type, g cm^{-3}
δ_ρ standard deviation of $\bar{\rho}$, g cm^{-3}
ρ_{max} maximum snow density for a snow type, g cm^{-3}
ρ_{min} minimum snow density for a snow type, g cm^{-3}
ρ_{50} median snow density for a snow type, g cm^{-3}
n_ρ number of density measurements for a given

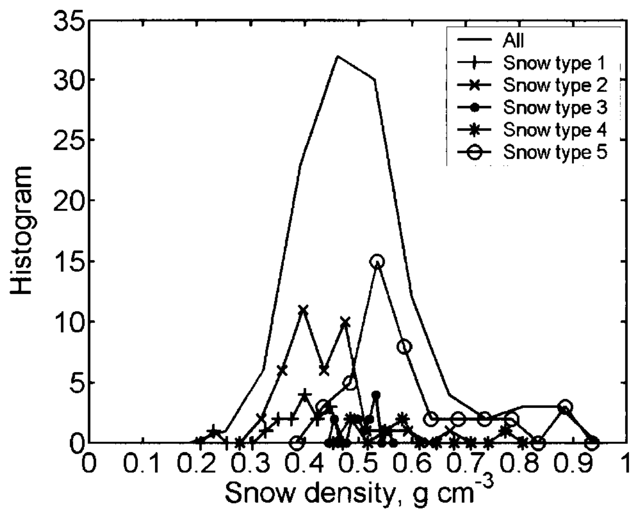

Fig. 3. Histograms for snow density measurements of different snow types in cross-country race ski tracks.

Table 4. Snow density statistics for different snow types in cross-country race ski tracks.

Snow type	$\bar{\rho}$ (g cm^{-3})	δ_ρ (g cm^{-3})	ρ_{max} (g cm^{-3})	ρ_{min} (g cm^{-3})	ρ_{50} (g cm^{-3})	n_ρ
All	0.50	0.13	0.92	0.22	0.49	117
1	0.39	0.06	0.46	0.22	0.39	15
2	0.43	0.08	0.69	0.30	0.43	39
3	0.51	0.03	0.56	0.45	0.52	14
4	0.57	0.12	0.79	0.47	0.56	6
5	0.59	0.12	0.92	0.41	0.56	43

snow type

The snow density values in the 117 measurements have ranged between 0.22 and 0.92 g cm^{-3}, *i.e.* up to the density of ice. The minimum density was registered for Snow type 1 in Granåsen, 27.03.1996. The highest measured density value was obtained for wet snow ($W_{vol,\%}=5.4\%$) in Sundance, 27.02.1999. The accuracy of this value can be questioned since the *Snow Fork*, although usable also for measuring higher snow densities, is primarily designed for measuring snow density below 0.6 g cm^{-3}. The highest measured snow density for new groomed snow types, 0.69 g cm^{-3}, was registered on a warm day ($T_a=+5.1$℃) in Lillehammer in April 1998. The lowest snow density value for transformed snow types, 0.41 g cm^{-3}, was obtained in Granåsen 24.02.1997, immediately after the 10 km classic race for men in the Nordic World Ski Championships' 97.

It can be seen from both Table 4 and the histograms in Figure 3 that the mean snow density is higher for transformed snow types than new snow types. While Snow types 1 and 2 have mean snow densities of 0.39 and 0.43 g cm^{-3} respectively, the mean snow densities of Snow types 3, 4 and 5 are 0.51, 0.57 and 0.59 g cm^{-3}.

Figure 4 shows snow density plotted as a function of LWC for different snow types in 116 ski tracks. We can see that the snow density increases with increased LWC, at least for LWC up to 6% per volume.

The LWC has ranged from 0 to 12.5% in the 117 measurements in ski tracks. No LWC ($W_{vol,\%}=0.0\%$) has been found at snow temperatures below approximately −6℃. The highest value was measured on 21 April 1998 at Lillehammer on a warm, sunny day with high net radiation. At this day the LWC increased from 0.6% at 9: 40 ($T_a=+3.1$℃ and $q_{net}=431$ W m^{-2}) to 12.5% at 11: 59 ($T_a=+5.8$℃ and $q_{net}=753$ W m^{-2}). Large variations in LWC have also been measured during ski competitions in winter. During the Nordic Combined competition in the Nordic World Ski Championships'97 in Granåsen (23.02.1997), the LWC changed from 2.4% at 11: 40 ($T_a=+2.6$℃ and $q_{net}=131$ W m^{-2}) to 6.8% at 14: 17 ($T_a=+6.7$℃ and $q_{net}=103$ W m^{-2}) due to rapid increase in air temperature.

