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Laboratory Testing of Tire Friction Under Winter Conditions

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16\. Abstract

An extensive test program was conducted to investigate:

- braking friction under winter conditions;
- sand friction; and
- the performance of de-icing chemicals in freezing rain.

The braking friction tests included an investigation of the effects of load and pressure. The tests showed that friction is strongly related to the load and should be further investigated.

The sand friction tests compared the performance of local sands with a sand meeting the Transport Canada specification. Although the differences in friction among the sands were small, relatively large differences in application rate were required for the various sands to provide the same friction. This is because large increases in application rate produce only small friction factor increases. Parametric tests were also conducted in which the sand's area coverage, grain size, and angularity were varied independently. A sand friction equation was developed and provides a reasonable data fit.

The freezing rain tests compared the performance of five de-icing chemicals at several application rates. For all chemicals, slush was formed at high to intermediate rates, while ice formed rapidly at low application rates. The protection times of the various chemicals were also compared. The laboratory test results should be verified against field data.

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16. Résumé

Un programme d'essais approfondi a été mené pour examiner :

- le coefficient de frottement de pneus dans des conditions hivernales;
- le coefficient de frottement du sable;
- l'efficacité de fondants dans des conditions de pluie verglaçante.

Les mesures du coefficient de frottement des pneus comprenaient un examen des effets de la charge et de la pression. Les essais ont révélé que le frottement est étroitement lié à la charge, relation qui devrait être l'objet d'une recherche plus approfondie.

Les essais de frottement du sable consistaient à comparer l'efficacité de sables extraits localement avec l'efficacité d'un sable respectant les exigences de Transports Canada. Bien que les différences au niveau des coefficients de frottement se soient avérées minimes, des variations assez importantes du régime d'épandage ont été nécessaires pour atteindre le même coefficient de frottement avec les divers sables. Cela s'explique par le fait qu'une forte augmentation du régime d'épandage ne produit qu'une faible augmentation du coefficient de frottement. Des tests paramétriques furent aussi menés en variant séparément la surface couverte, la grosseur du grain et son angularité (arêtes plus ou moins vives). Une formule servant à calculer le coefficient de frottement du sable a été établie et donne une adéquation des données satisfaisante.

Les essais sous pluie verglaçante consistaient à comparer l'efficacité de cinq fondants utilisés à différents régimes d'épandage. Dans tous les cas, les régimes d'épandage intermédiaires à élevés ont produit une neige fondante alors qu'à régime faible, de la glace se formait rapidement. Une comparaison des durées d'efficacité des différents fondants a aussi été effectuée. Les résultats des essais en laboratoire devraient être vérifiés par rapport aux résultats des essais sur le terrain.

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Sands – supplied by airports at:

- Waterloo-Guelph, Ontario (supplied two sand types)
- Kapuskasing, Ontario
- North Bay, Ontario
- Windsor, Ontario
- Sault Ste. Marie, Ontario
- Norway (Norwegian Civil Aviation Authority)

In addition, the airports below are thanked for supplying sands during a previous test program (see TDC report TP 12584E), as these results were used for comparison with the results obtained during the current program.

- Sault Ste Marie, Ontario (supplied two sand types)
- Kapuskasing, Ontario
- Timmins, Ontario
- Ottawa, Ontario
- Sudbury, Ontario
- Manitoulin Island, Ontario
- Dryden, Ontario
- Lynn Lake, Manitoba
- Red Lake, Ontario
- New Liskeard-Earlton, Ontario
- Churchill, Manitoba (supplied four sand types)
- Flin Flon, Manitoba

Aircraft de-icing fluids and runway de-icing chemicals – materials supplied by:

- Octagon Process Inc.
- Union Carbide
- Cryotech
- Hoechst Canada Inc.

EXECUTIVE SUMMARY

This project was undertaken to obtain more data to define the friction coefficient of typical surfaces found on airport runways during winter.

Braking friction tests – Tests were undertaken to:

- compare the friction measured for various tire types on a wide range of winter surfaces; and
- investigate the effects of load and pressure on friction.

The effects of tire type and pressure depended on the surface (i.e., asphalt vs. ice) and the type of material (i.e., liquid vs. solid) applied on the ice and asphalt, as shown in Table l.

Table 1: Trend Summary

Type of material on substrate	Substrate: asphalt	Substrate: ice
None (bare and dry)	Friction increases with tire pressure	Friction independent of tire type and pressure
Solid	Not tested	Similar trends for all tires tested
Liquid	Friction increases with tire pressure	Friction independent of tire type and pressure

The load and pressure tests were conducted on bare ice and frozen snow at -10°C, using the Type VII 26.6 x 6.6 aircraft tire. The friction decreased with the vertical load for both substrates. The friction was not related to the tire inflation pressure, as similar results were obtained for the three pressures tested. These results are similar to those from the load and pressure study conducted at the 1998 North Bay field trials.

