TP 14686E

Study of Warm, Pre-Wetted Sanding Method at Airports in Norway

Prepared for
Transportation Development Centre
of
Transport Canada

by

Norwegian University of Science and Technology
and
National Research Council Canada

March 2007

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Study of Warm, Pre-Wetted Sanding Method at Airports in Norway

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March 2007

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Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 14686E	2. Project No. 5459	3. Recipient's Catalogue No.
4. Title and Subtitle Study of Warm, Pre-Wetted Sanding Method at Airports in Norway		5. Publication Date March 2007
		6. Performing Organization Document No.
7. Author(s) Alex Klein-Paste and Nirmal K. Sinha		8. Transport Canada File No. 2450-BP-01
9. Performing Organization Name and Address Norwegian University of Science and Technology Høyskoleringen 7a 7491 Trondheim, Norway Institute for Aerospace Research National Research Council Canada M-13, 1200 Montreal Road Ottawa, Ontario, Canada K1A 0R6		10. PWGSC File No. MTB-3-00899
		11. PWGSC or Transport Canada Contract No. T8200-033517/001/MTB
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final
		14. Project Officer A. Boccanfuso

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by Avinor (Oslo Airport), Norway

16. Abstract

This report describes the study of a new sanding method that has been adopted at different Norwegian airports. The new method is based on wetting the sand with hot water before applying it onto the runway surface. It results in a sanding pattern where the particles are bonded to the surface, creating a sandpaper-like appearance.

The aim of the study is to improve general knowledge about this warm, pre-wetted sanding method for airside and road applications. A diversity of aspects are addressed, such as its performance in practice, how and why it works, optimization, possible negative effects, and limitations. Data was collected during a six-week field study at three different airports and during a testing workshop for warm, pre-wetted sand spreaders.

17. Key Words Warm pre-wetted sanding, freeze bonded sanding, sand application, foreign object damage, friction measurements, correlation, surface conditions reporting system, SNOWTAM	18. Distribution Statement Limited number of print copies available from the Transportation Development Centre. Also available online at www.tc.gc.ca/tdc/menu.htm

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages xvii, 53, app.	23. Price Shipping/ Handling

CDT/TDC 79-005
Rev. 96

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 14686E	2. N° de l'étude 5459	3. N° de catalogue du destinataire
4. Titre et sous-titre Study of Warm, Pre-Wetted Sanding Method at Airports in Norway		5. Date de la publication Mars 2007 6. N° de document de l'organisme exécutant
7. Auteur(s) Alex Klein-Paste et Nirmal K. Sinha		8. N° de dossier - Transports Canada 2450-BP-01
9. Nom et adresse de l'organisme exécutant Norwegian University of Science and Technology Høyskoleringen 7a 7491 Trondheim, Norway Institut de recherche aérospatiale Conseil national de recherches Canada M-13, 1200 chemin de Montréal Ottawa (Ontario) Canada K1A 0R6		10. N° de dossier - TPSGC MTB-3-00899 11. N° de contrat - TPSGC ou Transports Canada T8200-033517/001/MTB
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet A. Boccanfuso
15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.) Coparrainé par Avinor (aéroport d'Oslo), Norvège		

16. Résumé

Ce rapport porte sur une nouvelle méthode de sablage des pistes utilisée à différents aéroports de Norvège, qui consiste à arroser le sable d'eau chaude avant de l'épandre. L'eau, en gelant, fait adhérer le sable à la surface, donnant à celle-ci l'apparence d'un papier abrasif.

Le but de l'étude est d'enrichir les connaissances générales sur les applications aéroportuaires et routières de cette technique d'épandage de sable arrosé d'eau chaude. Une foule d'aspects sont abordés, comme l'efficacité de la méthode dans la pratique, comment et pourquoi elle fonctionne, son optimisation, ses effets néfastes possibles et ses limites. Des données ont été recueillies au cours d'une étude sur le terrain d'une durée de six semaines, menée à trois aéroports, et pendant un atelier d'essai sur les épandeurs de sable arrosé d'eau chaude.

17. Mots clés Épandage de sable arrosé d'eau chaude, sable lié par le gel, épandage de sable, dommage par corps étranger, mesure du frottement, corrélation, système de compte rendu de l'état de la surface des pistes, SNOWTAM	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires imprimés. Disponible également en ligne à www.tc.gc.ca/cdt/menu.htm			
19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xvii, 53, ann.	23. Prix Port et manutention

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Knut Kristoffersen, Kirkenes Airport Høybuktmoen, and Ole Martinus Rambech, Svalbard Airport Longyearbyen, for the hospitality at these airports and their full support during the study. The authors also thank Capt. Odd Helge Wang for his arrangements and active cooperation at Bardufoss Air Force Base.

Special thanks go to all runway maintenance personnel working at Kirkenes Airport, Svalbard Airport, and Bardufoss Air Force Base. Their willingness to share observations, experiences, ideas, and opinions was a vital contribution to the study. Special thanks also goes to test pilot LT. Hæfta, and winter maintenance officer Knut Ivar Morstøl for their assistance during the aircraft braking experiments.

Øystein Hagen, Oslo Airport OSL, Torgeir Vaa, Sintef, and Erik Eriksen, Svalbard Airport Longyearbyen, are acknowledged for answering the many questions regarding the warm, pre-wetted sanding method.

The authors are indebted to Armann Norheim, Oslo Airport OSL, Angelo Boccanfuso, Transportation Development Centre of Transport Canada, and Øystein Larsen, Norwegian Public Road Administration, for all the financial and practical arrangements that made this study possible.

EXECUTIVE SUMMARY

A new sanding method has recently been adopted at several Norwegian airports. The method forms an additional tool for winter maintenance (snow and ice control) of compacted snow and ice contaminated runways, taxiways, and aprons. It is based on wetting the sand with hot water before it is applied onto the surface. The added water freezes and binds the sand to the surface. The spreading pattern differs from loose sand applications: the pre-wetted sand deposits in lumps of particles and water, rather than in individual particles.

As the method becomes more regularly used, information is needed regarding the method itself: how and why it works, its performance in practice, optimization, possible negative effects, and limitations. A field study was conducted in the winter of 2005-2006 to find answers to these questions.

The data collected during the field study included experiences from runway maintenance personnel, observations from an application on compacted snow, practical experiences regarding Foreign Object Damage (FOD), and an aircraft braking test on smooth ice treaded with the new method, in comparison with traditional loose sanding. The study also included a case study, where comments were investigated from pilots who indicated that the runway surface was slipperier than reported in the SNOWTAM reports.

The study was primarily intended to provide information to airport operators and public road administrations who use, or are considering using this sanding method. The scope of the case study is wider and considers the issue of correlation between friction measurement devices and aircraft performance. The use of friction measurement devices as part of the runway surface conditions reporting system is discussed.

Conclusions

The warm, pre-wetted sanding method performs well at airports that operate under prolonged winter conditions. Maintenance personnel that have used the method for at least two winter seasons expressed a very positive general attitude toward the method. The main benefits are: (1) the durability of the result, (2) the larger increase in friction level after a sanding operation, and (3) reduction of sand that is blown to the sides of the runway by the engine thrust of operating aircraft.

The latter benefit shows that the method not only improves the surface conditions in terms of friction level, but also in terms of robustness against air traffic. The robustness of a surface is an important operational quality factor.

There are, however, some concerns regarding the new sanding method, especially with respect to the use of friction measurement devices to describe and report the runway surface conditions. Twelve pilot comments were received at two airports during one winter season, expressing that the runway was slipperier than reported. These comments were investigated as nine independent cases.

In all cases, the measured friction coefficients were high, describing the surface conditions as “medium to good” or “good”. The difference in response between friction measurement and aircraft on the runway surface appears to be the primary cause of the discrepancy between reported and experienced braking action. In 66 percent of the cases, there were clear indications (reduction or loss of directional control at low speeds) that the friction measurement gave a too optimistic picture of the actual situation. In addition, there were clear indications (meteorological and visual) that that the surfaces were not as good as suggested by the friction numbers in 66 percent of the cases. These surface conditions involved either ice close to 0°C that was wetted by melt water or precipitation, or conditions where ice deposition from the atmosphere onto the pavement was likely to occur.

When all the available information sources were considered, and not just the friction measurements, it could have been derived that the surface conditions were worse than “medium to good” or “good” in 66 percent of the cases. Hence, in principle, sufficient information was available to expect slippery conditions in these cases. These information sources could be used to form a more complete picture of the whole situation at the airport, but they must be interpreted in a real-time manner. High friction numbers can easily inhibit such critical evaluation because they give the impression that the surface is good.

Practical experience points out that the pavement surfaces have to be properly cleaned before application in order to reduce the risk of foreign object damage (FOD). When the warm, pre-wetted sand is applied on thick, weakly bonded snow surfaces, there is a chance that the lumps will break loose in one piece. Such pieces are large enough to be a FOD threat. In addition, it has to be considered that the freeze bonded sand loosens over time, because the ice that binds the sand to the surface sublimates. Excessive amounts of loose sand on the surface also form a FOD threat. Specifically, during prolonged stable weather conditions, the surface may need to be swept in order to reduce the amount of loose sand.

Observations during aircraft braking tests on iced surfaces that were treated with warm, pre-wetted sand in comparison with traditional loose sand showed that the whole interaction between tire, sand, and contaminated pavement changes with the addition of the water. It changes the way in which friction is provided to the aircraft. On the warm, pre-wetted sand, the interaction comprises both loose and fixed sand interaction, rather than only loose sand interaction. Part of the sand remains bonded during the interaction and acts in a similar way as road asperities. These fixed sand particles provide friction by increasing adhesional resistance, rubber hysteresis, and possibly tire wear. But there are also particles that break loose during the interaction. These loose particles provide friction by ploughing into the ice surface. Here, the friction mechanism is primarily ice deformation, rather than rubber deformation (hysteresis and rubber wear).

Recommendations

It is recommended that the risk of FOD be given attention in the education of runway maintenance personnel who use the warm, pre-wetted sanding method.

For research on, and development of, winter maintenance practices (e.g., equipment, procedures, guidelines) it is recommended that the robustness of the surface conditions be considered as a quality factor, in addition to the widely used measured friction coefficient. In practice, surfaces are exposed to different processes that deteriorate the surface conditions. Different surface conditions with initially similar friction levels can have different levels of robustness. Hence they lose their ability to provide friction in different magnitudes and in different time scales. A surface is only of operational value when it holds its properties over a certain period of time.

For the exploration of an alternative approach to the current surface conditions reporting system, it is recommended that criteria be systematically defined to identify situations where slippery conditions can be expected. These situations should be based on maintenance experiences and combined with meteorological and tribological knowledge of and insights into the mechanical behaviour of snow and ice.

It is also recommended that a study be conducted on the ways in which runway maintenance personnel could track the dew point of the air just above the pavement, in relation to the actual pavement surface temperature. This information makes the identification of ice deposition conditions possible. Such a study should address the accuracy that can be achieved with modern measuring techniques under the restricted possibilities for measurements in movement areas.

SOMMAIRE

Une nouvelle méthode de sablage des pistes est utilisée depuis un certain temps à plusieurs aéroports de Norvège. Cette méthode constitue un outil supplémentaire pour l’entretien hivernal (le déneigement et le déglaçage) des pistes, voies de circulation et aires de trafic contaminées par de la neige compactée et de la glace. Elle consiste à arroser le sable d’eau chaude avant de l’épandre sur la surface. L’eau, en gelant, fait adhérer le sable à la surface. Le mode de répartition du sable diffère selon qu’il est mouillé ou sec : le sable mouillé se dépose en petites mottes de particules et d’eau, plutôt qu’en particules isolées.

Comme la méthode gagne en popularité, il convient de recueillir de l’information sur celle-ci : comment et pourquoi elle fonctionne, son efficacité dans la pratique, son optimisation, ses effets néfastes possibles et ses limites. Une étude sur le terrain a été menée au cours de l’hiver 2005-2006, pour tenter de répondre à ces questions.

Au cours de l’étude sur le terrain, diverses données ont été recueillies, notamment les témoignages des préposés à l’entretien des pistes, les observations résultant d’une application sur de la neige compactée, les expériences pratiques concernant les dommages par corps étranger (FOD) et les résultats d’essais de freinage d’un aéronef sur de la glace lisse traitée au moyen de la nouvelle méthode, comparativement à la méthode classique d’épandage de sable lâche. La recherche comportait aussi une étude de cas, soit une analyse des commentaires de pilotes qui avaient indiqué que la surface de la piste était plus glissante que ne le laissaient prévoir les avis SNOWTAM.

L’objet principal de cette étude était de fournir de l’information aux exploitants d’aérodrome et aux administrations routières qui utilisent ou envisagent d’utiliser cette méthode de sablage. Quant à l’étude de cas, sa portée est plus large; elle examine la question de la corrélation entre les dispositifs de mesure du frottement et la performance des aéronefs. Le rôle des dispositifs de mesure du frottement en tant que composante du système de compte rendu de l’état de la surface des pistes est aussi examiné.

Conclusions

La méthode d’épandage de sable arrosé d’eau chaude fonctionne bien aux aéroports où les conditions hivernales sont persistantes. Ainsi, les préposés à l’entretien qui ont utilisé la méthode pendant au moins deux hivers s’en sont dits généralement très satisfaits. Les principaux avantages de celle-ci sont : (1) la durabilité du traitement, (2) l’augmentation marquée du frottement après une opération de sablage, (3) la diminution de la quantité de sable soufflé sur les côtés de la piste par la poussée des réacteurs.

Le dernier avantage montre que la méthode améliore l’état de la surface de la piste non seulement sous l’angle de son coefficient d’adhérence mais aussi de sa robustesse, ou sa résistance au trafic aérien. Or, la robustesse d’une surface est un important facteur de qualité opérationnelle.

La nouvelle méthode de sablage suscite toutefois des inquiétudes, notamment en ce qui a trait à l'utilisation des dispositifs de mesure du frottement pour rendre compte de l'état de la surface des pistes. En effet, à douze occasions en un seul hiver, des pilotes ont déclaré que la piste était plus glissante que le compte rendu le laissait croire. Ces commentaires ont été étudiés comme neuf cas distincts.

Dans tous les cas, les coefficients de frottement mesurés étaient élevés, et l'état de la surface était décrit comme étant «moyen à bon» ou «bon». La différence entre la réaction du dispositif de mesure du frottement et celle de l'avion sur la piste semble être la cause principale de l'écart entre l'efficacité de freinage déclarée et réelle. Dans 66 p. 100 des cas, il existait des indications claires (réduction ou perte de la maîtrise en direction à faible vitesse) que la mesure du frottement était trop optimiste par rapport à la situation réelle. De plus, des indices clairs (météorologiques et visuels) donnaient à penser que les surfaces n'étaient pas aussi bonnes que le laissaient supposer les mesures du frottement, dans 66 p. 100 des cas. On notait soit la présence de glace à près de 0 °C, qui était mouillée par de l'eau fondue ou des précipitations, soit des conditions propices au givrage de la surface.

Si toutes les sources d'information disponibles avaient été prises en compte, et non uniquement les mesures du frottement, on aurait pu conclure que l'état des surfaces était pire que «moyen à bon» ou «bon», dans 66 p. 100 des cas. Ainsi, en principe, on disposait d'une information suffisante pour s'attendre à ce que les pistes soient glissantes. Les sources d'information complémentaires permettaient de brosser un tableau plus complet de l'ensemble de la situation, mais il fallait interpréter sur le champ l'information. Or, des coefficients de frottement élevés peuvent facilement inhiber une telle évaluation critique, parce qu'ils donnent l'impression que l'état de la surface est bon.

L'expérience pratique indique que les surfaces doivent être bien nettoyées avant l'épandage, afin de réduire le risque de dommage par corps étranger (FOD, *foreign object damage*). Lorsque le sable arrosé d'eau chaude est appliqué sur des surfaces de neige épaisse faiblement liées, il y a un risque que des morceaux se décollent. Ces morceaux sont assez gros pour causer des FOD. De plus, il ne faut pas oublier que le sable lié par le gel se délie avec le temps, à cause de la sublimation de la glace qui sert de liant. Des quantités excessives de sable lâche sur la surface représentent elles aussi une menace de FOD. Plus précisément, lorsque les conditions météorologiques demeurent stables longtemps, il peut s'avérer nécessaire de balayer la surface pour réduire la quantité de sable lâche.

Les observations faites pendant les essais de freinage sur des surfaces glacées traitées avec du sable arrosé d'eau chaude, plutôt qu'avec du sable lâche selon la méthode classique, ont révélé que l'ajout d'eau modifie l'interaction du pneu avec le sable et la chaussée contaminée. L'ajout d'eau modifie la façon dont se produit le frottement. Sur du sable arrosé d'eau chaude, l'interaction se fait avec du sable lâche et du sable lié, et non uniquement avec du sable lâche. Une partie du sable demeure liée au cours de l'interaction, et agit de la même manière que les aspérités de la route. Le frottement offert par les particules de sable fixes vient de l'augmentation de la résistance d'adhérence, de l'hystérésis du caoutchouc, et peut-être de l'usure des pneus. Mais il y a aussi des particules qui se détachent pendant l'interaction. Le frottement offert par ces particules vient du fait qu'elles creusent dans la surface de la glace. Ici, le mécanisme de frottement tient avant tout à la déformation de la glace, plutôt qu'à la déformation du caoutchouc (hystérésis et usure du caoutchouc).

Recommandations

Il est recommandé que le risque de FOD reçoive toute l'attention voulue dans la formation donnée aux préposés à l'entretien qui utilisent la méthode d'épandage de sable arrosé d'eau chaude.

Pour la recherche et le développement sur les pratiques d'entretien hivernal (p. ex., le matériel, les procédures, les lignes directrices), il est recommandé de considérer la robustesse de l'état de la surface comme un facteur de qualité, en plus du coefficient de frottement mesuré, qui est largement utilisé. Dans la pratique, les surfaces sont exposées à différents processus qui entraînent la détérioration de l'état des surfaces. Différents états de surface offrant au départ des coefficients d'adhérence équivalents peuvent avoir différents niveaux de robustesse. Ainsi, ils n'ont pas tous la même capacité d'offrir le même coefficient d'adhérence pendant une même durée. Or, une surface n'a de valeur opérationnelle que si elle conserve ses propriétés pendant une certaine période.

Pour optimiser l'efficacité de la méthode sur d'épaisses couches de neige compactée, il est recommandé de mener une étude sur la possibilité de limiter la pénétration de l'eau/du sable dans la neige, en réduisant la température de l'eau. Toutefois, cette recommandation vaut uniquement pour les applications routières, en raison du risque accru de décollement de morceaux.