Figure 5 shows LWC plotted as a function of snow temperature for different snow types in ski tracks. In the present experiments it is found that the LWC is less than 2% for snow temperatures below −2℃ and less than 1% for snow temperatures below −7℃. Furthermore, the LWC is found to be less than 2% for new snow types and below zero snow temperatures. LWC-values above 0.5% at below zero snow temperatures can be explained by:

・Solar radiation *i.e.* $q_{net}>50$ W m^{-2} and $T_a<0$℃ (22 measurements), *e.g.* in Hakuba 31.01.97 at 13: 20: $W_{vol,\%}=1.1\%$, Snow type 2, $T_s=-4.9$℃, $T_a=-1.2$℃, $Rh=57\%$, $C=3$ and $q_{net}=114$ W m^{-2}.

・Air temperatures above the melting point of ice *i.e.* $T_a>0$℃ (15 measurements), *e.g.* in Granåsen 20.02.97 at 10: 41: $W_{vol,\%}=1.5\%$, Snow type 4, $T_s=-2.4$℃, $T_a=+2.2$℃, $Rh=67\%$, $C=8$ and $q_{net}=0$ W m^{-2}.

・"Falling" new snow or recently fallen new snow and relative air humidity above 75%, *i.e.* Snow type 1–2 and $Rh>75\%$ (9 measurements), *e.g.* in Hakuba 29.01.97 at 15: 41: $W_{vol,\%}=1.4\%$, Snow type 1, $T_s=-1.7$℃, $T_a=-2.4$℃, $Rh=88\%$, $C=8$ and $q_{net}=0$ W m^{-2}.

・Air temperatures below but close to the melting point of ice and relative air humidity above 70%, *i.e.* $T_a=-1.5$ –0℃ and $Rh>70\%$ (4 measurements), *e.g.* in Granåsen 19.02.97 at 10: 33: $W_{vol,\%}=1.3\%$, Snow type 3, $T_s=-4.4$℃, $T_a=-0.7$℃, $Rh=83\%$, $C=8$ and $q_{net}=37$ W m^{-2}.

Figure 6 depicts LWC versus air temperature for various snow types in ski tracks. It can be seen from

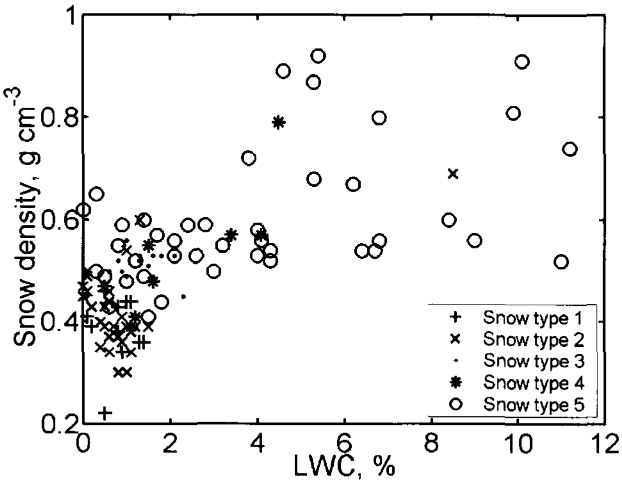

Fig. 4. Snow density plotted as a function of LWC for different snow types in ski tracks.

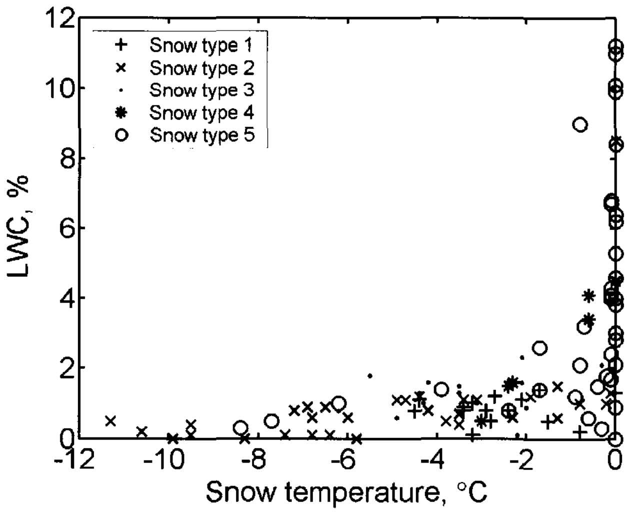

Fig. 5. LWC versus snow temperature (2 cm depth) for different snow types in ski tracks. LWC values lower than 0.5% are regarded as dry in these measurements.