Sand friction tests – Tests were conducted on ice and frozen snow at -5°C and -15°C. The friction increased with the application rate for all sands. Typically, sand applications at rates up to 400 g/m^2 increased the friction factor from about 0.1 (for bare ice or frozen snow) to a maximum value of 0.25 to 0.3.

Sands available locally at airports were compared to one that meets the Transport Canada specification (termed Ottawa TC sand). The differences in friction factor among the sands were small. But the relative amounts required for one sand to provide the same friction as another varied greatly. This is due to the fact that large increases in application rate produce only small friction increases. Most of the local sands provided better performance than the Ottawa TC sand since less material was required to provide the same friction.

The parameters controlling sand friction were investigated by conducting tests in which the area coverage, the grain size, and the angularity were varied independently. The friction was most strongly related to the surface area covered by the sand. Thus, the results generally show that the friction is expected to decrease slightly as the sand becomes coarser. The friction also increased with the sand's grain size and angularity. Sand applications at -5°C produced greater friction increases than at -15°C. Equations were developed that provide a reasonable data fit.

The equations were used to compare the friction expected across the size distributions specified by Transport Canada (TC) and the Federal Aviation Administration (FAA). The friction is expected to reduce slightly across the range from the fine edge of the FAA specification to the coarse edge of the TC specification at both -5°C and -15°C. This reflects the effect of area coverage, which decreases steadily over this range.

Freezing rain tests – Potassium acetate, UCAR, sodium acetate, urea, and sodium formate were tested in the laboratory. The test method appears to produce credible results and is highly repeatable.

The friction was affected greatly by the ice formation process. The ice formation processes were similar for all chemicals and varied with the application rate. At high and intermediate application rates, the surface initially remained wet, causing relatively high friction measurements. Eventually, slush was produced by the freezing rain, later hardening into ice on the test track. A steady drop in friction was recorded over the slush and ice formation process. For low application rates, the freezing rain quickly formed ice on the test track, resulting in low friction. Once ice had formed, the friction coefficient remained essentially constant with further exposure to freezing rain.

The protection time provided by the solid chemicals increased linearly with the application rate. The quantities required for sodium acetate and sodium formate to provide the same protection time as urea were about 70 percent and 40 percent of those for urea, respectively. The protection times provided by the liquid chemicals also increased with the application rate, although in contrast to the solid de-icers, the trend was non-linear. This variation may be due to the improved ability of the liquid de-icing chemicals to coat the surface in a uniform manner. The quantity of UCAR required to provide 30 minutes protection time was about 60 percent of that for potassium acetate.

Recommendations

Braking friction – The tests indicated that the vertical load and the contact pressure have a large effect on the friction factor on ice and frozen snow. Because this is an important issue for developing general correlations between aircraft and ground vehicle friction factors, parametric load and pressure tests should be conducted over a wider range of vertical loads, surfaces, temperatures, and tire types.

Sand friction – No further testing or analyses are recommended.

Performance of de-icing chemicals in freezing rain – The test method and results should be compared with field data. Also, simpler indexes (e.g., using the results from ice melting tests, or the freezing points of various solutions of the chemicals) should be investigated by comparing these trends with those obtained during the test program.

Finally, it is recommended that the effect of the impervious test surface used in this project be investigated in comparison to the porous surfaces found on runways.

SOMMAIRE

Ce projet a été entrepris dans le but de recueillir plus de données afin de déterminer le coefficient de frottement de pneus sur les surfaces caractéristiques des pistes des aéroports durant l'hiver.

Mesure du coefficient de frottement du pneu – Des essais ont été réalisés afin :
- de comparer le coefficient de frottement mesuré de différents types de pneus sur un large éventail de surfaces hivernales;
- d'examiner les effets de la charge et de la pression sur le coefficient de frottement.

Les effets du type de pneu et de la pression de gonflage dépendaient de la surface (asphalte ou glace) et du type de matière (liquide ou solide) épandue sur la glace et l'asphalte, comme le montre le tableau 1.

Tableau 1 : Sommaire des observations

Type de matière sur la surface	Surface : asphalte	Surface : glace
Aucune (surface de glace vive ou sèche et dégagée)	Le frottement augmente avec la pression du pneu	Frottement indépendant du type et de la pression du pneu
Solide	Pas d'essai	Comportement semblable pour tous les pneus
Liquide	Le frottement augmente avec la pression du pneu	Frottement indépendant du type et de la pression du pneu

Les essais de pression et de charge ont été menés sur de la glace vive et de la neige glacée à une température de -10 °C, avec le pneu de type VII 26.6 x 6.6. Le frottement diminuait avec la charge verticale sur les deux surfaces. Le frottement n'était pas relié à la pression de gonflage, puisque des résultats semblables ont été obtenus pour les trois pressions mises à l'essai. Les résultats sont semblables à ceux obtenus lors de l'étude sur la charge et la pression menée dans le cadre des essais tenus à l'aéroport de North Bay en 1998.