Pour ce qui est des approches susceptibles de remplacer le système actuel de compte rendu de l'état de la surface des pistes, il est recommandé de définir systématiquement les critères permettant de conclure qu'une piste est glissante, d'après les données météorologiques et les observations visuelles concernant l'aéroport. Ces critères devraient être fondés sur l'expérience du personnel d'entretien, combinée à une connaissance du comportement mécanique de la neige et de la glace dans des conditions météorologiques et tribologiques données.

Il est également recommandé de mener une étude sur les façons dont le personnel d'entretien des pistes pourrait surveiller la température du point de rosée de l'air juste au-dessus de la surface de la piste, par rapport à la température réelle de la surface de la piste. Cette information permet de reconnaître les conditions propices au dépôt de glace (givrage). Une telle étude devrait porter sur le niveau de précision que permettent d'atteindre les techniques de mesure modernes, compte tenu des limites à la prise de mesures sur les aires de mouvement.

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GLOSSARY OF TERMS

T_s = Snow temperature
T_i = Ice temperature
T_a = Air temperature
ρ_s = Snow density
V = Wind speed
D = Wind direction
T_d = Dew point temperature
T_p = Pavement surface temperature
T_{ss} = Sub-surface temperature

FOD	Foreign Object Damage
NOTAM	Notice To Airmen
METAR	French acronym meaning “aviation routine weather report”
SNOWTAM	A special NOTAM with information concerning snow, slush, ice and standing water on aerodrome/heliport pavements.
Braking Action	The ability to use wheel braking for retardation. In practice, the term is used in a broader sense to indicate the quality of movement surface areas in their ability to provide both retardation and directional control.
BA	Braking Action. When reported in a two-digit number, the braking action equals the average friction coefficient × 100. When reported in a one-digit number, it represents a judgment of the conditions in terms of good, medium, poor.
Track back	A term used when an aircraft taxis on the runway in the opposite direction of the landing direction.

1 INTRODUCTION

Sand application is a common method to improve the friction on pavements covered with ice or compacted snow. In traditional sanding, dry, loose sand particles are spread on the pavement. Depending on the equipment, it can be applied at relatively high speeds (60-80 km/h) and large application width (about 5-15 m). A disadvantage of traditional sanding is that it can be displaced by wind or traffic (FAA, 1991; Comfort and Gong, 1999; Klein-Paste and Sinha, 2006). A longer lasting result can be obtained when sand is adhered to the pavement. This is typically performed by freeze bonding the sand; for example, by using warm sand or heating the iced pavement prior to the application of sand. Recently, a new method to freeze bond sand has been developed, based on pre-wetting the sand with hot water (Vaa and Dahl, 2002; Vaa, 2004). These developments improved the operability of freeze bonded sanding. The method has now come to an implementation stage in Norway. The first airports started to use the method in 2003. At the end of the 2005-2006 winter, 13 Norwegian airports were equipped with warm, pre-wetted sand spreaders.

As the method becomes more regularly used, more information is needed regarding the method itself: how and why it works, its performance in practice, optimization, possible negative effects and its limitations. The aim of this study was to gather information and improve general knowledge about the warm, pre-wetted sanding method by addressing these questions.

To maximize the data volume, a six-week field study was conducted in January and February 2006 to collect information at three airports: Kirkenes Airport, Svalbard Airport, and Bardufoss Air Force Base. In addition, data was gathered in January 2006 in Dombås, Norway, during the testing workshop for warm, pre-wetted sand spreaders, arranged by the Norwegian Public Road Administration.

The collected data includes experiences from runway maintenance personnel, observations from an application on compacted snow, experiences with respect to Foreign Object Damage (FOD), and comparative aircraft braking tests on smooth ice treated with both loose and warm, pre-wetted sand. Prior to the field study, Kirkenes Airport and Svalbard Airport had received comments from pilots who had experienced conditions that were worse than reported by friction measurements. These comments were investigated in a case study.

The report was written primarily for airport operators and public road administrations who use, or are considering using this sanding method. The scope of the case study was wider, since it mainly focused on the runway surface conditions reporting system. The diversity of the information made it logical to treat each topic in a separate section. Hence each topic has its own introduction, results, discussion and conclusion. A brief introduction to warm, pre-wetted sanding is given in Section 2. The study is summed up in a general discussion in Section 8, followed by general conclusions and recommendations in Sections 9 and 10.

2 WARM, PRE-WETTED SANDING

2.1 Background

It has been recognized for a long time that both effectiveness and durability of sanding operations can be improved by adhering the sand particles to the snow or ice contaminated pavement. Different adhering techniques have been tested and practised, such as using warm sand and heating the contaminated pavement prior to the application of sand. The latter method is still practiced at some Norwegian Airports, as illustrated in Figure 1. Heating the iced pavement partly melts the ice. When the thin water layer refreezes, the sand becomes bonded to the pavement. The method can give good results, but is very time consuming and not energy efficient. It can take several hours to treat a whole runway surface.

Figure 1. Traditional method of freeze bonding sand to pavement, practised at Norwegian airports. The iced pavement is heated by open flame burners prior to sanding.

In 1997, the Norwegian Public Road Administration started a project called vinterfriksjonsprosjektet (Winter Friction Project). This project focused on practical, technical, and economic problems arising in providing good friction on winter roads (Dahlen and Vaa, 2001). Within this project, two concepts of freeze bonding sand were evaluated. The first concept was based on heated sand, while the second concept used hot water to pre-wet the sand. The latter was found to have most potential and was developed further.

Different manufacturers were encouraged to further develop the technology of warm, pre-wetted sanding. Through the years 1999 to 2005 the technology evolved and the dominant design became a rotating disk spreader where the water and sand is mixed in the feeding tube of the disk spreader. Currently, different manufacturers offer sand spreaders with warm pre-wetting functionality.

2.2 Description of the equipment

An example of a sanding truck with warm pre-wetting functionality is shown in Figure 2. The truck carries 9 m^3 sand and 2700 L water. The water in the tanks is pre-heated to 45°C. During application the water is further heated to 95°C and mixed with the sand in the feeding tube of the rotating disk spreader. The water is heated by three fuel driven heaters.

The sand/water mixture deposits in lumps in a bow pattern. Figure 3 shows an image taken with a thermal camera during the application. The warm lumps on the pavement are clearly visible. The deposition of the sand in lumps appears to be a key factor in the performance of the method. The warm lumps first melt a part of the contaminants, before the melted and added water freezes.

Figure 2. Sand spreader with warm, pre-wetting functionality.

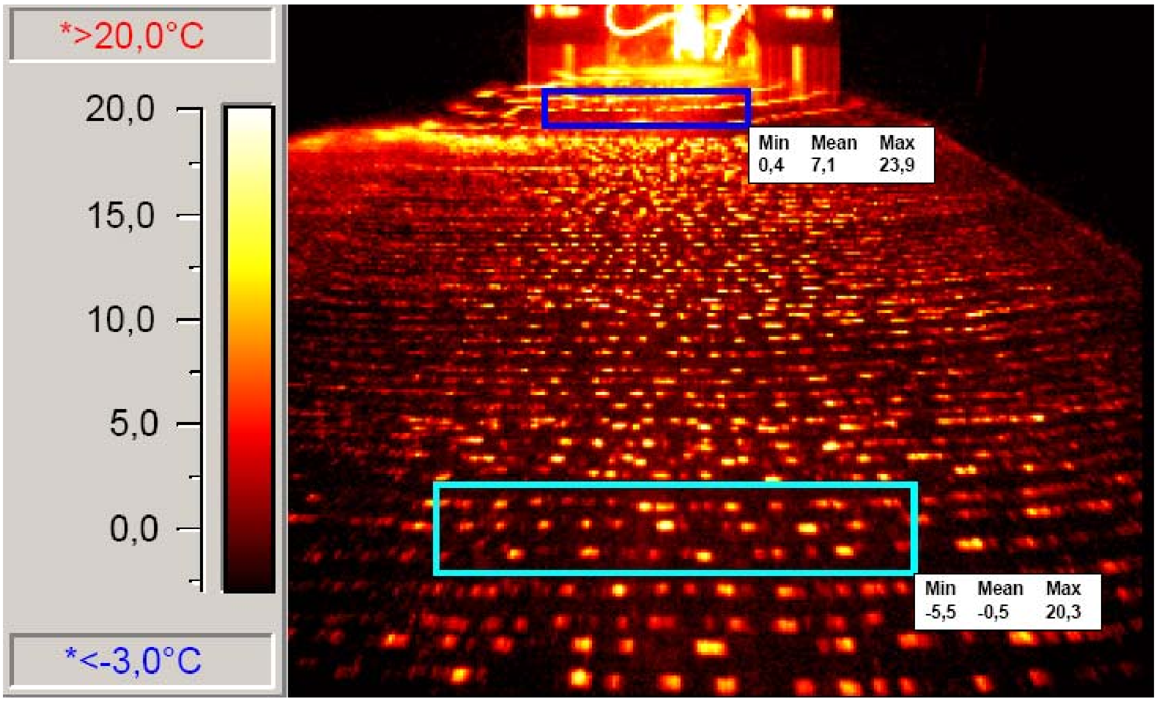


Figure 3. Thermal image showing the warm lumps of sand/water (Vaa, 2005, reprinted with permission).

2.3 Performance

The performance of a sanding operation is traditionally evaluated by the friction level increase after application and the durability (friction level as a function of time or traffic exposure). A large part of the testing program on warm, pre-wetted sanding focused on finding the settings (sand properties, sand application rate, sand/water ratio, water temperature, application width, and application speed) to maximize the friction level increase and durability. The current recommended settings to maximize performance are given in Table 1.

Table 1. Recommended settings for warm, pre-wetted sanding (Vaa, 2005; Vaa, 2006a)

Parameter	Recommended setting
Driving speed (km/h)	25
Application width (m)	2.5 – 3
Sand application rate (dry sand) (g/m^2)	180-200
Water ratio (vol%)	30
Water temperature (°C)	95
Sand size fraction (mm)	0-4

To create durable lumps, the sand needs to contain a certain fraction of fine sand. The application conditions also affect the lump quality. An excessive driving speed or application width (an increased angular velocity of the disk spreader) causes separation between the larger and smaller sand fraction, resulting in a spreading pattern that is less durable. The actual performance of a sanding operation largely depends on the weather conditions. Warm periods (air temperatures above 0°C), snowfall, or ice deposition limits the durability of an application. Therefore, in practice, the application may be optimized for local weather and traffic conditions.

3 PRACTICAL EXPERIENCES

3.1 Introduction

The implementation of a new technology can offer improvement in quality and reduction of costs, but it is also accompanied by uncertainties. Will the technology perform according to expectations under operational conditions? What is the operational range of the technology? Are there other activities, processes, or procedures that have to be adjusted? Are there undesired effects? These questions cannot always fully be answered before the technology is tested in an operational situation.

The first airports that received the new spreaders had at least two winter seasons of experience with the method at the time of the field study. Hence, practical experiences start to become available. Personnel from Kirkenes Airport, Svalbard Airport and Bardufoss Air Force Base were asked about their experiences with the warm, pre-wetted sanding method in operational use, and with the implementation process. These interviews were held in an open, informal manner, mostly in the form of conversations during their daily work activities. Afterwards, a short summary of the conversation was written. This summary was validated by the respondents on correctness and completeness.

3.2 Results

3.2.1 Kirkenes Airport

Kirkenes Airport received a Schmidt Stratos Lava 2 spreader in 2004. Airport Manager Knut Kristoffersen said he is, in general terms, satisfied with the new sanding method. “During the winter periods, runway conditions have been improved (higher measured friction coefficient) and the longer lasting result reduced the number of sanding operations. Moreover, the sand used for the new sanding method can be obtained from a local supplier, in contrast to the traditional, crushed rock sand, that had to be shipped to Kirkenes Airport. But we also have received comments from pilots that it was slipperier than reported. Therefore I am still wondering if the method is as good as the friction measurements tell us.”

Winter maintenance personnel at Kirkenes Airport expressed their satisfaction with the new sanding method. Although an application takes longer (about 1 to 1.5 hours) to treat a complete runway, compared to about 5-10 minutes during traditional sanding, the result is better (higher measured braking action) and the result is longer lasting. They also indicated that a treated surface can be swept, bringing out the bonded sand again. After a snow shower, only sweeping is often sufficient to result acceptable braking action. Under favourable conditions, a sanding operation can last for more than a week.

3.2.2 Svalbard Airport

Svalbard airport received its warm pre-wetted sand spreader in 2003. Airport Manager Ole Martinus Rambech pointed out that the new sanding method was very suitable for Svalbard Airport. “The personnel using it are satisfied, and it turned out to be more cost efficient than traditional sanding. The method uses cheaper sand and fewer sanding operations are required. The sand sticks so well to the surface that we can do up to three snow removals with the sweeper and still have good effect from the sand left. Moreover, the quality of the runway surface as been improved (higher measured friction coefficients).”

Winter maintenance personnel at Svalbard airport also said they were satisfied with the new method. Due to the frequent strong winds at Svalbard Airport, freeze bonding of sand has been frequently used. “With the old method of heating the ice before sanding, we could also get good results, but it was a very slow process. It took hours to treat the runway this way. In loose sanding during strong winds, a part never reaches the runway; it is blown to sides while it is being applied.”

Winter maintenance manager Erik Eriksen was involved in the implementation of the new sanding method at Svalbard Airport. Eriksen was very positive on the new method: “It is much better than the methods we had before. It is easier to use and cheaper. When we received the equipment, we had to learn to use it, find out the optimum speed, sand type and get used to the new methods, but we had no major problems. We went down in sand application rate from 120-130 g/m^2 to 80 g/m^2. Our machine delivers a constant water flow of 24-26 litres of water per minute, independent of sand application rate. At 120 g/m^2 the sand water mixture becomes too dry. You still get very good effect after sanding, easily 0.5 (measured with a BV-11), but it does not last so long. When we went down in sand application rate (so increasing the water/sand ratio), the effect is maybe a bit less, say 0.40 to 0.45, but it lasts much longer. The durability of a sanding operation depends largely on the weather conditions. Under favourable conditions it can last more than two weeks, but if you get snow, we have to sweep the runway and sand more frequently. Sometimes we sand every day. It has become easy to get high friction numbers. Earlier it was a struggle for the numbers. Also, with the old method (heating the ice before application) you needed a thicker ice contamination before you managed to get a good result. When we received the equipment, we were wondering if it also performs when it is cold and windy. But even at -30°C and a lot of wind, we got good results. Actually, even above 0°C on melting ice, you get better results compared to dry sanding. Here of course, the water does not freeze, but the water makes the lumps heavier and you still get this curved pattern.”

3.2.3 Bardufoss Air Force Base

Bardufoss Air Force Base received its warm, pre-wetted sand spreader in 2003. Winter maintenance personnel at Bardufoss are positive about the new method. ”With this method, higher friction levels are achieved, and the result lasts much longer.” One of the maintenance managers pointed out that the ice is now more difficult to remove, because it is “armoured” with sand particles. But because of the embedded particles, it is easier to maintain a good friction during this transition from “winter runway” to “black runway”.

Captain Odd Helge Wang has been responsible for the implementation, and has been involved in the development of the method. Wang pointed out that the implementation was much more than just replacing the old sand spreader for the new one, and getting familiar with the new buttons. “The whole strategy of winter maintenance has changed with the introduction of the warm, pre-wetted sand spreader. To be effective, it has to be an integrated solution. For example, due to the introduction of warm, pre-wetted sanding we are making more use of the underbody scarifying blade. During colder periods, ice and sand are building up. When too much ice is allowed to build up, you may face problems when the weather shifts to mild weather. If the forecast predicts mild weather, the maintenance manager may decide to scarify and sweep the ice, removing most of it. The last thin layer of ice that is left is removed with urea. Our challenge is to get a common strategy for the different shifts we are working in. When faced with difficult situations, we should ask ourselves ‘could we have done something differently?’ Good winter maintenance means anticipating the things to come. When you reach the point that it gets slippery, you are too late. Then there is often no time anymore, and your options to do something are greatly reduced. Specifically when using chemicals it is important that the planned strategy continues, or if needed, is adjusted by the next shift. What we really need are guidelines for using chemicals. When should we apply it to remove ice? How much? How long do we have to wait before we can start the sweeping, depending on ice thickness and temperature? Chemicals are not cheap. If you are too quick you can’t remove the ice and the money is lost. If you wait too long, it dilutes too much and freezes again.”

3.3 Discussion

Maintenance personnel from the three visited airports expressed a general positive attitude towards the use of warm, pre-wetted sand. The main improvements that were pointed out are the higher friction levels and the longer lasting effect. Compared to traditional freeze bonding (heating the pavement and loose sanding) the improved operability was also indicated.

The airport managers also indicated that they were satisfied with the new method, mainly due to cost reduction and quality improvement. But the question was raised as to whether the surfaces treated with warm, pre-wetted sand are as good for the aircraft as they are for the friction measurement device.

It should be taken into consideration that these three airports frequently have cold winter conditions. Earlier testing has shown that these conditions are most suitable for warm, pre-wetted sanding. In contrast to these known conditions, Eriksen also experienced a beneficial effect during warm, melting conditions. This is interesting because warm, melting conditions are more difficult to handle than cold conditions. Clearly, under the former conditions, warm, pre-wetted sanding does not lead to freeze bonded sand. But if it improves operability, compared to other methods for the same conditions, it may be worth conducting more research into the treatment of warm, melting ice with warm, pre-wetted sand.

A second interesting aspect is the opinion of Captain Wang: "Winter maintenance is anticipating the situation to come. If slippery conditions have occurred, there is often not time anymore, which reduces your options to do something." In this respect the warm, pre-wetted sanding currently belongs to the group of countermeasures that are no longer an option because it takes one to two hours to treat a runway surface. It would be favourable to avoid such a situation, but in practice this will not always be possible. There will remain situations where the runway conditions have to be improved while aircraft are waiting, either in the air on the ground. Improving the tools to handle such situations can be a topic for further research, and the concept of warm, pre-wetted sanding may be a useful starting point. Disregarding all practical, engineering difficulties, reducing the application time (by increasing application speed and/or width) will make the method more versatile for airport applications.

3.4 Conclusions

Runway maintenance personnel indicated that the warm, pre-wetted sanding method is a useful tool in winter maintenance of runways. The higher friction level and durability of the application were pointed out as the main benefits, compared to traditional sanding.