the figure that the LWC is less than 1% for air temperatures below −4℃ and less than 2% for air temperatures below −2℃. LWC exceeding 4% have only been registered at air temperatures above +1℃.

Figure 7 shows a contour plot of the measured LWC in ski tracks as a function of relative air humidity and air temperature. A C/E line (Condensation/Evaporation line) based on Petterssen (1956) has been added to the plot. This line indicates the limiting value of relative air humidity. If the relative air humidity in the air above the snow is higher than that indicated by the line, water vapour condenses on the snow, otherwise it evaporates. It can be seen from the figure that the highest LWC are registered on clear, warm days with relative humidities between 40 and 60% and air temperatures above +5℃. The LWC is relatively lower at relative humidities between 60 and 80%, probably due to less efficient solar radiation compared to lower relative humidities. At relative humidities above 80% the LWC shows an increasing tendency again when condensation processes start to be efficient. For relative humidities exceeding 65%, the LWC is highest to the right of the C/E line, *i.e.* when condensation on the snow dominates over evaporation from the snow.

Figures 8-11 depict LWC of snow surfaces. Examples of very wet, wet, moist and dry snow surfaces are presented in Figures 8, 9, 10 and 11, respectively. Figures 12 and 13 show examples of snow surfaces of Snow type 5 with high and low densities.

The mean snow grain diameter and the standard deviation of snow grain diameters were calculated for 34 snow surface microscope images of ski tracks in Moldestad (1999) and Løset and Moldestad (2000). It was shown that the typical grain size in ski tracks ranged from 0.26 to 1.89 mm for transformed snow types, *i.e.* Snow types 4 and 5, and from 0.08 to 0.38 mm for new snow types, *i.e.* snow types 2 and 3. The *in-situ* measurement procedure has proved to be very efficient for ski tracks with snow surface grains larger than approximately 0.1–0.2 mm. For smaller snow surface grains it has been difficult to capture microscope images with sufficient quality. The mean snow grain diameter, $\bar{d}$, and the standard deviation of grain diameters, δ_d, for the snow surface microscope images of ski tracks in Figures 8–13 are presented in Table 5 together with information of time, location, snow type, grain shape, snow humidity $W_{vol.,\%}$, snow density ρ, snow hardness H and snow temperature T_s. Table 6 presents data on air temperature T_a, relative humidity Rh, cloudiness C and net radiation q_{net} at the time of snow microscope image registration.

4. Discussion

The snow density has ranged between 0.22 and 0.92 g cm^{-3} (*i.e.* density of ice) in our measurements. It was commented in the results section that the accuracy of the highest value can be questioned since the measurement equipment, although usable also for measuring higher snow densities, is primarily designed for measuring snow density below 0.6 g cm^{-3}. In spite of this it can not be excluded that "snow" density in the proximity of the density of ice (0.92 g cm^{-3}) might occur in groomed compressed wet ski trails that have gone through several melt-freeze cycles and are approaching ice. Yosida (1963) showed that a snow pillar with initial density of 0.35 g cm^{-3} could be deformed with a compression machine until the density of ice was reached. This typically occurred when the snow pillar was compressed to approximately one-hundredth of its initial height. Sommerfeld and LaChapelle (1970) referred a typical density range of 0.80 to 0.83 g cm^{-3} for "firnification" induced