Mesure du coefficient de frottement du sable – Des essais ont été menés sur de la glace et de la neige glacée à des températures de -5 °C et -15 °C. Dans tous les cas, le frottement augmentait avec le régime d'épandage. Des régimes d'épandage de 400 g/m² ont fait passer le coefficient de frottement de 0,1 (sur la glace vive ou la neige glacée) à un maximum de 0,25 ou même 0,3.

Les sables disponibles à proximité des aéroports ont été comparés au sable respectant les exigences de Transports Canada (désigné sable TC Ottawa). Les différences entre les coefficients de frottement des différents sables étaient minimes. Mais la quantité de sable à épandre pour atteindre le même coefficient de frottement, quel que soit le sable, variait

grandement. Cela s'explique par le fait qu'une forte augmentation du régime d'épandage ne produit qu'une faible augmentation du coefficient de frottement. La plupart des sables extraits localement offraient de meilleurs résultats que le sable TC Ottawa, car une plus petite quantité de sable était nécessaire pour atteindre le même coefficient de frottement.

Les paramètres déterminant le coefficient de frottement du sable ont été étudiés en menant des essais durant lesquels on faisait varier séparément la surface couverte, la grosseur du grain et l'angularité. La surface couverte par le sable jouait le rôle le plus déterminant sur le frottement. Les résultats montrent que le frottement diminue légèrement lorsque le sable est d'une fraction plus grossière. Le coefficient de frottement augmentait également avec la grosseur et l'angularité des grains du sable. L'épandage du sable à -5 ^{o}C a donné de plus fortes augmentations du coefficient de frottement que l'épandage à -15 ^{o}C. Des formules ont été établies, qui donnent une adéquation des données satisfaisante.

Les équations ont été utilisées pour comparer les valeurs de frottement prévues sur les échelles de granulométrie définies par Transports Canada et la *Federal Aviation Administration* (FAA). Le frottement devrait diminuer légèrement, tant à -5 ^{o}C qu'à - 15 ^{o}C, le long de l'échelle de granulométrie allant du sable fin prescrit par la FAA au sable plus grossier prescrit par TC. Cela reflète l'effet de la surface couverte, qui diminue de façon régulière sur cette échelle.

Essais sous pluie verglaçante – L'acétate de potassium, l'UCAR, l'acétate de sodium, l'urée et le formiate de sodium ont été mis à l'essai en laboratoire. La méthode d'essai utilisée semble fournir des résultats plausibles et est facile à répéter.

Le frottement était grandement affecté par le processus de formation de la glace. Les processus de formation de la glace étaient les mêmes pour tous les fondants et variaient selon le régime d'épandage. Aux régimes d'épandage intermédiaire et élevé, la surface restait mouillée un certain temps, ce qui donnait des coefficients de frottement relativement élevés. À la longue, la neige fondante produite par la pluie verglaçante se transformait en glace. Une baisse régulière du coefficient de frottement a été notée durant le processus de formation de neige fondante et de glace. Aux régimes d'épandage faibles, la pluie verglaçante se transformait rapidement en glace sur la piste d'essai, ce qui donnait un faible coefficient de frottement. Aussitôt la glace formée, le coefficient de frottement demeurait sensiblement le même, malgré la persistance de la pluie verglaçante.

La durée d'efficacité des fondants solides augmentait de façon linéaire avec le régime d'épandage. Mais pour atteindre une durée d'efficacité égale à celle de l'urée, il fallait des quantités d'acétate de sodium et de formiate de sodium plus élevées de 40 % et 70 %, respectivement, que les quantités d'urée. Les durées d'efficacité des fondants liquides augmentaient également avec le régime d'épandage mais, contrairement à celles des fondants solides, cette augmentation était non linéaire. Cet écart entre les fondants solides et liquides pourrait être dû à la capacité des fondants liquides de recouvrir uniformément une surface. Pour atteindre une durée d'efficacité de 30 minutes, la quantité d'UCAR nécessaire était de 60 % plus élevée que celle de l'acétate de potassium.

Recommandations

Coefficient de frottement du pneu – Les essais ont montré que la charge verticale et la pression de contact ont un effet important sur le coefficient de frottement de pneus sur glace et sur neige glacée. Puisqu'il s'agit d'un point crucial dans le développement de corrélations générales entre les coefficients de frottement de pneu d'aéronefs et de véhicules routiers, des tests paramétriques de charge et de pression devraient être menés sur une plus vaste gamme de charges verticales, de surfaces, de températures et de types de pneus.

Coefficient de frottement du sable – Aucun autre programme d'essais ou d'analyses n'est recommandé.

Efficacité des fondants sous pluie verglaçante – La méthode d'essai et les résultats devraient être comparés aux données recueillies sur le terrain. De plus, des indices simplifiés (utilisant les résultats d'essais de fusion de la glace, ou les points de congélation de différentes solutions de fondants) devraient être étudiés et les résultats obtenus à l'aide de ces indices comparés aux tendances observées au cours du présent programme d'essais.