Airport managers indicated that the method reduces the costs of sanding because cheaper sand can be used and fewer applications are required.

Two topics for further research and development can de derived from the practical experiences with warm, pre-wetted sand at airports: (1) reduction of the application time and (2) use of the method in melting ice conditions.

4 WARM, PRE-WETTED SANDING ON COMPACTED SNOW

4.1 Introduction

A large part of the development of the warm, pre-wetted sanding method is optimization of the different parameters, such as sand type, application rate, water ratio, etc. The aim of optimization is to find the most favourable combination of settings for all these parameters. To determine this combination, it is important to consider the objective of the sanding operation. What is considered to be a good sanding operation? What do we want to achieve? What are the performance factors?

The most widely used performance factor for sanding operations is the increased friction level, indicated by friction measurements before and after the application. A high increase is typically considered to be a good performance. A second performance factor is the durability of the sanding operation. It is typically expressed in how long the sanding operation lasts, or how much exposure to traffic it withstands, before the friction level is back to its original value, or a predefined reference value.

The durability of a sanding operation, however, is greatly dependent on the weather conditions. Mild weather, snowfall, and ice deposition are just a few events that can limit the real durability of a sanding operation. During these situations the friction level can rapidly drop. But how severely and how quickly the surface conditions deteriorate also depend on the spreading pattern. For example, if only fine sand was used (say a maximum size of 1 mm), the sanding operation could result in a large increase in friction level, and the result may even be durable during stable weather conditions, but the surface will quickly and severely lose its frictional properties during ice deposition conditions. Hence, the robustness of the spreading pattern is its ability to hold its frictional properties during changing weather or traffic interactions.

These three performance factors (increased friction level, durability, and robustness) of the sanding pattern are to be optimized against operational factors like cost, vehicle range, and application time. Quantifying the increased friction level is relatively easy by conducting friction measurements before and after application. Quantifying the durability of an application is more difficult because it can take a long time (up to weeks) to measure the friction level as a function of time and traffic exposure. Quantifying the robustness is even more difficult because it is dependent on shifting weather conditions. These constrains imply that optimization is not straightforward and very time consuming. Therefore it is important to evaluate the spreading pattern. The combination of settings results in a certain spreading pattern, which cannot be controlled after its application. But the question that needs to be answered is what the spreading pattern should be. What is a favourable spreading pattern? What does a robust or durable spreading pattern look like? How does the pattern develop in time?

The experiences with warm, pre-wetted sand so far suggest that if the spreading pattern consists of lumps, the most durable results are obtained. To create these lumps, the sand needs a certain proportion of fine sand particles. With the current configuration of rotating disk spreaders, the creation of these lumps limits the speed and application width. When the speed or width exceeds a certain limit (currently 25 km/h and 3 m, respectively), separation of the small and large particles can occur. The increased friction level may still be high, but the result has a reduced durability. But there is clearly a further need for information regarding the spreading pattern in order to support further optimization.

During the tests for warm, pre-wetted sand spreaders, held in Dombås, Norway in January 2006, tests were performed on different surfaces. The results of the testing are presented elsewhere (Vaa, 2006b). One of the tested surfaces was a road covered with compacted snow. The very low traffic density and uniformity of the compacted snow layer, combined with the stable weather conditions, provided ideal conditions for observations of the spreading pattern.

4.2 Test details

The test location is shown in Figure 4. Note the uniformity of the snow layer. The compacted snow layer was about 10 mm in thickness. Below the snow layer, there was a continuous layer of ice. The density of the snow ρ_s was about 400 kg/m^3. The air temperature T_a and snow temperature T_s were -2.7°C and -5.4°C, respectively.

Figure 4. Application of freeze bonded sand on uniform, compacted snow.

The warm, pre-wetted sand was applied with a Falköping spreader at 25 km/h, 3 m application width and 65 g/m^2 sand + 26 g/m^2 water. The water temperature was 95°C and the used sand was 0-4 mm natural sand.

4.3 Results

An overview of the spreading pattern is shown in Figure 5. The distinct lumps located in the bow pattern and the whiteness between the bows indicate that most of the sand mass deposited in lumps. The continuous stripe through the pattern was caused by a small leak. A detail of the spreading pattern is shown in Figure 6a. The detailed view shows that a small fraction of sand is located as individual particles. It can be observed that the lump consists of a group of large particles situated on a patch brown-looking snow.

About 10 minutes after application the sand particles were carefully touched with the tip of a ruler. Both the lumps and individual particles were bonded to the compacted snow. The area was then exposed to firm rubbing by a shoe sole. The individually bonded sand particles were removed and the lumps disintegrated into loose particles. The finer sand particles located in the brown ice could not be removed by rubbing. The result after the rubbing is shown in Figure 6b.

The surrounding snow was carefully removed to get a vertical view of the lump. Figure 7 shows that the larger particles are located at the top, whereas the finer sand has penetrated into the snow layer. In this particular case, the water and fine sand penetrated about 10 mm and reached the underlying ice. While removing the snow to make this view possible, it was noticed that the brown ice was significantly stronger than the compacted snow.

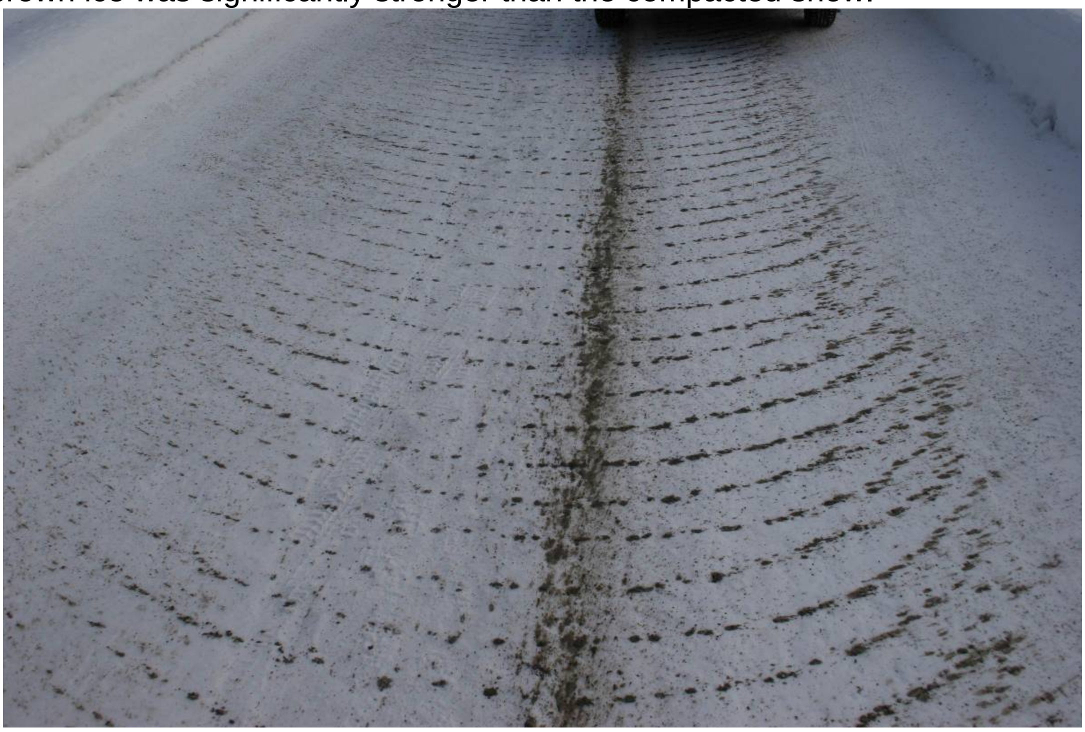


Figure 5. Spreading pattern on compacted snow.

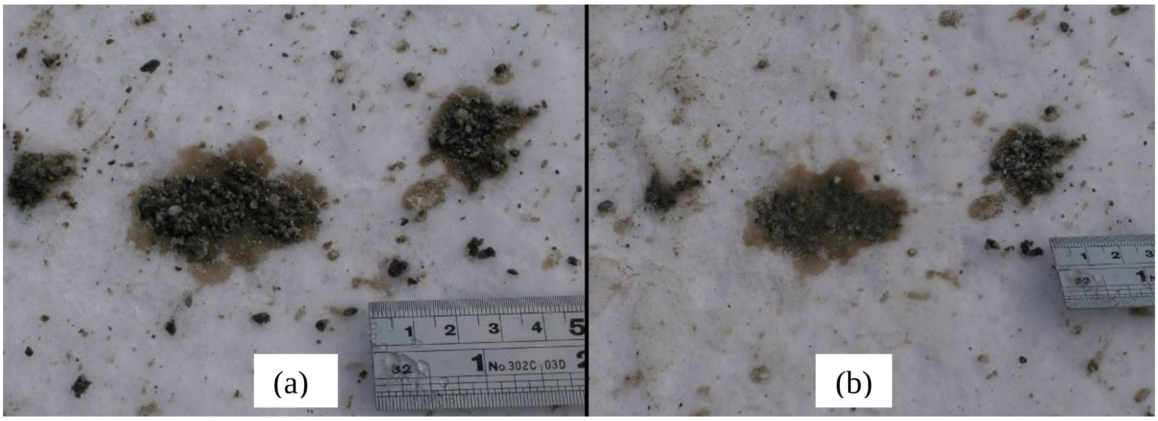


Figure 6. (a) Detailed view of spreading pattern. The sand is situated in lumps and as individual particles. (b) Same area after firm rubbing with a shoe sole. The individual particles are removed and the lumps disintegrated into separate loose particles.

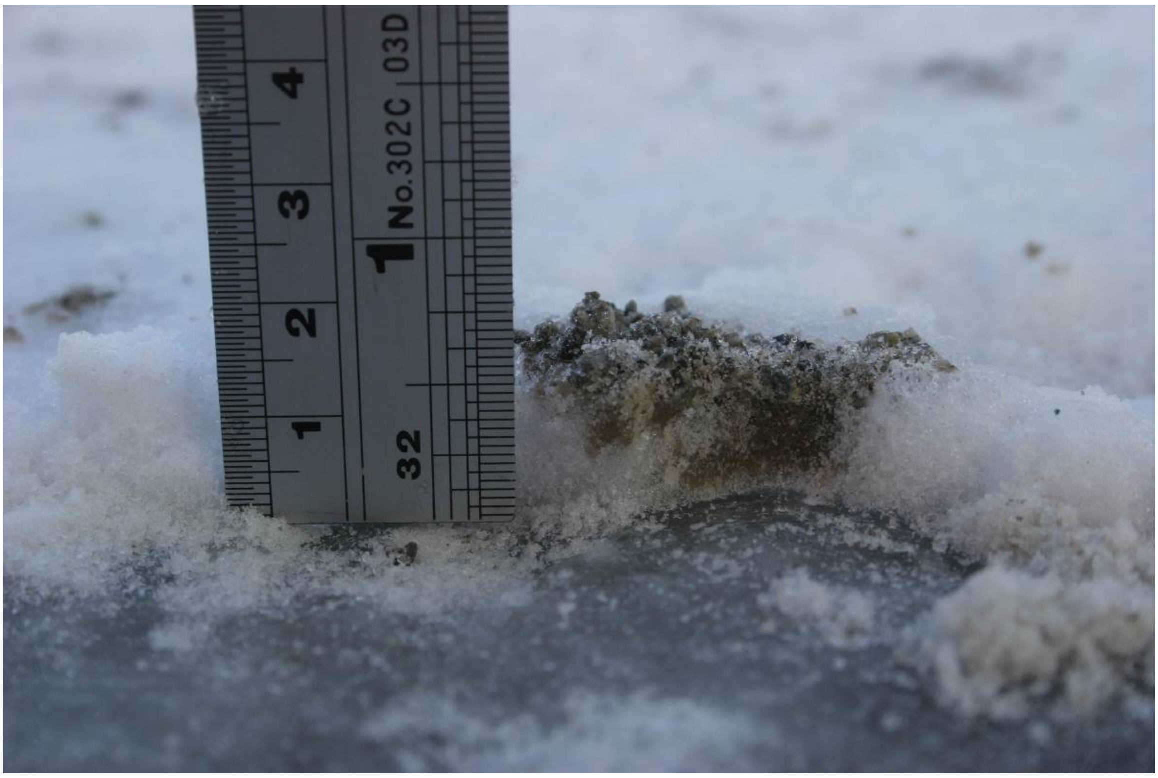


Figure 7. Penetration of fine sand and water into the compacted snow layer. The large particles are located at the top, whereas the finer sand and water penetrated about 10 mm into the snow layer.

4.4 Discussion

During the tests, the weather was rather mild (T_a = -2.7°C and T_s = -5.4°C) and there was little wind. There was no loose snow on top of the compacted snow. Since the water temperature was set to 95°C the lumps were rather warm (compared to tests performed at colder conditions) when they were deposited. However, close examination of the lumps revealed that they did not melt significantly deeper into the snow. They were still higher than the snow surface. But penetration of fine sand and water into the pore space was observed. This penetration caused a vertical separation between large and small particles. The larger fraction was too large to penetrate into the pore space and was left on top. The finer particles were mainly located within the snow layer. The question that arises is: “Is this the optimal spreading pattern?”

After freezing, the penetrated water and fine sand significantly strengthened the compacted snow. This was clearly noticed when removing the snow to make the vertical section shown in Figure 7. Such a strengthened foundation prevents the lump from breaking loose from the snow in one piece. Specifically for airport applications, this is important with respect to foreign object damage (see also Section 5). But the penetration implies that the large particles have less fine sand and frozen water surrounding them. It can thus be expected that the large particles are more easily removed by the action of traffic when penetration occurs.

When the large particles are removed, the fine sand embedded in the ice remains and the brown pattern stays clearly visible. This is illustrated in the right image of Figure 6. Judging from a distance, the colour of the pattern suggests that there is sufficient sand left. Friction measurements may also result in high readings when the fine sand has good contact with the measurement tire. The pattern may be durable as well since the fine sand is well supported by the surrounding ice, and this sand/ice matrix is significantly stronger than the surrounding snow. However, the removal of large particles likely reduced the robustness of the measure. It does not take much ice deposition (from humid air above the colder pavement) or freshly fallen snow before the fine sand is completely covered and does not make contact with the tire. Hence, although penetration is favourable for the bonding between the lump and the snow, excessive penetration may reduce the robustness of the application.

Could the penetration be controlled? In principle it should be controllable by adjusting the water temperature. Decreasing the lump temperature upon deposition reduces the amount of melt water that is produced and reduces the penetration time. A second adjustable parameter is the sand/water ratio. Reducing this ratio also reduces the lump temperature, since only the water is heated. Additionally, when the sand/water mixture becomes drier, less water is available to penetrate. The disadvantage of reducing the sand/water ratio is that less water is available to construct the sand/water matrix. Other effects of changing the lump temperature can also be expected. As the lump solidifies faster, the water freezes in smaller crystals and this affects the mechanical properties of the ice (Sinha, 1978b; Sinha, 1978c). The multiple consequences of adjusting a setting complicate the prediction of the effect. Therefore, it can be valuable to study the effect of the water temperature on the penetration and lump quality in a systematic manner.

4.5 Conclusion

The application of warm pre-wetted sand on a compacted snow layer resulted in a well-bonded sanding pattern, with locally strengthened snow. The observed penetration of fine sand and water constructed a strong base between the snow and the lumps. However, penetration also led to a vertical separation between the large and small particles. This may cause an accelerated removal of large particles, compared to an application on ice. With only small particles left, the robustness of the application is expected to be significantly reduced.

5 RISK OF FOREIGN OBJECT DAMAGE

5.1 Introduction

Loose objects that are located on movement areas of airports (runways, taxiways, and aprons) may damage aircraft. This type of damage is known as Foreign Object Damage (FOD). Loose sand applied on airfields can be a source of FOD and this has been considered while developing a guideline for sands that are used for airside applications (Comfort and Gong, 1999). Two types of FOD in relation to sand application can be identified: (1) impact damage, caused by large sand particles, and (2) abrasion, among other damages due to ingestion of small particles into turbines. These considerations have led to the following sand guideline (Comfort and Gong, 1999):

- Maximum sand size: Sieve size nr 4 (US standard, mesh opening 4.75 mm)
- Minimum sand size: Sieve size nr 80 (US standard, mesh opening 0.18 mm)

The fact that sand becomes bonded to the pavement by frozen water can effectively reduce the risk of FOD. In addition, the warm, pre-wetted sanding method reduces the total amount of applied sand (see Section 3). However, freeze bonding sand does not imply that the risk of FOD can be neglected. During the tests in Dombås, Capt. Odd Helge Wang from Bardufoss Air Force Base shared some of his experiences regarding warm, pre-wetted sanding and the risk of FOD.

5.2 Results

On the subject of FOD risk, Capt. Wang pointed out the importance of snow cleaning before applying warm, pre-wetted sand. He demonstrated it with a very a simple test on a parking area.

The parking area was partly covered with ice and patches of weakly bonded snow. Although the area was swept prior to the application, little or no maintenance had been performed during the past few days. The sweeping was performed with a small front-mounted rotating steel brush, not with a typical runway sweeper including plough, brush and blower.

This left patches of weakly bonded snow with a thickness of about 15 mm on the iced surface. The warm pre-wetted sand was applied a few hours before the demonstration. At the time of demonstration, the air, ice and snow temperature, and the dew point were T_a = -3.7°C, T_i = -5.1°C, T_s = -5.1°C, T_d = -7.8°C, respectively. The demonstration area is shown in Figure 8.

To estimate the quality of the bonding, Wang uses a very simple test. A lump of freeze bonded sand is rubbed firmly with a shoe sole. If the underlying compacted snow or ice is strong enough, the lump disintegrates into separate particles. This is shown in Figure 9. All that is left after the rubbing is brown ice, due to the remaining fine sand particles. But on weakly bonded snow, the lump does not disintegrate in single particles but breaks loose as a single piece (see Figure 10). A detail of the lump is shown in Figure 11 that clearly exceeds the dimensions recommended by the sand guideline.

Capt. Wang and his colleague, maintenance manager Knut Ivar Morstøl, have not experienced that lumps of sand indeed caused Foreign Object Damage at Bardufoss Airport. However, the need for proper cleaning (ploughing, sweeping and blowing) before application has been recognized and forms a standard preparation before sanding.

Figure 8. Overview of an area with patches of ice and weakly bonded snow.

Figure 9. (a) Lump applied on cleaned iced surface. (b) Rubbing the lump causes it to disintegrate into separate particles, leaving brown-looking ice behind.

Figure 10. (a) Lump applied on loosely bonded snow. (b) Rubbing caused the lump to break loose in one piece.