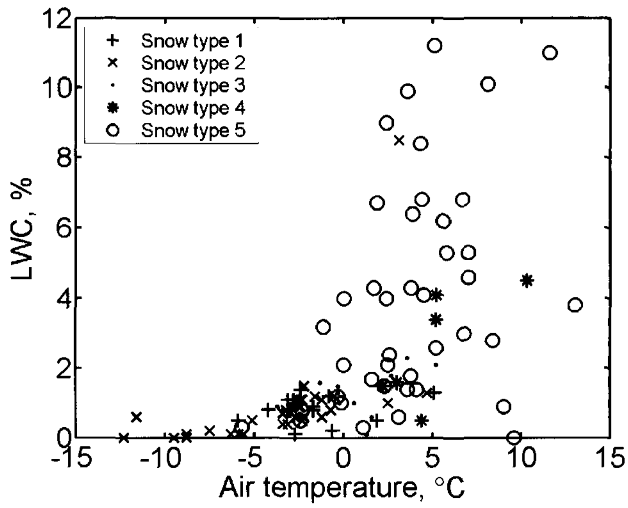

Fig. 6. LWC plotted as a function of air temperature for different snow types in ski tracks.

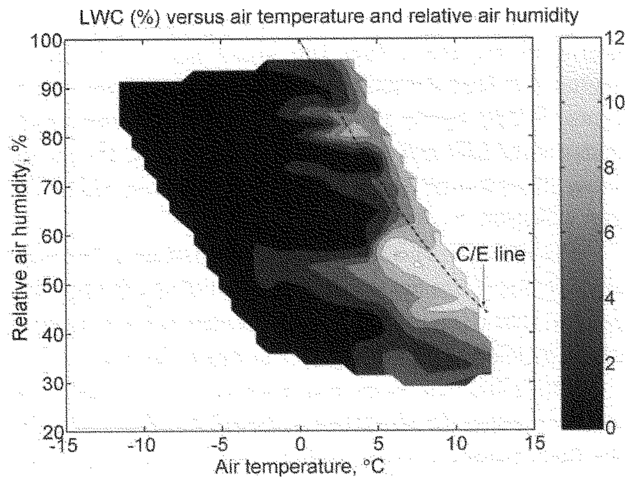

Fig. 7. Contour plot of the measured LWC in ski tracks as a function of relative air humidity and air temperature. A C/E line indicates the border line between condensation and evaporation on the assumption of 0℃ snow surface temperature (Petterssen, 1956).

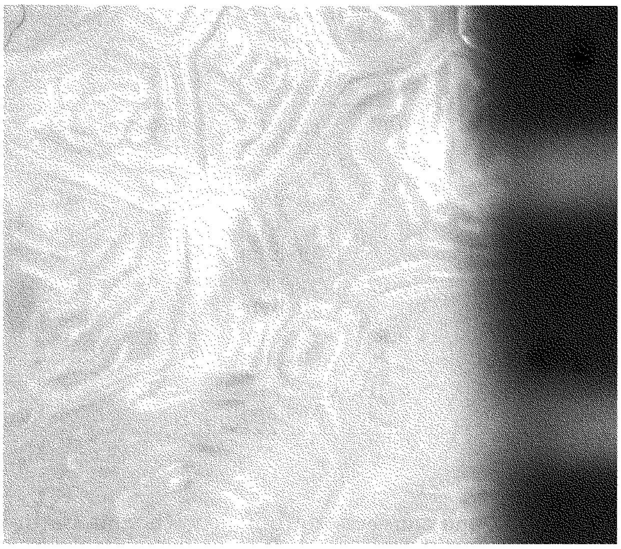

Fig. 8. Example of a very wet snow surface ($W_{vol.\%}$= 12.5%, $\bar{d}$=0.86 mm and δ_d=0.29 mm). The distance between the tick marks of the ruler to the right in the image is 1 mm.

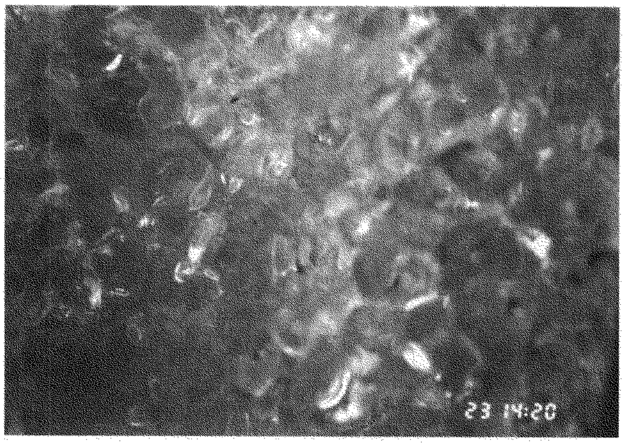

Fig. 9. Example of a wet snow surface ($W_{vol.\%}$=6.8%, $\bar{d}$ =0.72 mm and δ_d=0.2 mm).