Finalement, il est recommandé d'examiner les effets des surfaces d'essai imperméables utilisées durant ce projet en comparant celles-ci avec les surfaces poreuses des pistes d'aérodromes.

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GLOSSARY

ACRONYMS

AMD	Avions Marcel Dassault
ASTM	American Society for Testing Materials
DC-9	Trade name for aircraft manufactured by Boeing
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration
FTL	Fleet Technology Limited
IMAG	Friction-measuring device used by the French Civil Administration
ITTV	Instrumented Tire Test Vehicle
NASA	National Aeronautics Space Administration
NRC	National Research Council Canada
SFT	Saab Friction Tester
PIARC	World Road Congress (French acronym)
TC	Transport Canada
UCAR	Trade name for de-icing chemical manufactured by Union Carbide

1. INTRODUCTION AND OBJECTIVES

This project was undertaken to obtain more data to define the friction coefficient of typical surfaces found on airport runways during wintertime. Laboratory tests were conducted using a machine and setup that had been commissioned during an earlier project [1]. The tests conducted in this project were aimed at extending the database produced previously [1], and they comprised three parts:

- braking friction tests;
- sand friction tests;
- freezing rain tests.

1.1 Braking Friction Tests

Two types of braking friction tests were conducted with the following objectives:

- Winter Surface Braking Friction Tests:
    - (a) To investigate the influence of tire type and pressure on the measured friction coefficient for:
        - (i) bare and dry asphalt and ice surfaces;
        - (ii) a wide range of contaminated surfaces. The parameters varied included the contaminant type (i.e., liquid vs. solid, and chemical), the application rate, and the substrate (asphalt and ice);
        - (iii) temperatures of -2°C and -10°C.
    - (b) To compare the friction factors produced when potassium formate is present on various surfaces with those produced by other liquid contaminants.
- Load and Pressure Study: to investigate the effect of vertical load, tire inflation pressure, and tire contact pressure on the measured friction factor for bare ice and frozen snow at -10°C.

1.2 Sand Friction Investigation

The sand friction investigation consisted of two parts:

- Laboratory Tests – The objectives of the sand friction tests were:

(a) To compare the friction factors produced by applications of seven (7) local sands on frozen snow and ice at temperatures of -5°C and -15°C with those produced by applications of a sand meeting the Transport Canada (TC) specification. A sub-objective was to compare the results for these local sands with those for the other local sands tested previously [1].

(b) To investigate the factors controlling sand friction on ice and frozen snow by conducting tests in which the area coverage, the sand grain size, and the angularity were parametrically varied for three sands.

- Production of a Sand Advisory Circular – This was produced using the laboratory test data as well as many other sources of published information. The Sand Advisory Circular has been published under separate cover [2]. For completeness, it is copied in Appendix K.

1.3 Freezing Rain Tests

The objectives of the freezing rain tests were:

- To investigate the factors controlling ice control performance in freezing rain conditions and alternative test methods.

- To evaluate the performance of various ice control chemicals at a number of application rates.

2. TEST MATRIX

The laboratory test program was composed of three parts, as follows:

- braking friction tests;
- sand friction tests;
- freezing rain tests.

2.1 Braking Friction Tests

Two types of braking friction tests were conducted as follows:

(a) Winter Surface Braking Friction Tests – these tests were conducted to obtain data to define the friction coefficient for a wide range of winter surfaces.

(b) Load and Pressure Study – these tests were done by parametrically varying the tire pressure and vertical load for a range of surfaces and test temperatures.

2.1.1 Winter Surface Braking Friction Tests - Test Matrix Summary

A total of 75 and 107 braking friction tests were carried out on asphalt and ice respectively, as summarized in Tables 2.1 and 2.2 respectively.

Table 2.1: Winter Surface Braking Friction Tests: Tests Done on Asphalt

Material On Surface	Appl'n. Rate	Temp (°C)	Tire Type & Pressure (See Table 2.2 for legend)					
			No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
None	n/a	-2	√	√	√	√	√	√
Water	0.5 mm depth	-2	√	√	√	√	√	√
None	n/a	-10	√	√	√	√	√	√
Urea	146 g/m^2	-2	√	√	√	√	√	√
Urea	305 g/m^2	-10	√	√	√	√	√	√
Potassium Acetate	20 ml/m^2	-2	√	√	√	√	√	√
Potassium Acetate	40 ml/m^2	-2	√	√	√	√	√	√
Potassium Acetate	20 ml/m^2	-10	√	√	√	√	√	√
Potassium Acetate	40 ml/m^2	-10	√	√	√	√	√	√
Potassium Formate	20 ml/m^2	-2	√	√	√	√	√	√
Potassium Formate	40 ml/m^2	-2	√	√	√	√	√	√
Potassium Formate	20 ml/m^2	-10	√	√	√	√	√	√
Potassium Formate	40 ml/m^2	-10	√	√	√	√	√	√
Octagon Type II Fluid	16 ml/m^2	-2	√	√	√	√	√	√
Octagon Type II Fluid	16 ml/m^2	-10	√	√	√	√	√	√