Figure 11. Detail of the lump that broke loose.

5.3 Discussion

The relevance Capt. Wang's demonstration is apparent. As seen in Figure 11, the lump that broke loose was about 25 mm in diameter, which exceeds the maximum sand size of 4.75 mm, recommended by the sand guideline, and forms a hazard for impact damage. As can be seen in Figure 11, the fracture occurred within the snow. Hence, the snow, while strong enough to survive the sweeping, was too weak to sufficiently support the base of the lump during the rubbing. According to Wang and Morstøl, the surface was, for airport standards, insufficiently cleaned prior to the sanding.

It is questionable how representative rubbing with a shoe sole is of the stresses exposed by operating aircraft or other vehicles. Hence it is difficult to predict whether a lump would break loose in practice, based on a test performed with a shoe sole. But the important aspect of the demonstration was that well bonded lumps disintegrated into separate particles. By doing so, large loose lumps are avoided.

The danger of loose lumps appears to be directly related to the mechanical properties of the snow and the snow thickness. These properties change in time, due to sintering and by repetitive snow compression by vehicles. When a snow layer is heavily and/or repeatedly compressed and the conditions for sintering are favourable (which can be tested by making a snow ball) it rapidly gains strength. If, in addition, the thickness is kept to minimum (by intensive snow cleaning), the conditions are not favourable to get a snow layer with the characteristics described above. To form such snow, it should be thick enough, be moderately compressed, and have had time to sinter. These conditions typically occur on less maintained areas.

A second issue regarding FOD hazard is the fine sand fraction (below 0.18 mm). The sands currently in use contain finer sand than recommended by the sand guideline for loose sand application. This fine sand fraction appears to be one of the key factors for the performance of warm, pre-wetted sanding. During application, the sand becomes bonded and even embedded in the ice. The fine sand cannot be fully removed by rubbing. Hence at this stage there appears little FOD danger from the finer sand. But sand can loosen again by melting, wear or ice sublimation. Although it is not investigated here, it appears that frequent sweeping of the treated area is needed to avoid excessive amounts of fine sand particles on the pavement.

5.4 Conclusion

To reduce the risk of FOD, areas that are treated with warm, pre-wetted sand should be properly cleaned prior to application. When the sand is applied on weakly bonded snow, lumps may break loose because this snow insufficiently supports the base of the lump. Specifically, less maintained areas are susceptible for such snow conditions. Excessive loose sand, loosened by melting or sublimation, is to be avoided.

6 AIRCRAFT BRAKING EXPERIMENTS

6.1 Introduction

Aircraft need a certain level of tire-pavement friction for retardation and directional control. Pilots typically refer to it as braking action. But what causes braking action? The operational use and development of warm, pre-wetted sanding can benefit from insights in *how* the surface is providing friction to the aircraft.

Tire-pavement interactions are complex phenomena. When snow and ice are present as interfacial media, the complexity increases even further. The whole interaction can be viewed on different scales. Macroscopic interaction includes interaction of the tire, the (anti-skid) braking system, the spreading pattern, the contaminated pavement, and the atmosphere in which the interaction takes place. Microscopic interactions are confined to the contact area and include sand particle and asperity interaction with the rubber tread and iced pavement. On a nanoscopic scale, rubber molecules interact with frozen water molecules and the minerals from the sand or the pavement aggregates.

The facilities and cooperation of Bardufoss Air Force Base provided the necessary boundary conditions to perform an aircraft braking test on smooth ice treated with loose sand and warm, pre-wetted sand. The available aircraft was a small propeller aircraft and was not instrumented to measure or derive tire-pavement friction. Even without this data, it was still a useful opportunity to study the interaction by investigating the tracks left on the ice. It also provided an opportunity to study the microscopic interaction between the sand particles and the ice in the two sanding cases.

6.2 Test details

The tests were performed on January 25, 2006. It was cloudy, there was little wind, and it was relatively mild (T_a = -2.5°C). A parking area about 200 x 100 m provided a suitable test area. The pavement was covered with a thick, uniform layer of ice, with about 10 mm of loose snow on top. To minimize mechanical damage of the underlying ice, an attempt was made to remove the snow using the blower only. Although most of the snow was still loose, some snow particles had been sintered to the ice surface and could not be removed by blowing. Therefore, the pavement was cleaned using the rotating steel brush and blower. The snow cleaning was finished at 12:31. The ice had a bluish white appearance and was very uniform over the whole area. Only few visible cracks were present. The thickness, colour and uniformity of the ice indicate that it was formed by snow that had undergone freeze-melt metamorphism or that rain had precipitated on top of the undisturbed snow layer. Maintenance personnel confirmed that the weather had been mild with rain showers a few days before the test. Before snow removal, the snow layer and ice surface were colder than the air temperature: T_s = -4°C and T_i = -6°C, respectively. At the time of the tests, the ice surface had warmed up to T_i = -5°C, while the air temperature remained stable. It took about 1.5 hours from the start of the snow cleaning to the first test run.

Two test beds of sand were prepared, both about 150 × 6 m. The first test bed was made with 150 g/m^2 loose sand, 0-4 mm sand size fraction. The second test bed was made with 150 g/m^2 sand, pre-wetted with 30 vol% water (T_w=95°C). Both sand applications were performed at 25 km/h and 3 m application width. The test beds were finished at 13:31. The difference between the sand applied with and without the hot water is illustrated in Figure 12. An overview of the two test beds is shown in Figure 13.

The Air Force flight school at Bardufoss supplied the aircraft, a Saab Safari MFI 17, and instructor LT. Hæfta performed the test runs. One braking test was performed on each test bed. First, the aircraft was accelerated to about 50 km/h, then the engine was turned to idle, and finally the brakes were firmly applied until the aircraft came to a complete stop. The pilot was informed that the goal of the braking test was to come to a full stop as quickly as possible. The first run (13:54) was performed on loose sand. At 14:30 the run on freeze bonded sand took place. A photograph of the aircraft during the first test run is shown in Figure 14.

The tracks were closely inspected after each test. These macroscopic observations were documented by taking photographs. In addition, the tracks were investigated on a microscopic level. Here, the etching and replica method for ice (Sinha, 1978a; Sinha, 1977) was used as the analytical method. Replicas of the ice surface were prepared both before and after the tests. The test beds were also measured with a Saab Friction Tester after the macroscopic observations and preparation of the replicas.

Figure 12. (a) Applied sand (150 g/m^2), pre-wetted with 30 vol% hot water on an iced surface. (b) The same type and amount of sand applied without the water.

Figure 13. Overview of the test beds. Left: freeze bonded sand, right: loose sand.

Figure 14. SAAB Safari on the loose sand test bed.

6.3 Results

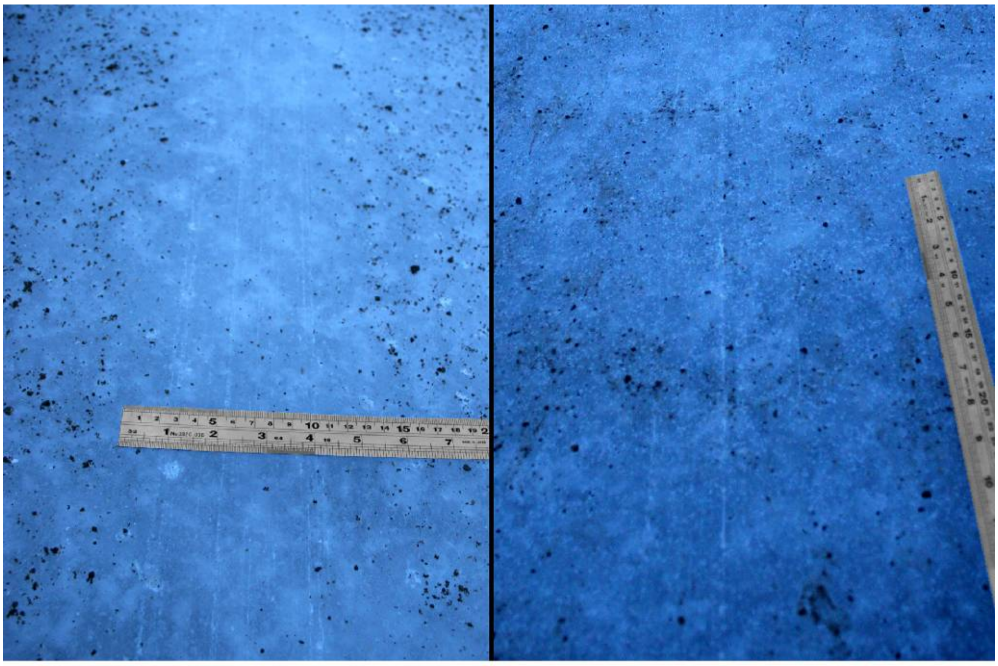
Macroscopic observations

An overview of the track on the loose sand test bed is shown in Figure 15a. The track is clearly visible because most of the sand particles were removed from the track. Both the (braked) main gears and the free-rolling nose gear displaced the sand particles. The aircraft experienced two non-simultaneous tire lock-ups, one on each main gear. The pilot stated that he had felt the tires skidding and released the brake pressure twice to get the tires rolling again. He did not experience tire lockups on the freeze bonded sand.

The tracks on the freeze bonded sand test bed were also visible (Figure 15b) because some of the particles were removed by the tire. However, there was still a significant amount of sand left in the track. This remaining sand survived the stresses from the tire and remained bonded to the underlying ice. Scratch marks on the ice were observed inside the tracks, both in the loose sand test bed and in the freeze bonded sand test bed (Figure 16).

(a) (b)

Figure 15. Overview of the tracks after the braking test on (a) loose sand, and (b) freeze bonded sand.



(a) (b)

Figure 16. The ice in the tracks exhibited scratch marks, both on (a) loose sand, and (b) freeze bonded sand.

The skidding tires on the loose sand test bed caused sand particles to pile up. The pile-up from the right main gear is shown in Figure 17a. The detailed view (Figure 17b) shows that the pile-up consists of loose sand particles and a patch of packed particles and ice debris. The loose particles were located in the front of the pile-up. The patch of packed particles and ice debris was broken into two pieces. The largest piece (Piece 1) was still located in the track, while Piece 2 was deposited a few centimetres above the track. Two “ridges” were present in the patch; one of them was fragmented when the two pieces broke loose from each other. The spacing between the two ridges was about 37 mm, which corresponded well with the measured spacing between the longitudinal grooves of the tire (40 mm).

The ridges and the known spacing of the longitudinal grooves were used to reconstruct the approximate dimensions of patch before it broke into pieces (Figure 17b). The dimensions of the patch correspond reasonably well with the apparent contact area of the tire. This suggests that sand particles and ice debris accumulated under the tire during the skidding, and were not just pushed in front of the skidding tire. This created a patch of sand and ice debris that slid together with the skidding tire on the ice.

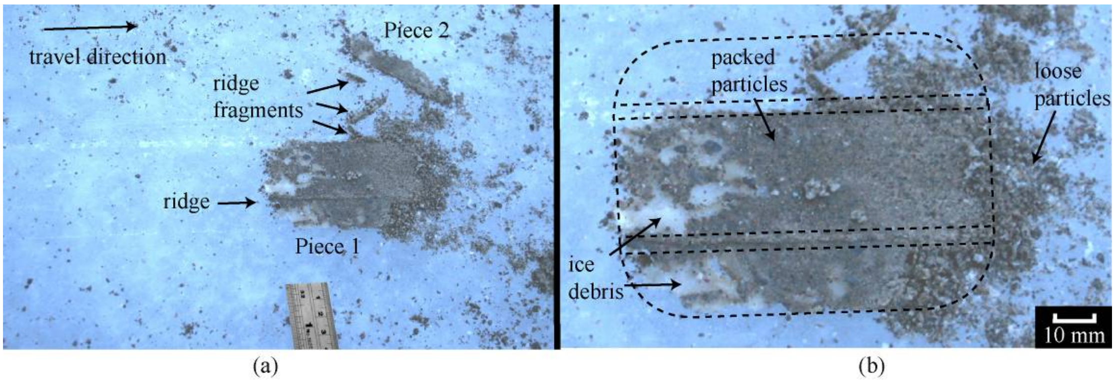


Figure 17. (a) Pile-up of sand and ice debris caused by skidding right main gear tire. (b) Dashed lines show approximate dimensions of patch.

The pilot noticed a clear difference in the response of the aircraft during the braking on the two test beds. He estimated the braking action as “poor” for ice treated with loose sand and “medium” for the ice treated with freeze bonded sand. This difference, however, was not reflected in the friction measurements performed with a Saab Friction Tester. It measured consistently a friction coefficient of 0.17 on the loose sand and 0.19 on the freeze bonded sand. This means that the friction measurements described both surfaces as “poor”.

Microscopic observations

Replicas of the ice surface were prepared by the etching and replicating method, using a 2.5% Formvar solution. Replicas from the ice surface were prepared prior to the testing, after the snow was removed. This gave a documentation of the original microstructure of the ice. The replicas revealed that the surface was, on a microscopic scale, severely damaged by the snow cleaning operation. An illustration of the replicated ice surface is shown in Figure 18. The original grain boundaries can be identified, but the area is dominated by countless scratch marks caused by the sweeper. Most of the surface was re-crystallized inside these scratches. It is also possible that the observed cells are the result of breaking the bond between the sintered snow and the ice surface. Nevertheless, it is clear that the sweeping caused significant microscopic damage to the ice surface.

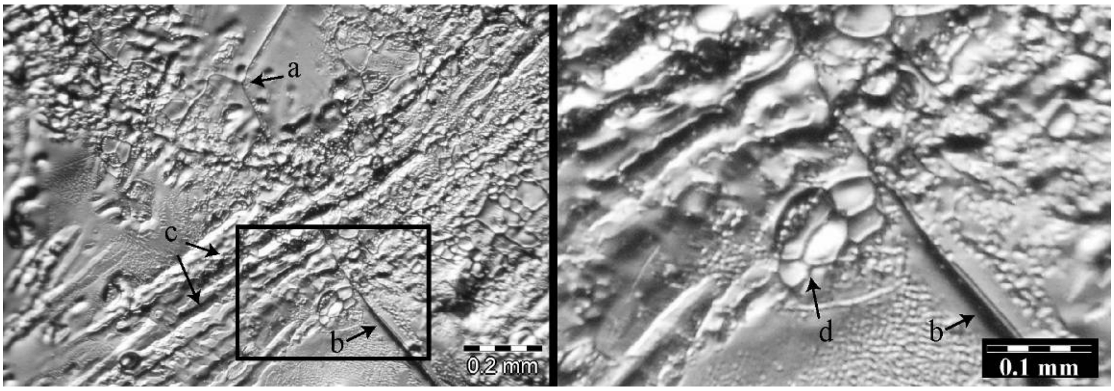


Figure 18. Replica of the ice surface before sand application. The micrograph shows a triple-point (a) and the original grain boundaries (b). It also shows numerous trans-granular scratch marks (c), containing small cells (d) due to highly localized deformation.

After each braking test, replicas were prepared from the ice surface inside the tire tracks. Snow started to drift closely above the surface during the drying process of the replicas on the loose sand test bed. The replicas were covered by a plastic box, but snow contamination could not fully be fully avoided. This created dark, fluffy artefacts on the replica. Nevertheless, large scratch marks could be distinguished. Figure 19a shows a part of the replica where two scratches run horizontally through the micrograph. It shows a region with small cells that were already present before the interaction (Figure 19b). Inside the two scratches there are also small cells present (Figure 19c-d) but it is not possible to determine whether these cells are caused by the highly localized deformation induced by the ploughing sand particles.

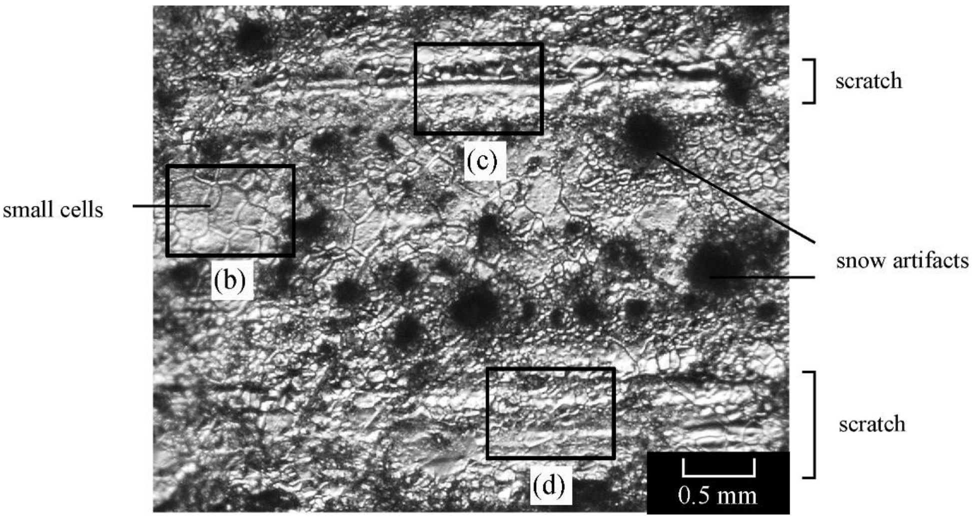


Figure 19a. Replica of the ice surface inside the tire track on the loose sand test bed. The replica shows two scratches and the small cells that were present before the brake test. The black fluffy artefacts are snow crystals that deposited on the replica during the drying process.

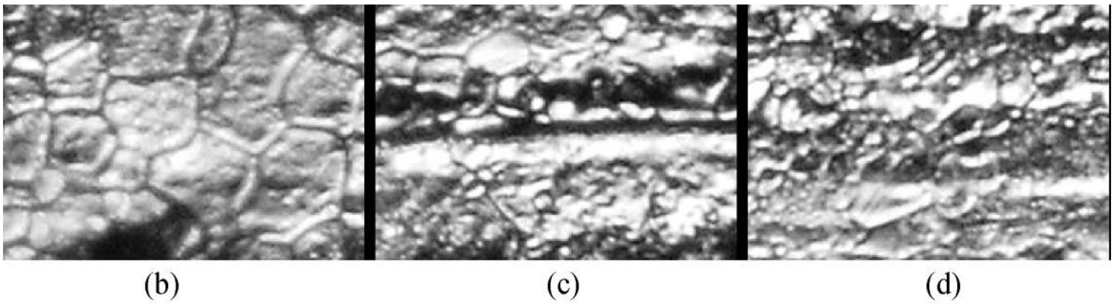


Figure 19b-d. Detailed view of three selected regions indicated in Figure 19a.