Fig. 10. Example of a moist snow surface ($W_{vol.\%}$= 2.4%, $\bar{d}$=0.84 mm and δ_d=0.29 mm).

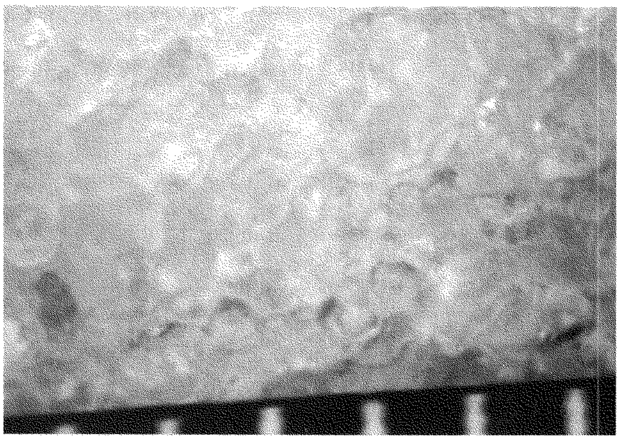

Fig. 11. Example of a dry snow surface ($W_{vol.\%}$=0%, $\bar{d}$ =1.11 mm and δ_d=0.54 mm). The distance between the tick marks of the ruler in the lower part of the image is 1 mm.

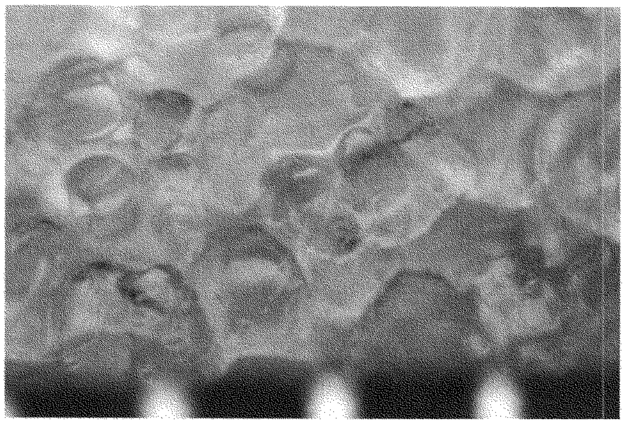

Fig. 12. Example of a snow surface with high density (ρ=0.89 g cm^{-3}, $\bar{d}$=0.95 mm and δ_d=0.34 mm). The distance between the tick marks of the ruler in the lower part of the image is 1 mm.

Fig. 13. Example of a snow surface with low density (ρ=0.41 g cm^{-3}, $\bar{d}$=1.38 mm and δ_d=0.44 mm). The distance between the tick marks of the ruler to the right in the image is 1 mm.

Table 5. Table of snow measurements for the snow surface microscope images in Figures 8-13.

Fig.	Date (Time)	Location	Snow type	Grain shape	$\bar{d}\pm\delta d$ (mm)	$W_{vol,\%}$ (%)	ρ (g cm^{-3})	H (Pa)	T_s (℃)
8	21.04.98 (11: 59)	Lillehammer	5	○	0.86±0.29 Medium	12.5 Very wet	0.61	1.1 ± 10^4 Medium	0.0
9	23.02.97 (14: 17)	Granåsen	5	○	0.72±0.20 Medium	6.8 Wet	0.8	2.6 ± 10^4 Medium	−0.1
10	23.02.97 (11: 40)	Granåsen	5	○	0.84±0.29 Medium	2.4 Moist	0.59	4.1 ± 10^4 Medium	−0.1
11	03.03.99 (10: 55)	Sundance	5	○	1.11±0.54 Coarse	0 Dry	0.62	3.6 ± 10^4 Medium	0.0
12	02.03.99 (13: 43)	Sundance	5	○	0.95±0.34 Medium	4.6 Wet	0.89	2.2 ± 10^4 Medium	0.0
13	24.02.97 (11: 45)	Granåsen	5	○	1.38±0.44 Coarse	1.5 Moist	0.41	2.2 ± 10^4 Medium	−0.4

Table 6. Table of weather measurements for the snow surface microscope images in Figures 8-13.