Table 2.2: Winter Surface Braking Friction Tests: Tests Done on Ice

Material On Surface	Appl'n. Rate	Temp. (°C)	Tire Type & Pressure (see note 1)					
			No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
none	n/a	-2	√	√	√	√	√	√
water	0.5 mm	-2	√	√	√	√	√	√
none	n/a	-10	√	√	√	√	√	√
Potassium Acetate	20 ml/m^2	-2	√	√	√	√	√	√
Potassium Acetate	40 ml/m^2	-2	√	√	√	√	√	√
Potassium Acetate	20 ml/m^2	-10	√	√	√	√	√	√
Potassium Acetate	40 ml/m^2	-10	√	√	√	√	√	√
Potassium Formate	20 ml/m^2	-2	√	√	√	√	√	√
Potassium Formate	40 ml/m^2	-2	√	√	√	√	√	√
Potassium Formate	20 ml/m^2	-10	√	√	√	√	√	√
Potassium Formate	40 ml/m^2	-10	√	√	√	√	√	√
Octagon Type II Fluid	16 ml/m^2	-2	√	√	√	√	√	√
Octagon Type II Fluid	16 ml/m^2	-10	√	√	√	√	√	√
Transport Canada Sand	50 g/m^2	-2	√	√		√	√	√
Transport Canada Sand	100 g/m^2	-2	√	√		√	√	√
Transport Canada Sand	200 g/m^2	-2	√	√		√	√	√
Transport Canada Sand	400 g/m^2	-2	√	√		√	√	√
Transport Canada Sand	50 g/m^2	-10	√	√		√	√	√
Transport Canada Sand	100 g/m^2	-10	√	√		√	√	√
Transport Canada Sand	200 g/m^2	-10	√	√		√	√	√
Transport Canada Sand	400 g/m^2	-10	√	√		√	√	√
Urea	146 g/m^2	-2	√	√		√	√	√
Urea	305 g/m^2	-10	√	√		√	√	√

Notes: Legend For tire type and pressure:
No. 1: Type VII 26 x 6.6 aircraft tire inflated to 1550 kPa (225 psi)
No. 2: Falcon aircraft tire inflated to 930 kPa (135 psi)
No. 3: Saab friction tester (SFT) aero tire inflated to 690 kPa (100 psi)
No. 4: Saab friction tester (SFT) smooth ASTM tire inflated to 210 kPa (30 psi)
No. 5: Locked truck tire inflated to 240 kPa (35 psi)
No. 6: PIARC tire inflated to 145 kPa (21 psi)

2.1.2 Test Tires Used for the Winter Surface Braking Friction Tests

Tests were done with the five tires listed in Table 2.3.

Table 2.3: Winter Surface Braking Friction Tests: Tires Used in the Test Program

Description (used throughout the report to denote that tire)	Pressure (kPa [psi])	Vertical Load (kN [lbs])	Slip Ratio
Type VII 26.6 x 6.6 aircraft tire	1550 [225]	9.0 [2000]	12 %
Falcon aircraft tire (size: 26.6 x 6.6)	930 [135]	6.0 [1350]	14 %
SFT aero tire (size: 4.00 x 8)	690 [100]	1.3 [300]	12 %
SFT low-pressure tire (size: 4.00 x 8)	210 [30]	1.3 [300]	15 %
Locked truck tire (size: P225/75 R16)	240 [35]	4.0 [900]	100 %
PIARC	145 [21]	1.8 [405]	15 %

The "Type VII 26.6 x 6.6 Aircraft Tire" is used on a number of aircraft including the Canadair Challenger (as the main wheel), and the DC-9 (as the nose wheel). This tire type was tested because: (a) it is the same one that was used during the previous laboratory test program [1]; and (b) it was used on the NASA Instrumented Tire Test Vehicle (ITTV) during the recent field trials held in North Bay, Ontario.

The "Falcon Aircraft Tire" is used as the nose wheel on the Falcon 20, which is a business jet designed and built by Avions Marcel Dassault (AMD). This tire type was included because the National Research Council's (NRC) Falcon 20 was one of the aircraft tested at the recent field trials held in North Bay [3].

The "SFT Aero Tire" is a tire that can be mounted on the Saab Friction Tire (SFT). It has a ribbed tread pattern. This tire type was tested because: (a) it is the same one that was used during the previous laboratory test program [1]; and (b) this tire type was mounted on one of the SFTs during the recent field trials held in North Bay.

The "Low-Pressure SFT Tire" is a smooth tire, and it has been used most commonly to date on the Saab Friction Tire (SFT) by Transport Canada during its Summer Maintenance Runway Friction Monitoring program. This tire type was tested because: (a) it is the same one that was used during the previous laboratory test program [1]; and (b) this tire type was mounted on one of the SFTs used during the recent field trials held in North Bay.