The snowdrift lasted only for a few minutes and was not present while the replicas on the freeze bonded sand were prepared. Recovering replicas from the freeze bonded sand surfaces was difficult because the Formvar (the plastic film) strongly adheres to sand, which in turn is bonded to the surface. Nevertheless, a few replicas from the ice between the sand lumps could be recovered. The replicas also showed the highly damaged surface, but an area was found where the original ice structure was reasonably intact (Figure 20). This area contains several small scratches that were aligned along the travel direction and one scratch that was aligned at an angle θ of 23°. The latter scratch was presumably caused by a steel wire of the rotating brush. The angle coincides reasonably well with the attack angle of the brush, relative to the travel direction of the sweeper (about 30°). Cell formation within the original grain structure can also be observed in the scratch that is aligned with the travel direction.

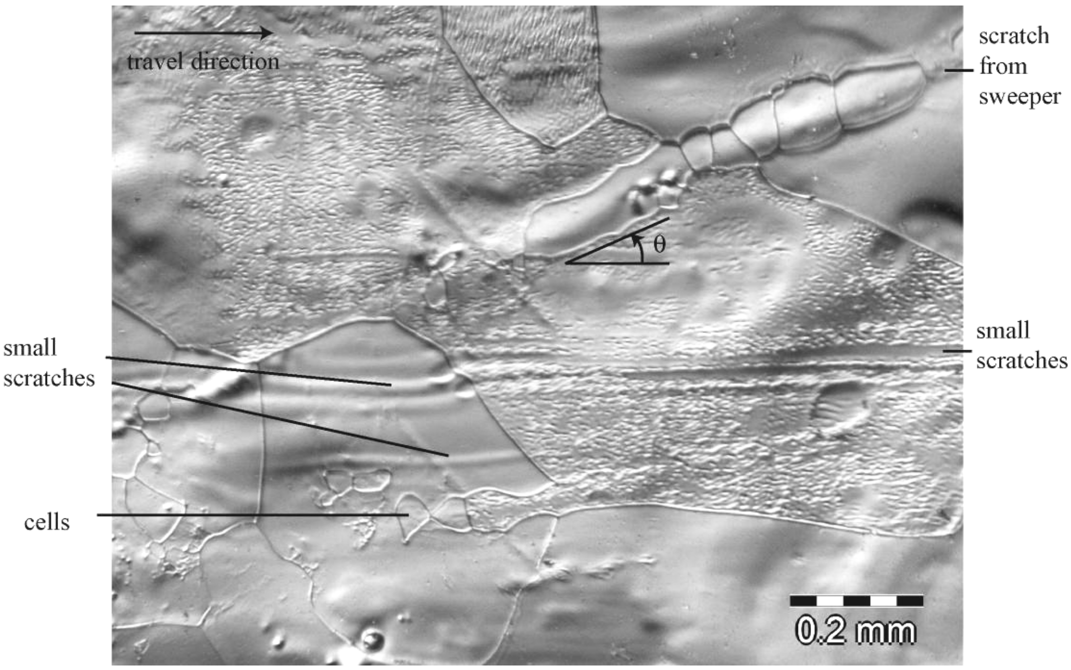


Figure 20. Replica of the tire track on the freeze bonded sand test bed. The replica shows scratches aligned along the travel direction and a scratch that is aligned at an angle θ of 23° to the travel direction, presumably from the sweeping.

The results of the friction measurements are shown in Table 2.

Table 2. Measured friction coefficients from the SAAB Friction Tester

Time	Test bed	Measured friction coefficient	Time after sand application (HH:MM)
14:16	Freeze bonded sand	0.19	0:45
14:18	Freeze bonded sand	0.19	0:47
14:18	Loose sand	0.17	0:47
14:18	Loose sand	0.17	0:47
16:34	Loose sand	0.26	3:03
16:37	Freeze bonded sand	0.29	3:06

6.4 Discussion

During the preparation of the test beds, care had to be taken not to disturb the loose sand test bed. Friction measurements were therefore only performed after the aircraft test. This required precaution highlights the poor robustness of loose sand applications on smooth ice. Unfavourable redistribution of loose sand easily occurs. In this respect, the freeze bonded sand performs significantly better.

The test pilot noticed a clear difference between the two test beds and estimated the braking action on loose sand as “poor” and on freeze bonded sand as “medium”. Surprisingly, the friction measurements did not show a clear difference; the friction coefficients measured 0.17 and 0.19 on the loose and freeze bonded sand, respectively. The measurements on freeze bonded sand had been expected to be higher. After the tests and replica sampling (about 2¼ hours after the first measurements), the friction coefficients had increased by 52 percent to 0.26 and 0.29 for the loose sand and freeze bonded sand, respectively.

For the freeze bonded sand it was initially hypothesized that the added water formed a thin ice layer that still covered (at least partly) the sand during the first friction measurement. As the ice sublimates, more fine sand particles become exposed to the surface and this could explain the observed friction coefficient increase. But the friction coefficient measured on the loose sand increased as well. Therefore, other (unknown) factors appear to have influenced the measurements.

The replica of the original ice surface revealed severe damage on a microscopic level, caused by the rotating steel brush of the runway sweeper. The ice surface consisted of many small grains and a high concentration of grain boundaries. This clearly affected the mechanical surface properties of the ice.

On the loose sand test bed, the sand was displaced during or after the interaction. The ice in the track exhibited scratch marks. These scratch marks were observed in a previous study (Klein-Paste and Sinha, 2006) and are related to the ploughing action of sand particles into the ice surface. Despite the poor quality of the replica, the scratch marks can also be seen on a microscopic level. The ploughing mechanism is a generally accepted friction mechanism contributing to the total sliding friction (Bowden and Tabor, 1964; Bowden and Tabor, 1954; Rabinowicz, 1995; Bhushan, 1999).

On the freeze bonded sand, some of the sand particles broke loose and were displaced under the action of the tire. Also in this case, scratch marks were observed, both macroscopically and microscopically. But the track also exhibited sand particles that were still bonded to the ice surface. Such particles, mainly located in the lumps, do not plough into the ice surface. Instead, they form asperities, similar to road asperities. On a dry road surface, the soft rubber drapes around surface asperities (Moore, 1975; Moore, 1972) and adhesion and deformation (e.g. rubber hysteresis and wear) resists the sliding (Grosch, 1963).

The test on loose sand showed another interaction phenomenon: a tire lock-up. A tire lock-up changes the interaction characteristics on sanded ice because sand particles are either pushed to the sides by the skidding tire or, as shown in the tests, accumulate in the contact area. Most modern aircraft are equipped with anti-skid braking systems that prevent tire lock-ups. These systems, however, are typically disabled below a certain ground speed. For a Boeing 737-600/700/800/900 this speed is 25 knots (46 km/h) (Boeing, 2002) and for a Dash-8 100/300 series it is 17 knots (31 km/h) (Widerøe, 2000). So, tire lock-ups can still occur at low ground speeds. An example of a skid mark caused by a locked tire is shown in Figure 21.

The test area was too small to safely perform a comparison braking test on the ice without any sand application. But considering the mild temperatures and the smoothness of the ice, it may be assumed that the braking action would have been negligibly low. In that case, the majority of the attainable friction would have been provided by the sand. On the loose sand test bed it implies that ploughing of particles into the ice was the dominating friction mechanism. Hence friction was provided by ice deformation. On the freeze bonded sand, there are different friction mechanisms at work: adhesion and deformation in the tire tread, as well as ice deformation by ploughing particles that broke loose.

The smoothness of the ice and the lack of other winter contaminations provided favourable test conditions for the comparison of the tracks. Hence the value of the results lies in the identification of interaction mechanisms that provided the braking action on smooth ice treated with the two sanding methods. However, the test conditions and aircraft size were not representative for operational conditions. Care should therefore be taken with interpreting the results in an absolute manner.

6.5 Conclusion

Comparison of an aircraft braking on smooth ice treated with loose sand and freeze bonded sand showed that the interaction providing the tire-pavement friction differed. On loose sand, the braking action was provided mainly by ploughing sand particles into the ice surface. On freeze bonded sand, particles broke loose under the action of the tire, creating friction in a similar way. A part of the sand remained bonded to the ice and provided braking action in a way similar to road asperities: by rubber-sand adhesion and deformations within the tire tread.

7 CASE STUDY: PILOT COMMENTS ON REPORTED BRAKING ACTION

7.1 Introduction

Airports have a system in place that collects information regarding surface conditions and disseminates it to relevant stakeholders (Air Traffic Control, aircraft operators, and pilots). The information consists of visually collected information (type, depth, and coverage of snow, ice, and slush contamination) and friction measurements. The objective of this system is to provide the relevant stakeholders with the necessary information to make decisions such as whether conditions are within the envelope to operate the aircraft (go / no go decision) and the initiation of maintenance activities.

It is a known problem that pilots do not always experience braking action as predicted by friction measurements. On runway surfaces treated with freeze bonded sand, such discrepancies have been reported (Klein-Paste and Sinha, 2006). Clearly, this discrepancy is a potential threat for safe aircraft operation. Besides this important safety aspect, there is a simple business issue involved. Airline companies are the airport's customers, and pilots are the airline's representatives. Pilots who state that they experienced a lower braking action than reported are, in fact, dissatisfied customers of the airport. Such comments are subjective, leaving room for discussion as to whether the runway was indeed slipperier than reported. But regardless of this discussion, the comment was an expression of a displeased customer and is taken serious by the airport operator.

Svalbard Airport and Kirkenes Airport use warm, pre-wetted sanding on a regular basis during wintertime. As reported in Section 3, maintenance personnel are satisfied with this new sanding method, but along with the positive indications of this method, pilot comments on the braking action have been received. These comments raise questions such as: “Were the conditions overestimated by the friction measurements?”, “What are probable causes of the discrepancy?”, and “What can be done to avoid such comments?”

During the winter 2005-2006, the comments were investigated by collecting all relevant information regarding the airport operation at the time of the comment. It was hoped that such data compilation could contribute to answering the above posed questions. All data was made available by Svalbard and Kirkenes Airports on a voluntary basis. The presented data is compiled from the internal documentation, including logbooks, runway status reports, confirmed departure/arrival times, meteorological data, and undesirable event reports. The comments were treated anonymously; hence no pilot-specific information was collected.

7.2 Factual data

Between November 1, 2005, and March 31, 2006, 12 comments were received, 6 at Kirkenes Airport, and 6 at Svalbard Airport. The comments are numbered from 1 to 12. Comments 7, 8, and 9 occurred on the same date at the same airport, within 1.5 hours of each other.

7.2.1 Pilot comments

Table 3 lists the phrases used by the pilots to comment on the braking action. On 10 occasions, the pilot initiated the comment. On two occasions, the pilot was asked to comment on the braking action. General information regarding the aircraft size (large/medium/small) aircraft type (jet/propeller), customer type (established/new) and airport usage (frequent/rarely/incidental) is given in Table 4.

Table 3. Pilot comments.

Nr	Pilot comment	Initiated by:
1	The braking action was much lower than reported	Pilot
2	Possibly a bit slippery because part of the sand was blown by previous take-off	Tower
3	It is very slippery on the runway	Pilot
4	It was slippery	Pilot
5	It was slippery	Pilot
6	It was slippery	Pilot
7	It is very slippery; BA below 30 on RWY and poor on apron	Pilot
8	It is slippery, max BA 30, but probably closer to 25 (Poor)	Pilot
9	Estimated Braking Action around 30	Tower
10	Estimated Braking Action around 20 (Poor)	Pilot
11	It feels slippery	Pilot
12	It was horribly slippery on the runway	Pilot

Table 4. Airline company characteristics.

Nr	Aircraft size[1]	Aircraft type	Customer type[2]	Airport usage[3]
1	Large	Jet	Established	Frequent
2	Large	Jet	Established	Frequent
3	Large	Jet	Established	Frequent
4	Large	Jet	Established	Frequent
5	Large	Jet	Established	Frequent
6	Medium	Prop	Established	Frequent
7	Large	Jet	Established	Frequent
8	Large	Jet	Established	Frequent
9	Small	Prop	Established	Frequent
10	Large	Jet	Established	Frequent
11	Large	Jet	Established	Frequent
12	Large	Jet	Established	Frequent

[1] Classification aircraft size: large: >50 seats, medium: 15-50 seats, small: < 15 seats.
[2] Definition customer type: Established: airline companies using the airport at least 5 winter seasons. New: airline companies using the airport for less than 5 winter seasons.
[3] Classification airport usage: frequent: > 5 scheduled flights/week, rarely: < 5 scheduled flight/week, occasionally: not on a scheduled basis.

7.2.2 Runway status reports

The runway status reports that were valid at the time of the comments are presented in Table 5. The age is the time between when the information was collected (time stamp) and the time of the comment. The reported braking action is given in three numbers, each describing one third of the runway. These numbers represent the average measured friction coefficient, measured with a friction measurement device, multiplied by 100.

The ICAO specification is an interpretation of the friction measurements in terms of good, medium to good, medium, medium to poor, and poor (ICAO, 2003).

Table 5. Runway status reports.

Nr	Age (H:MM)	Reported braking action	ICAO specification	Description
1	0:00	47 / 46 / 46	Good / Good / Good	<3 mm dry snow on ice
2	1:20	54 / 68 / 81	Good / Good / Good	Ice with sand
3	0:32	37 / 39 / 39	Med-good / Med-good / Med-good	Ice, 100%
4	0:18	46 / 45 / 45	Good / Good / Good	Rime, ice, 100% coverage
5	2:01	59 / 56 / 51	Good / Good / Good	Ice and sand
6	1:15	61 / 55 / 60	Good / Good / Good	100% ice with sand on top
7	0:38	39 / 40 / 39	Med-good / Good / Med-good	Sanded ice
8	0:18	45 / 45 / 43	Good / Good / Good	Sanded ice
9	0:42	45 / 45 / 43	Good / Good / Good	Sanded ice
10	0:51	38 / 41 / 44[4]	Med-good / Good / Good	Sanded ice
11	0:27	32 / 33 / 39	Medium / Medium / Med-good	Sanded ice
12	0:33	50 / 47 / 48	Good / Good / Good	Sanded ice

Nr	Remarks
1	100% coverage, swept runway, freeze bonded sand
2	Ice, 50 % coverage in patches with sand, rime
3	100% coverage, runway is sanded with freeze bonded sand, variation in BA between 50 and 30
4	Freeze bonded sand, from earlier application
5	sand from earlier application
6	100% ice with sand on top
7	Freeze bonded sand (well bonded, checked by rubbing with shoe sole[5])
8	
9	
10	Sanded ice, some wet patches
11	
12	Ice with newly applied freeze bonded sand[6]

[4] The reported braking action (38 / 41 / 44) was measured 5 hours earlier, but the validity of this information was verified 51 min before the comment. The braking action measured during this last measurement was 46 / 42 / 38.

[5] This information was not included in the original report. It was additional information taken from the undesired event report.

[6] This information was not included in the original report.

7.2.3 Meteorology

A summary of the meteorological conditions at the time of the comments is given in Table 6. The table lists the air temperature T_a, dew point temperature T_d, wind speed V, wind direction D, precipitation type and the temperature trend in the last 12 hours prior to the comment. The meteorological conditions are summarized in 48 hour meteograms, presented in the appendix.

Table 6. Summary of meteorological conditions.

Nr	T_a	T_d	V	D	Precipitation	Temperature trend last 12 hours	
						Trend	Magnitude
	(°C)	(°C)	(m/s)	(°)			(°C)
1	0.0	-2.3	4.2	335	-	Increase	8
2	-5.1	-6.0	4.2	145	-	Decrease	3.5
3	-8.3	-9.1	3.2	130	Snow	Decrease	6
4	-15.4	-16.8	2.5	130	-	Decrease	8
5	3.0	0.6	5.7	240	-	Increase	6
6	-16.8	-20.5	15.4	165	-	Increase	8
7	2.8	0.0	2.8	235	Rain/snow	Increase	2
8	0.9	0.0	4.8	245	Rain/snow	Increase	2
9	0.9	0.0	4.8	245	Rain/snow	Increase	2
10	1.9	-3.9	5.8	185	-	Fluctuating	±1
11	5.8	-0.4	4.6	164	Rain before event	Increase	4
12	-7.8	-13.2	6.3	210	-	Fluctuating	±2

7.2.4 Traffic

Table 7 shows the number of aircraft that used the runway between the time stamp of the status report and the comment.

Table 7. Number of take-offs and landings prior to the comments.

Nr	Landings	Take-offs
1	0	0
2	4	1
3	2	0
4	1	1
5	2	0
6	2	1
7	0	0
8	0	0
9	0	1
10	0	0
11	0	0
12	0	0

7.2.5 Runway maintenance

The last runway maintenance operations that were performed within 24 hours prior to the comment are listed in Table 8. The start and finish times of the operations are given relative to the time of the comment. They are either presented either exactly, in HH:MM before comment, or estimated in hours before comment. It was not always possible to determine the time of these operations.

Table 8. Runway maintenance operations in past 24 hours.

Nr	Last maintenance action within 24 hours	Start	Finish
1	Sweeping	Unknown	unknown
2	No maintenance, sand from earlier application		
3	Sweeping and Sanding	Unknown	Unknown
4	Sweeping	Unknown	>12 h
5	Sweeping and Sanding	10:30	8:30
6	No maintenance, sand from earlier application		
7	Sanding with freeze bonded sand	2 h	0:40
8	Sanding with loose sand	0.5 h	0:17
9	Sanding with loose sand	1 h	0:45
10	No maintenance, sand from earlier application		
11	Continuous sweeping and dry sanding	3:35	0:00
12	Freeze bonded sanding prior to the event	1 h	0:00

7.2.6 Indications for insufficient retardation or directional control

Reported observations that could indicate insufficient retardation or directional control are listed in Table 9.

Table 9. Indication of insufficient retardation or directional control.

Nr	Indication
1	
2	At start of the take-off, the aircraft skidded towards right sideline. Take-off was aborted.
3	Aircraft used long time to turn around on the runway and taxi back (after landing)
4	
5	
6	Difficulty turning on runway
7	Skidded between taxiway and apron
8	Pilot reports skidding on locked wheels on runway
9	
10	Aircraft experienced difficulty turning on the runway. Skidding on runway while turning to taxiway
11	Difficulty turning on runway
12	Skid marks were observed at the end of the track, just before the 180° turn for track back.

The skid marks observed after comment 12 are shown in Figure 21.