Fig.	T_a (℃)	Rh (%)	C (octoparts)	q_{net} (W m^{-2})
8	5.8	53	0	753
9	6.7	64	8	103
10	2.6	87	8	131
11	9.6	23	8	94
12	7.0	29	1	440
13	2.3	61	8	0

by advanced pressure metamorphism in their classification of snow by metamorphic state. Anyhow, the mean density of snow in the upper 5 cm of ski tracks (0.50 g cm^{-3}) is considerably higher than typical densities of seasonal snow covers. Sturm *et al.* (1995) referred bulk densities of 0.38 g cm^{-3} for tundra, 0.26 g cm^{-3} for taiga and 0.35 g cm^{-3} for maritime snow covers in their seasonal snow cover classification system. Yosida (1971) concluded that the ideal snow density for slalom and giant slalom races should not be much less than 0.5 g cm^{-3}. This corresponds to the mean snow density in our measurements in the upper 5 cm of ski tracks.

The snow density is important for the permeability of the snow and the potential drainage of frictional water film down in the snow during skiing. The results section showed that the mean snow densities were higher for transformed snow types than new snow types. Although fine-grained compact snow can have lower permeability than coarse-grained snow in spite of lower density (Shimizu, 1970), this might indicate higher frictional water film thickness in average during skiing on transformed snow. Higher frictional water film thickness means that coarser ski base structures have to be used in order to attain optimum sliding properties. See Moldestad (1999) or Moldestad and Løset (2000) for more details.

LWC-values above 0.5% per volume at below zero snow temperatures (2 cm depth) can be explained by penetration of solar radiation into the snow, and heat conduction and convection from air with temperature above the melting point of ice, that cause melting at the snow surface and local melting in the snow pack. Humid precipitation and air introduce airborne liquid/moisture on the snow surface, which further can be transferred into the snow pack. Furthermore, recent AFM (Atomic Force Microscope) studies by *e.g.* Döppenschmidt *et al.* (1998) and Bluhm and Salmeron (1999) have shown that liquid can exist below the melting point of ice. Döppenschmidt *et al.* (1998) found the thickness of the liquidlike layer on the surface of ice to vary between about 12×10^{-9} m at −24℃ and 70×10^{-9} m at −0.7℃. The relative air humidity determined with an electronic thermo-hygrometer was 80%. Bluhm and Salmeron (1999), using AFM and SPFM, found a layer thickness of $5\pm0.5\times10^{-9}$ m between −20 and −10℃ and at a relative humidity of ~83% for thin layers of ice on mica. Ion growth experiments on ion-free substrates showed the existence of a liquid water layer at temperatures down to −40℃. Dash (2002) stated that the transformation of a crystalline solid into a liquid begins at lower temperatures than the melting point of the bulk. It starts at the edges of crystal planes, progresses across the surface, evolves into the successive melting of atomic layers, and ends in bulk coexistence. The memory of the process remains within a few molecular distances at the crystal-melt interface. Premelting occur at interfaces with solid substrates, *i.e.* interfacial melting, and at grain boundaries of polycrystalline materials, *i.e.* grain boundary melting. This implies that premelting at the snow surface and in the snow pack also is an explanation for LWC-values above 0% at below zero snow temperatures.

The LWC of the upper part of the ski track can be viewed as an indicator of the initial water film thickness in the ski track and the frictional water film thickness that is possible to attain during skiing. This makes it a very important parameter for optimum choices of ski base structure, glide wax/powder and kick wax in a ski competition. Shimbo (1961) has also pointed out the importance of LWC on snow friction.

Table 7. Typical relations between optimum structure roughness, LWC and snow type in sliding tests of cross-country skis in cross-country race ski tracks (from Moldestad, 1999).

Optimum structure roughness $\bar{R}_{a,yws}$ ($\times 10^{-6}$ m)	LWC $W_{vol,\%}$ (%)	Snow type
$\leq$5-6	$\leq$0.6	2
$\approx$5-6	$\leq$1.3	2
$\approx$9	$\approx$0.3-4	4 and 5
$\approx$13	>4	2 and 5

The typical distribution of LWC with relative air humidity and air temperature was shown for the measurements in Figure 7. This figure indicates under which weather conditions the LWC (and thereby the initial water film thickness) is significant and needs to be measured. For instance it is sufficient to perform LWC measurements at air temperatures above -3℃ when the relative air humidity is 40%, while it has to be considered for temperatures down to -10℃ when the relative air humidity is 80%. Typical relations between optimum ski base structure roughness, $\bar{R}_{a,yws}$, LWC and snow type in sliding tests of cross-country skis in cross-country race ski tracks from Moldestad (1999) are summarised in Table 7.