The "locked truck tire" was tested to better understand the results obtained from Transport Canada's electronic recording decelerometer (ERD), which is the device currently used at most Canadian airports for measuring runway friction coefficients in wintertime. The particular tire tested was obtained from one of the pickup trucks used to make ERD measurements during the recent field trials held in North Bay.

The PIARC tire was included because it is used on the IMAG device, which is one of the ground vehicles currently available for friction factor measurement. The IMAG was included in the recent tests conducted at the North Bay airport (e.g., [4]).

2.1.3 Winter Surface Braking Friction Tests: Tests Done on Asphalt

The following solid and liquid contaminants were tested:

(a) Liquid contaminants – Tests were done with water, potassium acetate, potassium formate, and the "Forty Below" Type II de-icing fluid manufactured by Octagon Process Inc. (hereafter referred to as "Octagon Type II fluid"). The same application and test techniques used in the previous laboratory test program were used in this test program.

(b) Solid contaminants – Tests were done with urea on asphalt. The same procedures used during the previous laboratory test program [1] were followed again. The asphalt was first wetted with water to a depth of about 0.5 mm before applying the urea. The friction factor was measured 10 and 15 minutes after application at temperatures of -2°C and -10°C, respectively. This procedure caused the urea prills to be partially dissolved, and in a slurry form, at -2°C. At -10°C, the urea prills were still hard and intact.

2.1.4 Winter Surface Braking Friction Tests: Tests Done on Ice

As was done for the previous laboratory test program [1], ice was formed by freezing water on the steel plate test track. The following solid and liquid contaminants were tested:

(a) Liquids applied on the ice surface – Tests were done with water, potassium acetate, potassium formate, and the Octagon Type II fluid. The same application and test techniques used in the previous laboratory test program [1] were used in this test program.

(b) Solid materials applied on the ice surface – Tests were done with sand and urea on the ice. The same procedures used during the previous test program [1] were used for each material.

A sand that met the Transport Canada specification was used. Because this sand was obtained from the Ottawa airport, it is referred to in this report as Ottawa TC sand. This is the same type of sand that was used during the previous laboratory test program [1] and during the parametric sand friction tests conducted during this project (which are described subsequently in this report).

2.1.5 The Load and Pressure Study

A total of 18 tests were carried out as summarized in Table 2.4. All tests were conducted with the Type VII 26 x 6.6 aircraft tire at a fixed slip of 12 percent The following parameters were varied:

(a) the vertical load – this was varied from 6.7 to 17.8 kN (1500 to 4000 lbs);
(b) the inflation pressure – this was varied from 210 to 940 KPa (30 to 136 psi); This is the same range of inflation pressures that was tested with the ITTV during the 1998 North Bay tests [4].
(c) the surface – tests were done on bare ice and on frozen snow.

The gross and net tire footprint areas were measured for the Type VII 26.6 x 6.6 aircraft tire on frozen snow at -10°C for each combination of vertical load and inflation pressure below.

Table 2.4: The Load and Pressure Study: Test Matrix Summary

Surface	Temp. (°C)	Tire Press.	Nominal Vertical Load (kN [lb])		
		(Kpa [psi])	6.7 [1500]	13.3 [3000]	17.8 [4000]
Bare Ice	-10	210 [30]	√	√	√
		550 [80]	√	√	√
		940 [136]	√	√	√
Frozen Snow	-10	210 [30]	√	√	√
		550 [80]	√	√	√
		940 [136]	√	√	√

2.2 Sand Friction Tests

2.2.1 Local Sand Friction Tests

A total of 70 tests were carried out as summarized in Table 2.5. All tests were conducted on an ice surface using the Type VII 26.6 x 6.6 aircraft tire inflated at 1550 kPa (225 psi). The following parameters were varied:

(a) The sand type – seven (7) local sands were tested. In addition, a sand meeting the Transport Canada (TC) specification was tested to allow direct comparisons.

(b) The application rate – each sand was tested at five (5) application rates.

(c) The test temperature – tests were done at -5° and -15°C.

Table 2.5: Local Sand Friction Test Matrix

Tire and inflation pressure, (in kPa) used	Surf.	Sand source and description	Temp. (°C)	Application rate (g/m^2)				
				50	100	200	300	400
Type VII 26.6 x 6.6 (1550)	Ice	Norway	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Windsor Airport	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Waterloo-Guelph Airport Crushed Limestone 1	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Waterloo-Guelph Airport Crushed Limestone 2	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	North Bay Airport MTO highway sand	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Kapuskasing Airport Fine sand	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Sault Ste. Marie Airport Coarse sand	-5	√	√	√	√	√
			-15	√	√	√	√	√
Type VII 26.6 x 6.6 (1550)	Ice	Ottawa TC sand	-5	√	√	√	√	√
			-15	√	√	√	√	√

2.2.2 Parametric Sand Friction Tests

A total of 300 tests were carried out using the Type VII 26.6 x 6.6 aircraft tire inflated at 1550 kPa (225 psi), as summarized in Table 2.6. One hundred and twenty (120) tests were carried out using the SFT low-pressure tire inflated at 210 kPa (Table 2.7).