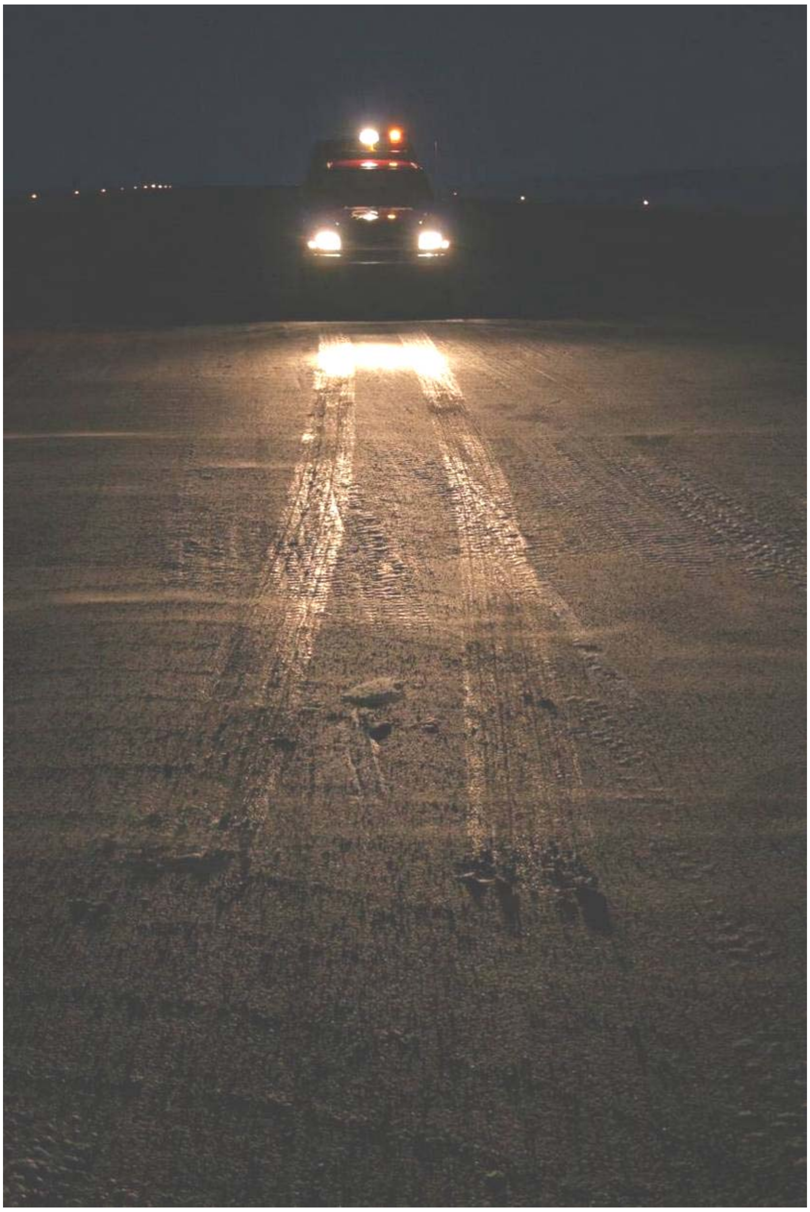


Figure 21. Skid marks observed after comment 12. The skid marks are located just before the point where the aircraft made a 180° turn on the runway. A pile-up of snow and sand can be seen at the end of the skid marks.

7.2.7 Measurement equipment

Control measurements and other observations directly after the comment are listed in Table 10.

Table 10. Control measurements and other observations after the comment.

Nr	Documented control measurements	Undocumented measurements and documented observations
1		Control measurements confirmed reported values[7]
2		"Not particularly slippery"; judgment maintenance manager
3		"It was slippery"; judgment maintenance manager
4	46 / 46 / 52	
5	51 / 48 / 50	
6	54 / 50 / 56	
7		Around 34-35[8]
8		
9		
10	39 /36 /38[9] 49 /41 49[10]	
11		From driving the ground vehicle it was noticed that the conditions were not good. The measured values were perceived as "surprisingly good".
12		

Maintenance personnel inspected the equipment at both airports for possible error sources, such as calibration offset, test tire wear, and changes in conspicuity of the equipment. No indications for errors were found that could be related to the comments. The devices remained in service and functioned normally.

However, at one of the airports, maintenance personnel indicated that sometimes test tires had become sticky. This observation could not be directly related to the comments, but given the nature of the observation, it was given further attention. An example of a sticky tire is shown in Figure 22. The airport sent a tire to the manufacturer and it was determined that the tire had been exposed to extreme heat and that a phenomenon called "reverted rubber" had occurred.[11]

[7] The measurements were performed, but not documented
[8] The measurements were performed, but not documented
[9] Measured in the track
[10] Measured outside the track
[11] Information based on correspondence between the airport manager and tire manufacturer.

Figure 22. A coin pressed against the sticky measurement tire stayed adhered while hanging upside down.

7.3 Discussion

Comments 7, 8, and 9 occurred on the same date at the same airport, within 1.5 hours of each other. Three comments describe approximately the same conditions and are therefore considered as one case. Comment 2, which was initiated by the tower, is not considered as a case because it was more of a reply than a complaint, and the comment “probably a bit slippery” and the judgment of the maintenance manager “not particularly slippery” gives insufficient support to treat this comment on an equal basis with the other comments. This left 9 independent cases, which are defined in Table 11.

Table 11. Definition of the cases.

Case	Comment(s)
A	1
B	3
C	4
D	5
E	6
F	7, 8, and 9
G	10
H	11
I	12

The first similarity is that in all cases the reported braking action values were high. Except for case H (comment 11), the values are close to, or above 40 (friction coefficient, μ = 0.4), which is interpreted as “medium to good” or “good”, according to ICAO specifications (ICAO, 2003). These numbers do not suggest the need for any further maintenance actions. Comment 11 would be interpreted as “medium” and “medium to good”. These high values create the expectation that sufficient retardation and directional control can be achieved. This expectation is the first clue as to why the comments occurred. Pilots and maintenance personnel did not expect slippery conditions because the measurements described the surface as “good” or “medium to good”. This can be directly related to the warm, pre-wetted sanding method. One of the main benefits of the sanding method, indicated by maintenance personnel, is the higher friction levels that are achieved. As Eriksen pointed out in Section 3.2.2: “It has become easy to get high friction numbers”. But these high numbers create high expectations among pilots. When then the runway is not able to live up to this high expectation, the pilot will complain. A second aspect of these high numbers is that they can inhibit the evaluation of other factors that may suggest that the surface conditions are not that good.

Were the surface conditions indeed worse than reported? Aircraft that are currently in use are not designed to measure actual experienced tire-pavement friction. Hence the experience of the pilot is a subjective indication. Pilots who are not familiar with winter conditions may describe surface conditions as being slipperier than do pilots with extensive experience on winter contaminated runways. All comments were received from pilots working at established airline companies, operating frequently at these airports. Although possible, this does not indicate that the pilots were unfamiliar with operation on winter contaminated runways, or with the local situation at the particular airports.

In 66 percent of the cases, signs of reduced directional control were reported. These mainly included skidding with locked wheels at low ground speed, and difficulty turning the aircraft on the runway. Indications of insufficient retardation were not observed. All manifestations occurred at a very low ground speed, usually during taxiing and turning on the runway. In none of these cases there was a very strong wind. With a reported braking action of “good” or “medium to good”, these signs are not expected to occur. Therefore, in 66 percent of the cases there were clear indications that the conditions were worse than reported.

Runway maintenance personnel could not identify sources of errors in the measurement equipment that could be related to the comments. The equipment remained in service and continued to function normally. The observation from one of the airports that test tires sometimes become sticky is suspicious. It is a clear indication of changed rubber properties and can thereby affect the result of the friction measurements. However, it should be emphasized that comments could not be brought into direct connection with the sticky test tires (comments were received when the tire was not sticky). At the other airport, sticky tires were not observed. In 66 percent of the cases, control measurements were performed. All these measurements continued to predict “good” or “medium to good” conditions. These measurements disprove the explanation that changes in the conditions after the status report were the primary cause of the comment. In the remaining 33 percent of the cases it is possible that the conditions had changed after the measurements were taken.

The lack of indications for malfunctioning measuring equipment, the observed signs of reduced directional control, and the performed control measurements suggest that differences in response between the measurement equipment and operating aircraft (the correlation issue) was the primary cause of discrepancy between reported and experienced conditions.

The fact that different systems interact differently on snow and ice contaminated surfaces has been recognized for a long time, and extensive research has been conducted into correlating different systems with each other (Andrássy, 1999; Anon., 2004). Predicting aircraft performance on winter contaminated runways has been an issue for over 50 years and has resulted in numerous types of friction measurement devices (Norheim, 2004). Each device and each aircraft is a system, with its own device-dependent characteristics (Norheim et al., 2001; Sinha and Norheim, 2000). One of the airport managers expressed the wish for a new friction measurement device: a Boeing 737. This illustrates the desire to have measurement equipment that responds similarly on all surface conditions as the systems used by the airline companies. Practical difficulties preclude such a solution and compromises are made, causing the differences in system characteristics. Efforts to correlate different systems showed that it is not easy to solve the problem (Boccanfuso, 2004).

The main question for the airport managers is, “What can be done to prevent this discrepancy?” At first sight, the difference in response between measurement equipment and aircraft would suggest focusing on improving the measurement equipment. If such an approach is considered, attention should be paid to lessons learned in the Joint Winter Runway Friction Measurement Program (Boccanfuso, 2004). Avinor has initiated an effort to explore alternative approaches to the problem. The data collected in the present case study could be helpful in the preliminary stages of this exploration.

The cases are situations where friction measurements described the surface conditions as “good” or “medium to good”, while the pilot described the conditions as worse. Based on the measurements, the slippery conditions were unexpected. But from a runway maintenance point of view, were the slippery conditions really unexpected? Or had there been indications that suggested that the situation at the airport was not as good as predicted? Did the information that was available at the airport prior to the comment contain clues that slippery conditions were likely to be expected?

During wintertime, there are periods where runway maintenance personnel have good control of the runway surface conditions. Although maintenance activities may be required, maintenance managers would describe such situations as “easy”. But there are also periods that would be described as “difficult”. The ease or difficulty of a particular situation is subjective and depends on many factors such as weather, traffic, experience, available manpower and equipment. But despite all these factors, there appears to be little debate among maintenance personnel that prolonged, cold, dry periods are easier to handle than conditions in which the air temperature fluctuates around 0°C, where rain or other wet precipitation deposits on a cold runway, or when they try to keep the airport operational during heavy snowfall. Hence, it may be generally derived that the difficult situations are those situations where maintenance tools are less effective and/or where the surface conditions are unstable. In this respect, unstable runway conditions are understood as conditions where the properties of the contamination change rapidly or where mass transport from, to, and within the area occurs at high rates. A list of such situations, which have been described by maintenance personnel, is given in Table 12. Note that the list not intended to be complete or mutually exclusive.

Table 12. Examples of difficult situations.

Type of difficult situation
Wet precipitation (wet snow, slush, or rain) on a cold runway
Super-cooled rain
Ice deposition (dew point higher than the runway surface temperature)
Melting ice
Freezing of a wet runway
Heavy snowfall
Loose sand displacement by engine thrust

Not all situations listed in Table 12 could be identified from the available data. A missing key parameter is a continuously measured pavement (sub-) surface temperature. Without the pavement temperature measurements, the pavement temperature can be indicated relative (colder/warmer) to the air temperature. A colder air temperature history indicates that, at the time of the comment, the pavement was colder than the air temperature. The indications that suggest difficult situations based on the available data are given in Table 13.

Table 13. Available indications for difficult situations.

Type of difficult situation	Indication
Wet precipitation on a cold runway	Reported precipitation + colder air temp history
Super-cooled rain	
Ice deposition	Rapidly increasing dew point + colder air temp history
Melting ice	Air temperature prolonged above 0°C
Freezing of a wet runway	Wet runway + decreasing air temperature
Heavy snowfall	Directly reported
Loose sand displacement	Loose sand on ice + air traffic prior to comment

The available data was used to identify indications for difficult situations. The indications that were found are listed in Table 14.

Table 14. Indications for difficult situations.

Case	Indication
A	T_a = 0°C, dew point increase of 8°C within 12 hours, colder air temperature history
B	
C	
D	T_a = 3°C, dew point increase of 6°C within 12 hours, colder air temperature history
E	T_a = -16.8°C, dew point increase of 8°C within 12 hours, colder air temperature history
F	0.9< T_a <2.8°C, rain/wet snow, possibly melting ice
G	Melting ice, T_a>0°C for 60 hours
H	Melting ice, T_a= 5.8°C, Rain
I	

The indications that are shown in Table 14 exhibit two distinct characteristics. The first characteristic is the wetness of the surface conditions. Cases F, G, and H are typical examples of “0°C conditions” (referring to the air temperature), where the contamination is wetted due to melting or precipitation. Although the air temperature in case A and C also reached or exceeded 0°C, it is not certain whether surface melting indeed had started. The reason is the colder temperature history and lack of precipitation.

The second characteristic is the significant increase in dew point prior to the comment. The lack of an accurate pavement temperature estimate makes it difficult to determine whether and when ice deposition started to occur; however, the rapidly increased dew point and the colder temperature history make it likely that ice deposition (rime) from the humid air above the pavement did indeed occur.

Both the presence of a liquid water phase and the conditions for ice deposition have been related to previous incidents and accidents (HSLB, 2004; HSL, 2001b; HSL, 2001a; HSL, 2000b; HSL, 2000a). A significantly reduced friction level in these situations can also be explained from a tribological point of view. When a macroscopic water phase is present on the runway it will act as a lubricant. Without snow and ice, the runway texture will prevent a too dramatic drop in friction because water is squeezed out of the contact area, allowing the rubber to drape around surface asperities (Moore, 1975). But it is very likely that melting ice contains very little roughness on a microscopic scale. Hence the presence of water, in combination with ice, is expected to give very low friction. The conditions can of course be improved by sanding. At the melting point, warm, pre-wetted sanding will not produce bonded sand. But if the sand is applied before the melting starts, it will be bonded. During melting, the “glue” that binds the sand particles melts as well. Hence particles can break loose more easily or become loose solely by melting. Therefore, despite efforts to improve the surface conditions by sanding (either loose, or freeze bonded before the melting started) there are still few possibilities to create friction. Describing such a surface as “good” or “medium to good” seems, from a tribological point of view, unjustified. When ice deposits on the runway, it covers the surface, including the sand, with a thin layer. Hence it quickly reduces the ability to generate deformation in the rubber tread or adhesion. This is another situation that cannot be described as “good” or “medium to good”, irrespective of any friction measurement device. To summarize, the available information gave strong indications to suspect slippery conditions in 66 percent of the cases. These indications were not taken into consideration when describing the surface conditions, or by developing the correct situation awareness among pilots.

In the remaining 33 percent of the cases were no clear indications available that the surface conditions were not good. The air temperature in case B (comment 3) was -8°C and decreasing while it snowed lightly. There was little wind (3 m/s) and the age of the report was about 0.5 hours. It has been reported that dry snow on ice can give slippery conditions at low temperatures (SAS, 1972), but since the ice was treated with freeze bonded sand, this does not give a satisfactorily explanation. Although the conditions could have changed within this half hour, from a maintenance point of view, the situation appears not to be particularly difficult.

In case C (comment 4) the air temperature and dew point were -15°C and -17°C, respectively, and both decreasing. The pavement temperature was therefore warmer, which does not suggest ice deposition. In case I (comment 12), the air temperature fluctuated around -8°C while the dew point was -13°C. The runway was newly sanded with freeze bonded sand and there was no precipitation. These situations are cold conditions where ice deposition is not likely to occur. Hence from a maintenance perspective, these situations would be described as easy.

To summarize, the data that was available at the airport at the time of the comments suggest that in six of the nine cases, the situation at the airport gave strong indications to expect slippery conditions. In one case there was no clear indication, but the conditions could have changed due to snowfall. In two cases, the situation may have been described as “easy” for maintenance personnel and did not suggest particularly slippery conditions.

7.4 Conclusions

The difference in response between the measurement equipment and the aircraft appeared to be the primary factor for the comments.

The common element in the comments was that the reported braking action was high. It created the expectation that sufficient retardation and directional control could be obtained. This may have been the direct result of the warm, pre-wetted sanding method because it generally results in higher friction levels. High friction levels are generally considered as desirable, but may lead to an unwanted effect in that they create too high expectations among pilots.

In 66 percent of the cases there were indications that the conditions were worse than reported by the friction measurements. These all occurred at very low ground speed and were manifestations of reduced or lost directional control.

An evaluation of the situation at the airport showed that in 66 percent of the cases the situation was, from a maintenance perspective, difficult to handle.

These conditions involved either ice close to 0°C that was wetted by melting or precipitation, or conditions where ice deposition from humid air above the pavement was likely to occur.

8 GENERAL DISCUSSION

The aim of this study was to improve general knowledge about the warm, pre-wetted sanding method for airside and road applications. A diversity of aspects was addressed, such as the performance of the method in practice, how and why it works, optimization, possible negative effects, and limitations.

The airports that were visited (Svalbard Airport, Kirkenes Airport and Bardufoss Air Force base) operate in a climate that has prolonged periods where the temperatures are below 0°C. These airports have used the warm, pre-wetted sanding method for at least two winter seasons. They are therefore past the initial implementation stage of getting used to the new method, exploring its possibilities, and implementing it within the total set of maintenance procedures. Maintenance personnel were very positive toward the method. They indicated that it is a very useful tool for them. The obtained friction levels are higher and the result lasts longer. The method also provides a solution to the problem of sand being displaced by wind or engine thrust (FAA, 1991; Comfort and Gong, 1999; Klein-Paste and Sinha, 2006). Hence, the warm, pre-wetted sanding method appears to have major operational advantages.

At first sight, there appears a banality in the question of how and why the method works. Ice is generally known to be slippery. To reduce the slipperiness, sand is applied. If water is added to the sand, it freezes to the surface. It reduces slipperiness further (creating a sandpaper-like finish) and the result lasts longer. But a more sophisticated explanation is desirable when addressing questions such as: “How can the method be optimized?”, “How do sanded surfaces behave during weather changes?”, and “How can friction measurements be interpreted in relation to aircraft performance?” For these types of questions it is necessary to evaluate how the warm, pre-wetted sanding changes the surface conditions and how friction is provided by it.