Throughout this paper a simple classification system for snow types on snow surfaces has been applied. This system has been used quite extensively in practice by ski technicians due to its ease to use when no measurement equipment is accessible. It is for instance easy to interpret Snow type 5 in this system as snow where klister wax ought to be applied as kick wax, and Snow type 2 as snow where hard wax should be applied. The grain shape and grain size classification system presented by Colbeck *et al.* (1990) should be used in addition when a microscope or hand lens is accessible for inspection of the snow surface.

The typical grain size of snow surfaces in cross-country race ski tracks has ranged from 0.08 to 1.89 mm. This corresponds well with Schemenauer *et al.* (1981) who have stated that individual snow crystals observed at the surface of the earth range in maximum dimension from approximately 0.05 mm to 5 mm. Wiesmann *et al.* (1998) found that grain sizes in snow covers ranged from less than 0.1 mm to 3 mm. In our few analysed microscope images of new snow types in ski tracks grain sizes have ranged from 0.08 to 0.38 mm. Smaller grain sizes would probably also have been obtained if we had been able to register more snow microscope images of new snow types. *In-situ* microscope imaging of ski tracks is very difficult for new snow types with snow surface grains below 0.2 mm.

More microscope images of ski tracks need to be registered in order to find typical distributions of grain sizes for different snow types. The sizes of the snow surface grains are essential for the contact configuration between the ski base structure and the snow surface, and the design of optimum ski base structures for different snow conditions.

5. Conclusions

During measurement campaigns in ski tracks in Norway (1995-98), Hakuba/Japan (1996-98) and Sundance/USA (1999), the following parameters have been registered: air temperature, relative air humidity, net radiation, snow temperature, snow hardness, LWC (liquid water content), snow density, snow type, snow grain structure, electrolytic conductivity and ionic content of melted snow samples. Specific attention has been paid to LWC and snow density and to some extent snow grain structure in this paper.

The measurements of snow density in the upper 5 cm of ski tracks have shown that:

- The snow density typically ranges between 0.2 and 0.9 g cm^{-3}.
- The mean density of snow in ski tracks (0.50 g cm^{-3}) is considerably higher than typical densities of seasonal snow covers (0.26-0.38 g cm^{-3}).
- The mean snow densities are higher for transformed snow types (0.51-0.59 g cm^{-3}) than new snow types (0.39-0.43 g cm^{-3}).

The measurements of LWC in the upper 5 cm of ski tracks have resulted in the following findings:

- The LWC typically ranges between 0 and 12.5% per volume. It has been measured an increase in the LWC from 0.6% to 12.5% during two hours on a warm, sunny day in April at Lillehammer ($T_a = +5.8$℃ and $q_{net} = 753$ W m^{-2}). The LWC of the upper part of the ski track can be viewed as an indicator of the initial water film thickness in the ski track and the frictional water film thickness that is possible to attain during skiing. It is thus a very important parameter for optimum choices of ski base structure, glide wax/powder and kick wax in a ski competition.
- The LWC is typically less than 2% for snow temperatures (2 cm depth) below -2℃ and less than 1% for snow temperatures below -7℃.
- LWC exceeding 4% have only been registered at air temperatures above $+1$℃.
- The highest LWC has been registered on clear, warm days with relative humidities between 40 and 60%, and an air temperature above $+5$℃. Due to condensation processes being more efficient, the LWC has shown an increasing tendency at relative humidities above 80% and air temperatures between $+1$ and $+6$℃ compared to relative humidities between 60 and 80%.

The mean snow grain diameter and the standard deviation of snow grain diameters were calculated and shown for 34 snow surface microscope images of ski tracks in Moldestad (1999) and Løset and

Moldestad (2000). The typical grain size ranged from 0.26 to 1.89 mm for transformed snow types and from 0.08 to 0.38 mm for new snow types. *In-situ* microscope imaging of ski tracks is very difficult for new snow types with snow surface grains below 0.2 mm.

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