Tests were conducted on ice and frozen snow surfaces at temperatures of -5° and -15°C.

The Ottawa TC sand, the Red Lake airport sand, and the Flin Flon airport sand were used for the tests because they cover most of the ranges found in the local sands tested to date (Table 2.8). These sands are described further in section 5. Size gradations for these sands are plotted in Appendix A.

Each of the sands was sieved into four size ranges:

(a) less than 1.18 mm;
(b) 1.18 to 2.0 mm;
(c) 2.0 to 2.4 mm;
(d) 2.4 to 4.0 mm - all sizes larger than 4.0 mm had already been removed by passing the local sands through a no. 4 sieve prior to the test program.

The materials in the various grain size ranges were tested separately by applying them on the prepared ice and frozen snow surfaces at the application rates of interest (Tables 2.5 and 2.6). As a result, the area coverage, sand grain size, and sand grain angularity were all varied parametrically. This is discussed further in section 5.3, which presents the results of these tests.

Table 2.6: Parametric Sand Friction Tests Conducted with the Type VII 26 x 6.6 Aircraft Tire for Each of the Three Local Sands Tested
(i.e., Ottawa TC Sand, Flin Flon Sand, and Red Lake Sand)

Surface	Temp. (°C)	Sand Size Range (mm)					Application Rate (g/m^2)				
		< 1.18	1.18 - 2.0	2.0 - 2.4	2.4 - 4.0	Whole Grad'n	50	100	200	300	400
Ice	-5	√					√	√	√	√	√
			√				√	√	√	√	√
				√			√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Ice	-15	√					√	√	√	√	√
			√				√	√	√	√	√
				√			√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Frozen Snow	-5	√					√	√	√	√	√
			√				√	√	√	√	√
				√			√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Frozen Snow	-15	√					√	√	√	√	√
			√				√	√	√	√	√
				√			√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√

Table 2.7: Parametric Sand Friction Tests Conducted with the Low-Pressure SFT Tire for Each of the Two Local Sands Tested (i.e., Ottawa TC Sand, and Red Lake Sand)

Surface	Temp. (°C)	Sand Size Range (mm)					Application Rate (g/m^2)				
		< 1.18	1.18 - 2.0	2.0 - 2.4	2.4 - 4.0	Whole Grad'n	50	100	200	300	400
Ice	-5	√	not tested	not tested			√	√	√	√	√
							√	√	√	√	√
							√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Ice	-15	√	not tested	not tested			√	√	√	√	√
							√	√	√	√	√
							√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Frozen Snow	-5	√	not tested	not tested			√	√	√	√	√
							√	√	√	√	√
							√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√
Frozen Snow	-15	√	not tested	not tested			√	√	√	√	√
							√	√	√	√	√
							√	√	√	√	√
					√		√	√	√	√	√
						√	√	√	√	√	√

Table 2.8: General Comparison of the Three Sands Used for the Parametric Test Program

Sand Source & General Description	Area Coverage (%) at 100 g/m^2	Average Grain Size (mm)	Angularity Index (note 1)
Ottawa TC Sand - Crushed rock with large coarse particles	4.1	1.34	380
Flin Flon airport - natural sand with rounded & angular particles - mainly falls within the TC size specification	4.6	1.20	260
Red Lake airport - natural sand with rounded particles mainly - finer than the TC specification	10.6	0.52	140

Note: 1. See Section 5 and equation 5.2 for definition of the "Angularity Index".

2.3 Freezing Rain Tests

First, a series of tests were carried out to investigate freezing rain formation on the test surfaces, and to select a test procedure. These are described in section 6, which presents the freezing rain test results.

A test procedure was then established and tests were conducted using several de-icing chemicals. A total of 18 and 7 tests were carried out on a non-slip deck coating (described in sections 3 and 6) and on concrete respectively, as summarized in Table 2.9. The following parameters were varied:

(a) the chemical – 5 chemicals were tested;
(b) the application rate;
(c) the test surface – tests were on an impervious non-slip deck coating and on concrete. The reasons for this variation are discussed in Section 6, which presents the freezing rain test results.

Table 2.9: Freezing Rain Test Matrix

Test Surface	Rainfall Rate	Ice Control Chemical	Application Rate
Non-Slip Deck Coating	5 mm/hr	Urea	75; 300 & 600 g/m^2
		Potassium Acetate	20; 81; 205; & 405 ml/ m^2 (note 1)
		Sodium Formate	20; 80; 150 & 150 (repetition - note 2) g/m^2
		Sodium Acetate	20; 80; 150 & 300 g/m^2
		UCAR	20; 81; & 205 ml/ m^2 (note 1)
Concrete	5 mm/hr	Urea	75; 300 & 600 g/m^2
		Potassium Acetate	20; 81; 205; & 405 ml/ m^2 (note 1)

Notes: 1. For reference, 20.4 ml/m^2 is equivalent to 0.5 US gal / 1000 ft^2.
2. This test was done to check the repeatability of the test method.