The addition of water creates a matrix of sand and ice. Specifically, the fine sand fraction becomes strongly bonded to, and embedded in, the ice. This gives a “sandpaper-like” result. Over time, however, it can be observed that the sand loosens because ice sublimates. Hence, the number of loose particles increases during prolonged cold periods without sweeping activities. They can be noticed while driving on the treated surface by the sound of the particles hitting the wheel housing.

The aircraft braking experiment, together with earlier observations on an operational runway (Klein-Paste and Sinha, 2006), showed that the tire-pavement interaction on warm, pre-wetted sand comprises both loose and fixed sand interaction. A part of the sand is sufficiently bonded to remain attached to the ice. These sand particles act in a similar way as road asperities. The rubber tire tread can drape around these asperities and provide friction by rubber deformation (hysteresis and tire wear) and possibly adhesion between the rubber and the sand. Particles that were initially loose or broke loose during the interaction contribute to the friction by ploughing (deforming) the ice surface. This was observed both on a macroscopic and microscopic scale in the aircraft braking experiment.

Optimization of sanding methods is typically performed by using friction measurements. However, not only do airport operators need surface conditions with a high friction level, they also need robust surface conditions. The following analogy clarifies the difference between friction and robustness. A bare and dry runway provides good friction to aircraft. Pilots can brake firmly and obtain good directional control on dry runways. When the dew point becomes higher than the pavement temperature, ice can deposit on the surface, causing a rapid reduction in the ability to provide friction. Before ice has actually deposited, but with the conditions for ice deposition present, a bare and dry runway is no longer a good runway (but it will still result in high friction numbers). Something has to be done to prevent the surface from rapidly losing its ability to provide friction; for example, applying anti-icing agents. At the time of application, it does not improve the attainable friction, but it improves the robustness. It improves the ability to maintain acceptable frictional properties under conditions that otherwise result in very slippery runways. How robust the surface is depends on the amount and type of chemicals that are present. A similar consideration of robustness may be given to freeze bonded sanded surfaces. Even if loose sand were to give a friction level increase similar to bonded sand, it is preferable to have bonded sand because it is more robust against air traffic.

The robustness does not determine how well the surface supports air traffic, but it does determine how well maintenance personnel have control over the surface conditions. It is important to consider that maintenance personnel cannot always be on the runway to check the conditions, or immediately conduct maintenance operations when needed. They have to trust that the surface conditions hold the ability to provide friction until they can inspect the surface again. The robustness of a surface is therefore at least as important as the level of friction it can provide.

The consideration of robustness may be useful in further developments of the method, such as optimization. An example is given in the observations of warm, pre-wetted sand on compacted snow. If the penetration of water and sand into the snow layer can be controlled, more robust results are expected.

An important aspect of any sand application at airports is the risk of Foreign Object Damage (FOD). The fact that the sand becomes bonded to the surface with warm, pre-wetted sanding is beneficial to reduce FOD risks. In addition, the total amount of applied sand is reduced by the method, which is also beneficial. However, these benefits do not imply that the risk of FOD can be neglected when using the warm, pre-wetted sanding method. The experience from Bardufoss Air Force base demonstrated that lumps may break loose in one piece if the underlying snow is not sufficiently strong. This shows a limitation of the method for airside applications. Warm, pre-wetted sand can only be applied on surfaces that are properly cleaned before application, such that firm bonding with the surface is obtained.

Probably the least known aspect of the warm, pre-wetted sanding method is the question of how to interpret readings from friction measurements on freeze bonded sand, with respect to aircraft performance. As pointed out by one of the airport managers in Section 3.2.1: “I am still wondering if the method is as good as the friction measurements tell us.” The fact that 12 pilot comments were received at two airports during one winter season illustrates that this is a real concern. In the case study, it was concluded that differences in response between friction measurement and aircraft indeed appear to be a primary cause of the comments.

The high measured friction coefficients that are typically obtained on freeze bonded sand are generally interpreted as indicating a good performance. It is one of the reasons maintenance personnel are so positive toward the method. There are, however, negative effects related to these high numbers. High friction values create high expectations among pilots. It gives the impression that the runway surface conditions are good (in some cases, even very good). Hence pilots expect to obtain sufficient retardation and directional control. However, it is easy to become disappointed when expectations are high. From a maintenance perspective, it is more difficult to satisfy high expectations. The discrepancy between experienced and reported conditions can increase because of the high friction values measured on warm, pre-wetted sand. There is also another negative effect related to high friction values. They can easily inhibit the evaluation of other parameters that suggest that the conditions are not that good. In the case study there were clear indications that the surface conditions were not that good in 66 percent of the cases.

As mentioned at the beginning of this section, the sanding method has now been in use for at least two winter seasons at the visited airports. Given the number of aircraft movements that have taken place (5 to 20 per day at these airports), the 12 comments in the case study are rare events. This supports the idea that slippery conditions occur mainly in distinct situations, caused by an unfavourable combination of surface conditions, weather, and traffic. Focus may therefore be directed to monitoring the whole situation and trying to identify these distinct situations, irrespective of the readings from friction measurement devices. A first step was made in the case study where all available information at the airports was considered. This information, combined with practical experience and tribological understanding, showed clear indications that the surface conditions were worse than the created expectation in 66 percent of the cases.

9 GENERAL CONCLUSIONS

Maintenance personnel who use the warm, pre-wetted sanding method expressed a positive attitude toward the method. The main benefits for them are the durability and the greater increase in friction level, compared to traditional sanding. Surfaces can be swept without the need for new sanding operation. The method also provides a solution for the problem of sand being displaced by wind or engine thrust of operating aircraft.

Surfaces should be properly cleaned prior to the application. Application on thick, weakly bonded snow is to be avoided because lumps may break loose in one piece, creating a hazard for foreign object damage.

Adding water to the sand changes the interaction between tire, sand, and contaminated pavement. Hence, it changes the way friction is provided to the aircraft. On warm, pre-wetted sanded surfaces, tire-pavement friction comprises both loose and fixed sand interaction. The part of the sand that remains bonded during the interaction acts in a similar way to road asperities. Particles that are initially loose (e.g., due to ice sublimation) or that break loose during the interaction provide friction by ploughing (deforming) the ice surface.

Warm, pre-wetted sanding can improve the robustness of the surface conditions, compared to traditional loose sanding. The robustness of surface conditions is an important property for operational surface conditions.

The higher friction levels that are typically obtained with the new sanding method do have negative effects. The high reported friction values create high expectations among pilots, regarding retardation and directional control; however, they can also inhibit the evaluation of other parameters that suggest that the conditions are not that good. The case study showed that the created expectations could not always be met.

The evaluation of all available data at the airports showed that there were clear indications that the situation was worse than the expectations created by the friction measurements in 66 percent of the cases. These conditions involved either ice close to 0°C that was wetted by melt water or precipitation, or conditions where ice deposition from the atmosphere onto the pavement was likely to occur. Such a holistic evaluation of all available information may be developed further as an alternative system to report runway surface conditions.

10 RECOMMENDATIONS

It is recommended that the risk of Foreign Object Damage be given attention in the education of runway maintenance personnel who use the warm, pre-wetted sanding method.

For research on, and development of, winter maintenance practices (e.g., equipment, procedures, guidelines) it is recommended that the robustness of the surface conditions be considered as a quality factor, in addition to the measured friction coefficient.

For the development of an alternative approach to the current surface conditions reporting system, it is recommended that criteria be systematically defined to identify situations where slippery conditions can be expected. These situations should be based on maintenance experiences and combined with meteorological and tribological knowledge of and insights into the mechanical behaviour of snow and ice. The criteria should be used to evaluate an entire winter season to investigate the frequency of difficult situations.

It is recommended that a study be conducted on the ways in which runway maintenance personnel could track the dew point of the air just above the pavement, in relation to the actual pavement surface temperature and how this information can be interpreted. Such a study should address the accuracy that can be achieved with modern measurement techniques under the restricted possibilities for measurements in movement areas.

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Appendix: Meteorological data of the cases

Explanation

A summary of the meteorological data is presented in a meteogram for each case (an example is given in Figure A-1). The meteogram covers a 48 hour period. The time of the comment is indicated by a vertical marker line. The air temperature and dew point was measured at the airport, at 2 m height. The precipitation intensity is given as light, modest or heavy. These data are taken from METAR observations conducted in the tower every 30 minutes.

The air temperature and dew point temperature are presented as continuous lines. The precipitation intensity is presented as vertical bars. The wind speed and direction are given as the 1-hour average and are presented by an integer (m/s) and arrow, respectively.

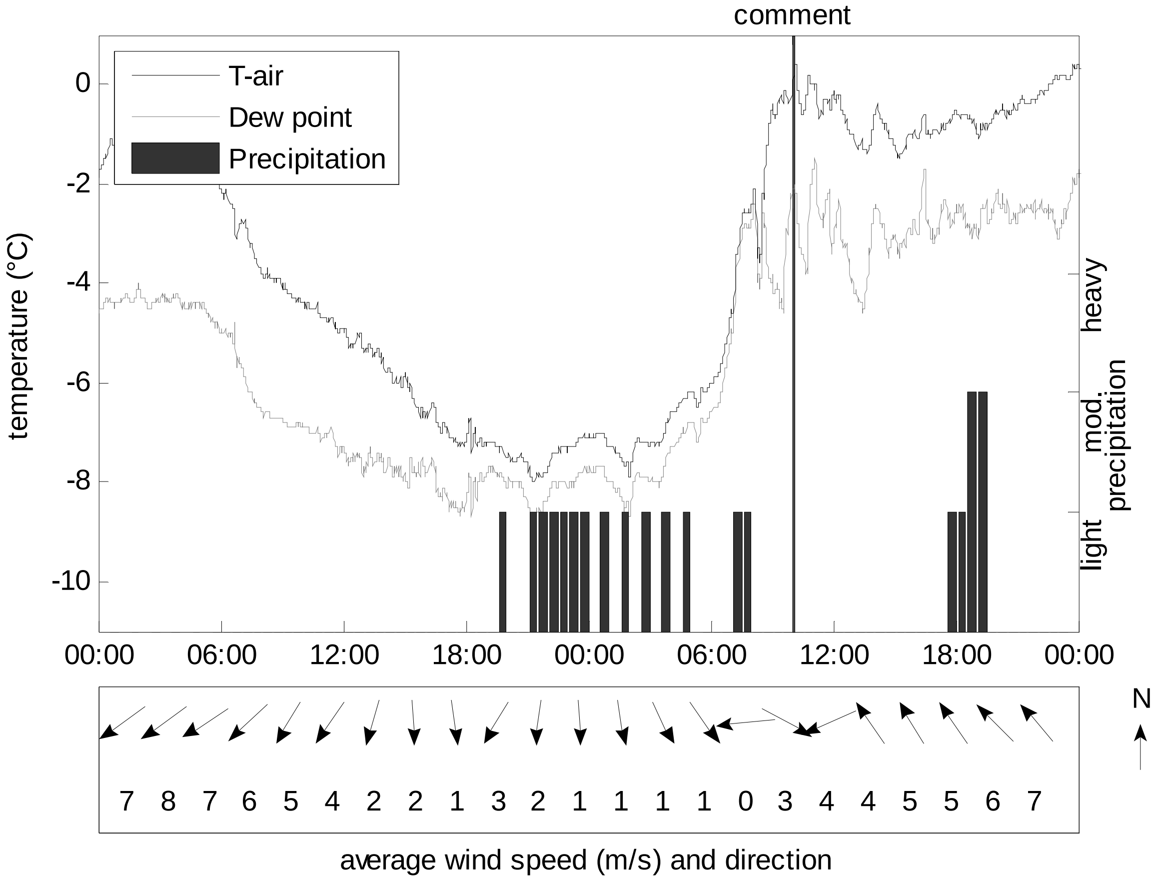

Figure A- 1. Sample meteogram

Meteogram Case A

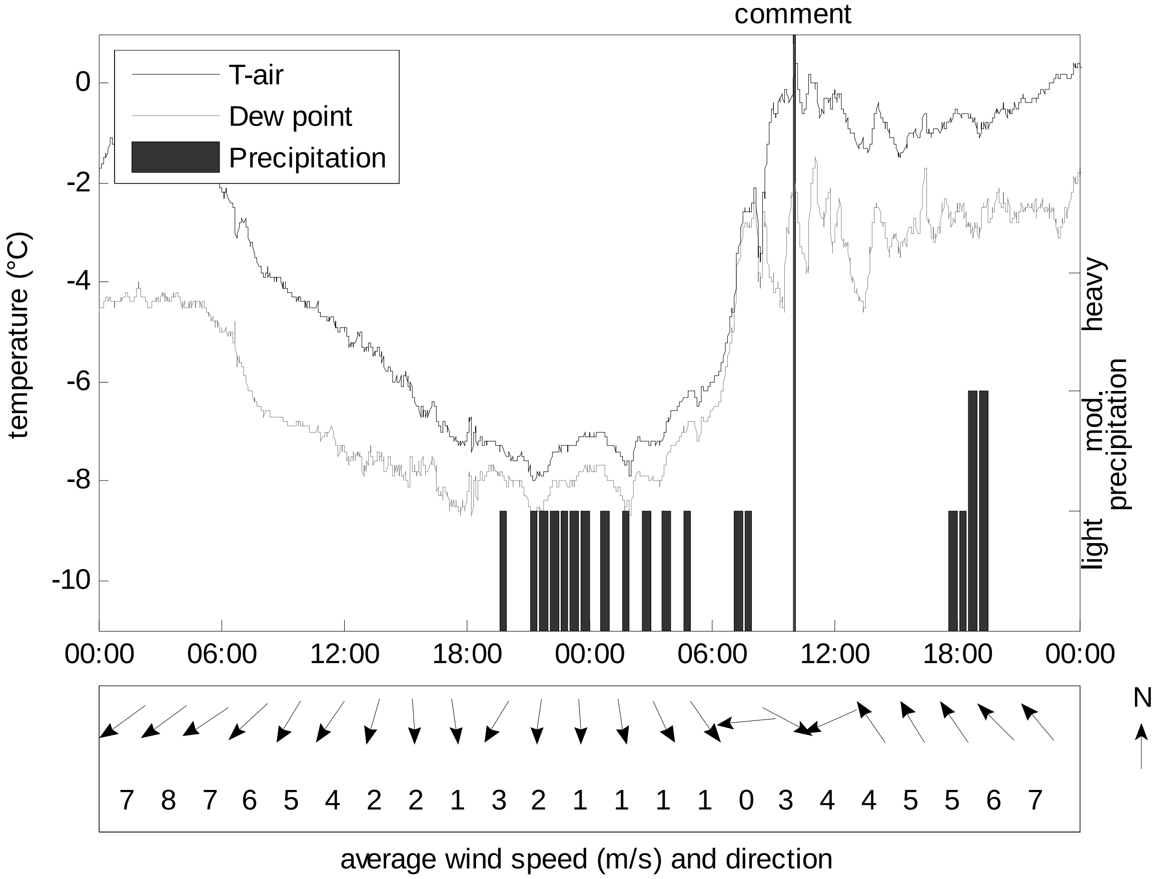

Figure A- 2. Meteogram Case A.

Meteogram Case B

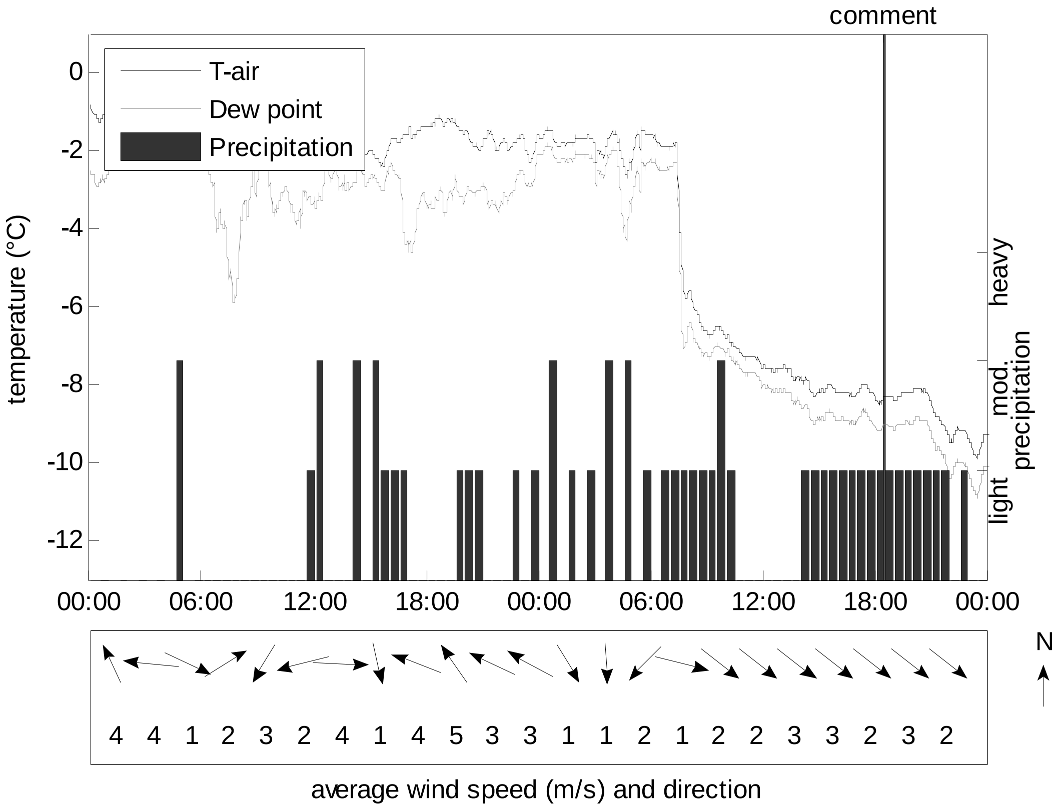

Figure A- 3. Meteogram Case B.

Meteogram Case C

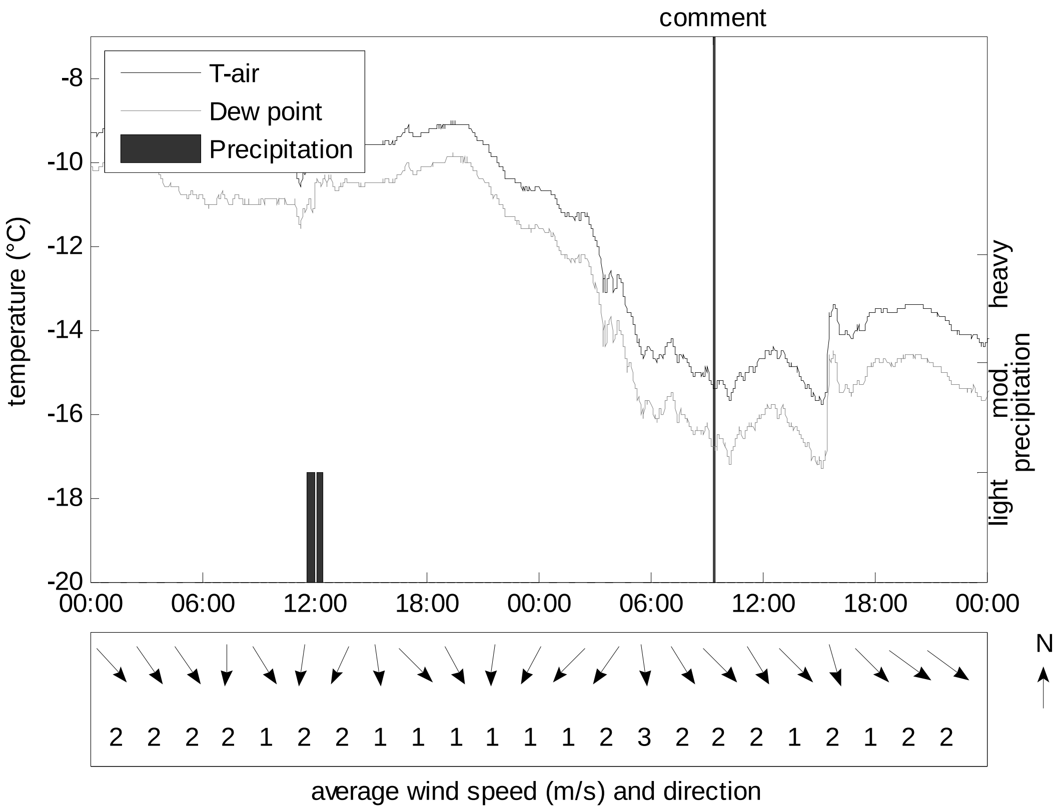

Figure A- 4. Meteogram Case C.

Meteogram Case D

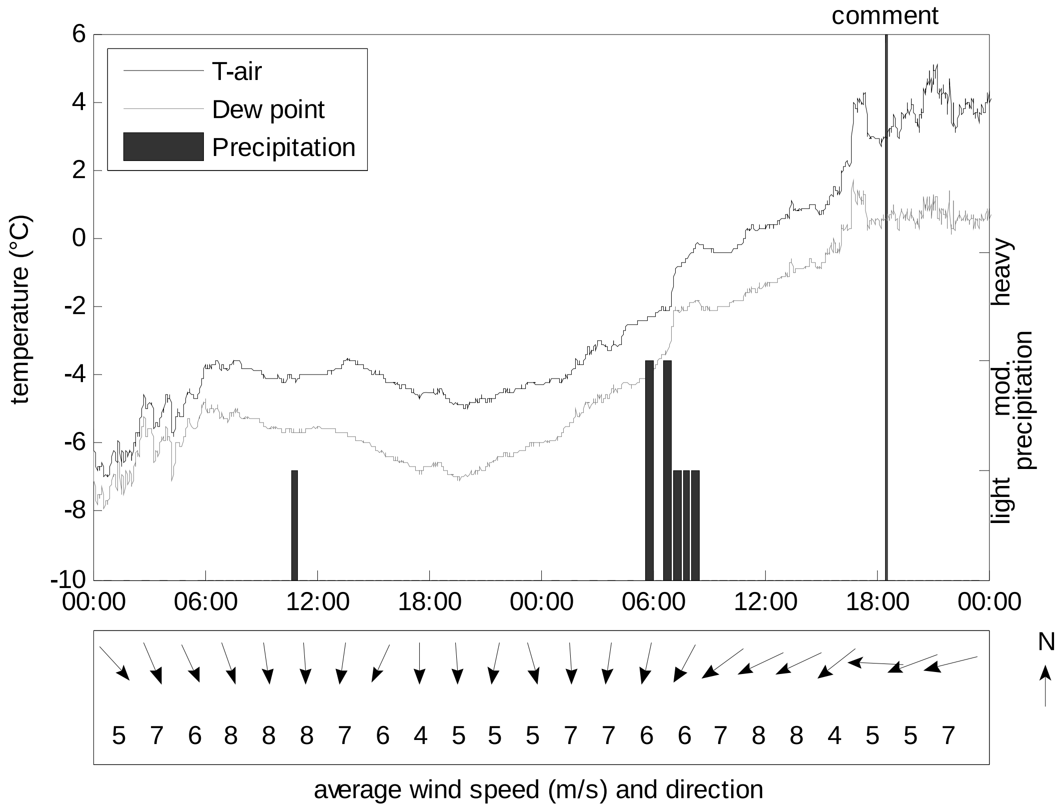

Figure A- 5. Meteogram Case D.

Meteogram Case E

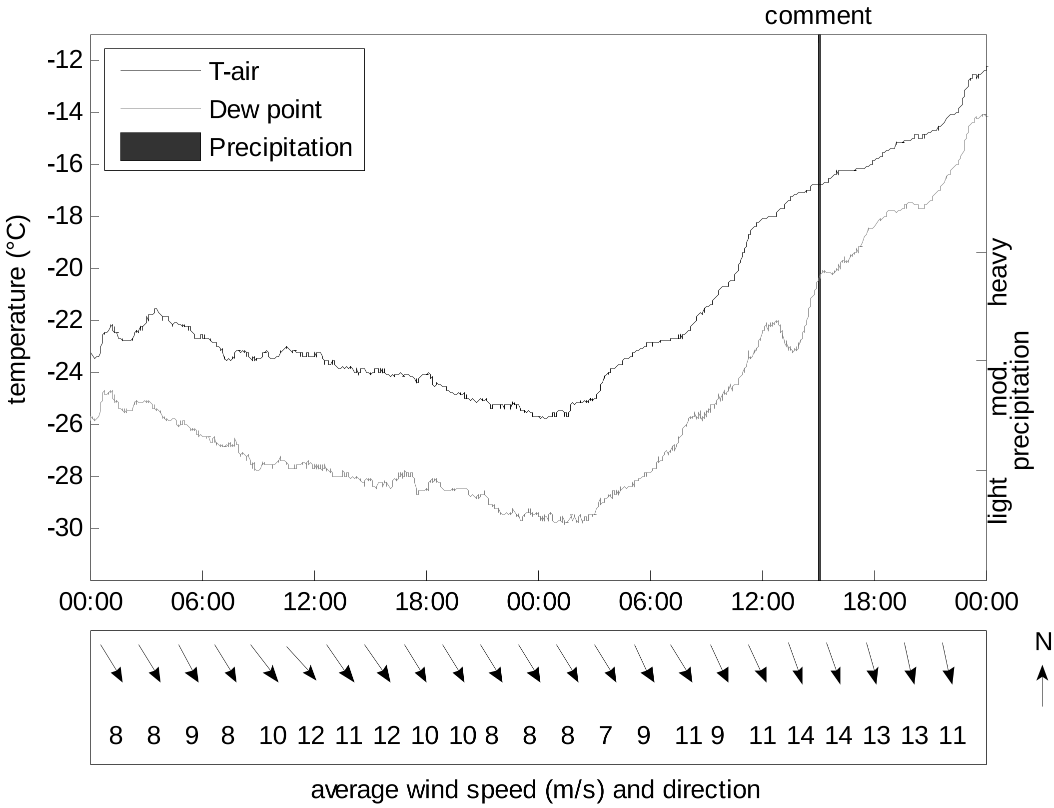

Figure A- 6. Meteogram Case E.

Meteogram Case F

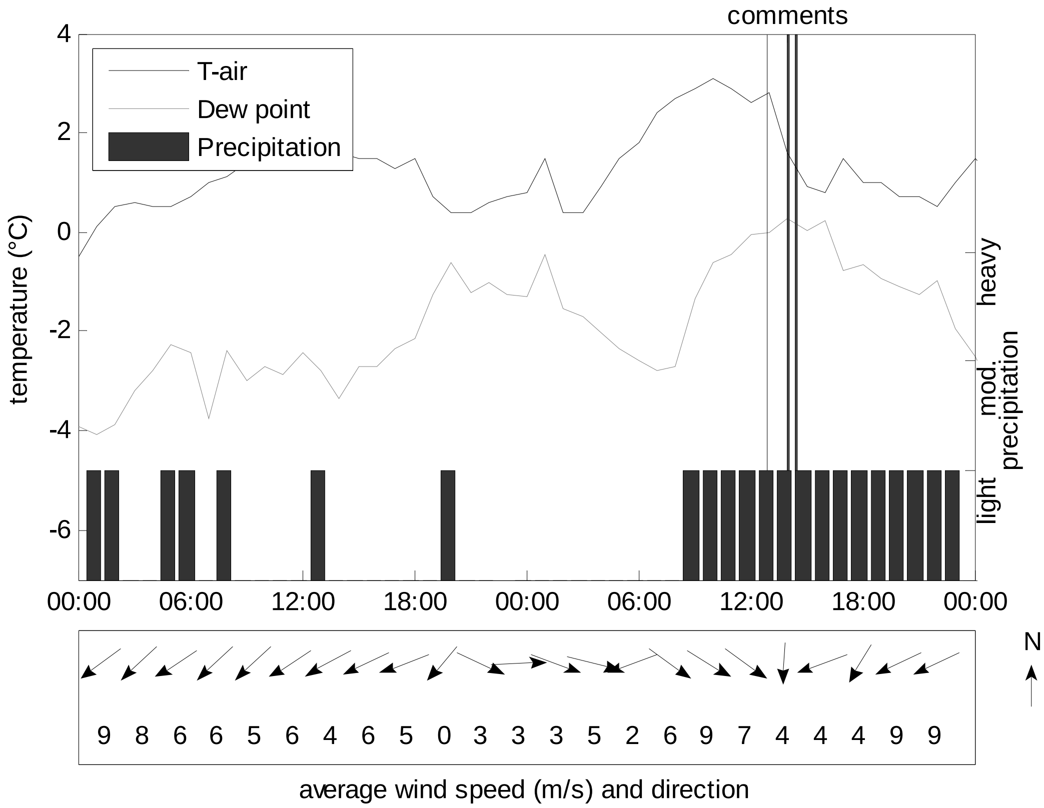

Figure A- 7. Meteogram Case F.

Meteogram Case G

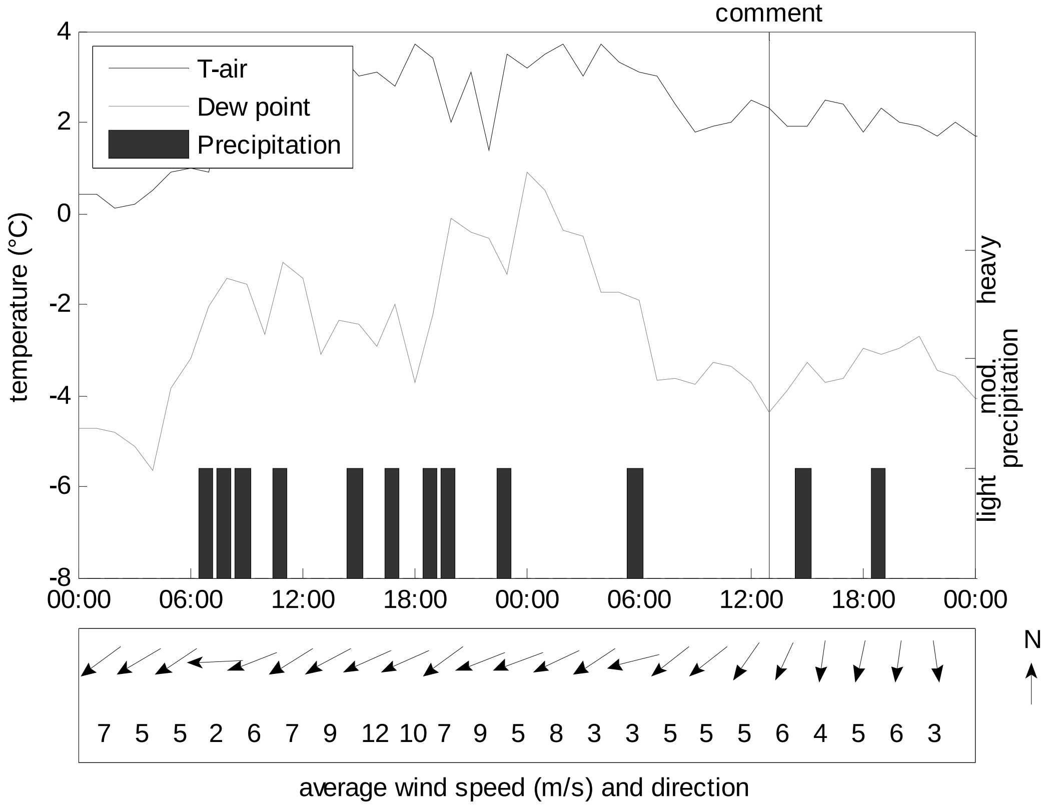

Figure A- 8. Meteogram Case G.

Meteogram Case H

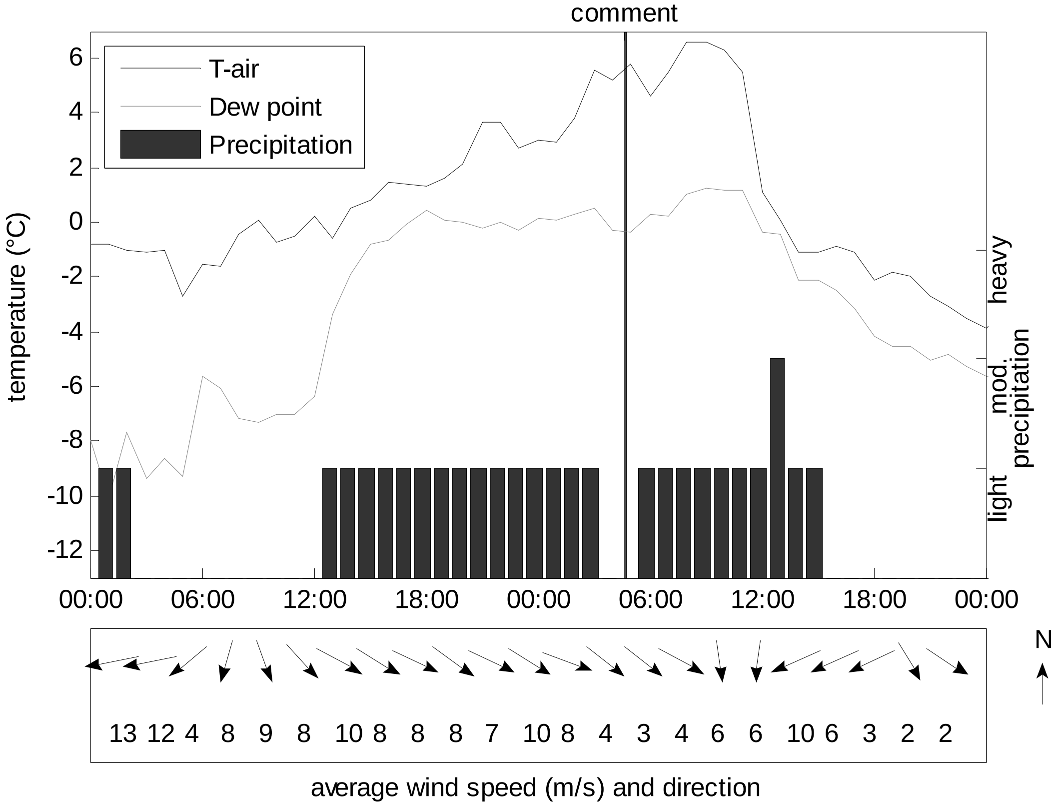

Figure A- 9. Meteogram Case H.

Meteogram Case I

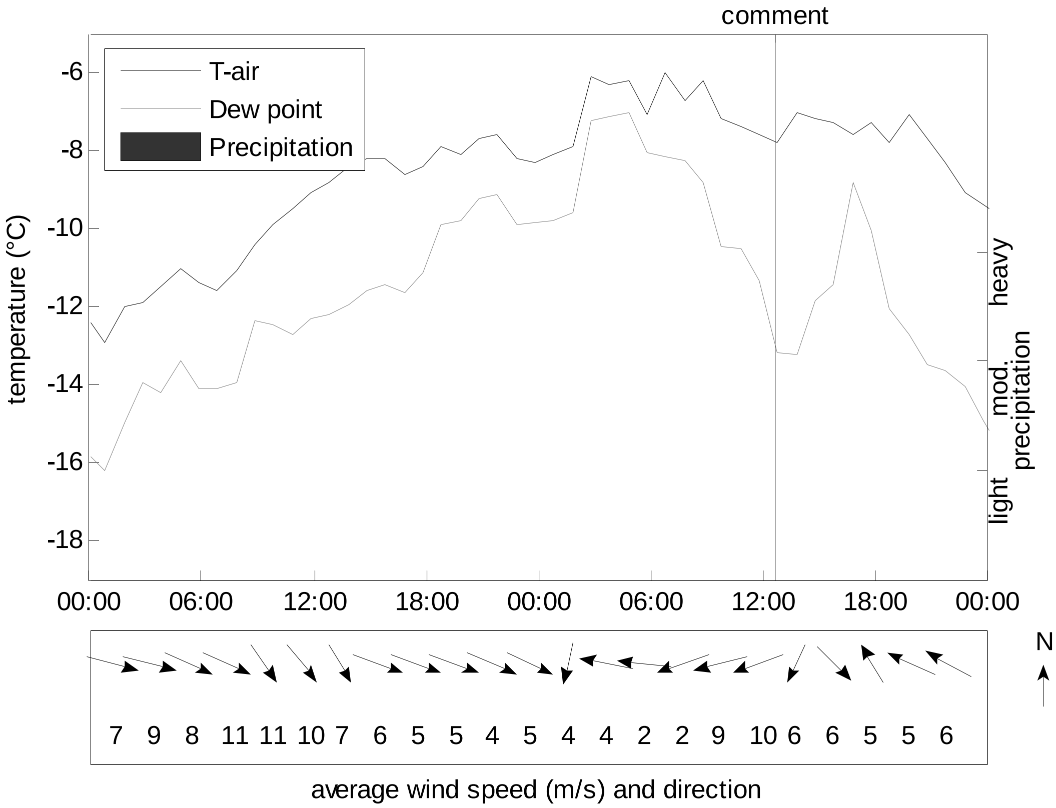

Figure A- 10. Meteogram Case I.