3. TEST FACILITY

The tests were conducted using a test machine and facility in FTL's refrigerated laboratory in Kanata, Ontario. This setup had been commissioned during a previous test program [1]. Figure 3.1 and Plates 3.1 and 3.2 show the test facility. Its specifications are listed in Table 3.1.

The facility has three 12.8 m (42 ft) long test surfaces, made up of ungrooved concrete and asphalt and a smooth steel plate that provides a surface with negligible microtexture. The asphalt was produced by placing HL3 asphalt on top of the existing concrete floor. Ice, snow, and freezing rain surfaces were tested by forming those conditions on top of the test surfaces.

The steel plate test track was added to provide data for a basic case, where pavement microtexture effects were removed and the friction was governed by viscous effects of the contaminant. To avoid damage to the asphalt and concrete surfaces, the ice and frozen snow surfaces used for testing were prepared on the smooth steel plate.

An impervious textured surface was installed for use in the freezing rain tests by mounting coated steel plates on top of the concrete track. The coated steel plates were prepared by painting steel plates with Morgan MS-440G, which is a non-slip deck coating that has been used to provide a non-skid surface on aircraft carriers (Appendix C). This surface worked well and is described further in Section 6.

The test tire is supported in a steel-framed trolley, which is pulled along a test surface with a high-speed electrical winch. A vertical force is produced and controlled using manually adjustable screw jacks. Load cells are in place to measure both the normal and the drag load on the tire.

A rack and pinion arrangement provides a guide for the trolley, as well as a means of control for producing various fixed braking slips. The system operates at fixed braking slips that are controlled by a belt-driven gearing arrangement that is selected in combination with the diameter of the test tires. Different tires can be mounted on the machine. It was configured for the six tires listed in Section 2 (Table 2.4).

Table 3.1: General Specifications of the Tire Friction Test Facility

Winter Conditions And Surfaces:	
Test Surfaces	Asphalt, concrete, smooth steel plate, anti-skid textured plate
Winter Conditions Tested	Ice and frozen snow: bare ice or frozen snow wetted with water coated with de-icing chemicals sand applied to the ice or frozen snow surface Freezing rain: falling on bare concrete or anti-skid surface falling on surface coated with de-icing chemicals Asphalt or Concrete: wetted with water coated with de-icing chemicals slush on surface
System Parameters:	
Track Length	12.8 m (42 ft)
Tire Types and Slip	As listed in Section 2 (Table 2.4)
Speed	2.3 & 4.1 m/sec (7.5 & 13.5 ft/sec)
Drive	High speed electrical winch (75 HP)
Max. Vertical Load	18 kN (4000 lbs)
Temperature Range	Ambient to -20° C
Measurements	Vertical and drag loads on tire, air temperature, humidity, and tire speed.

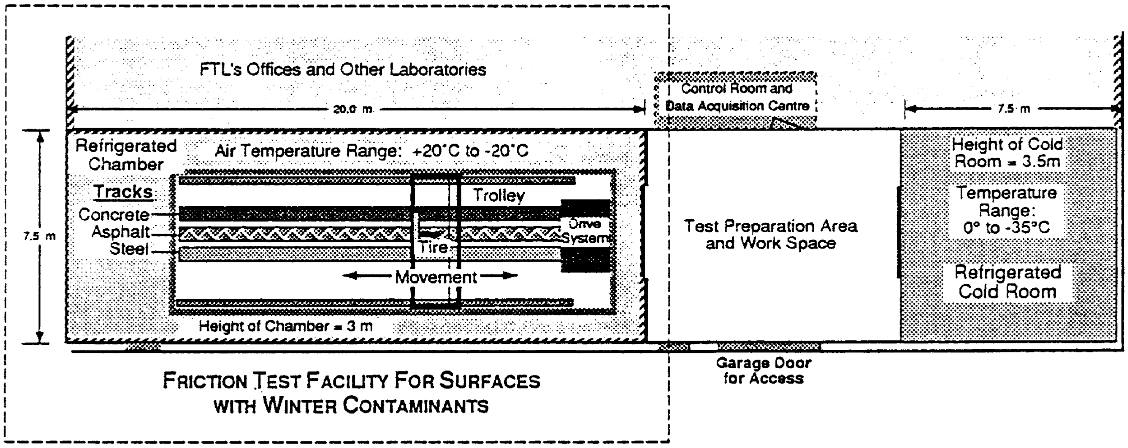


Figure 3.1: Test Facility Layout: Plan View

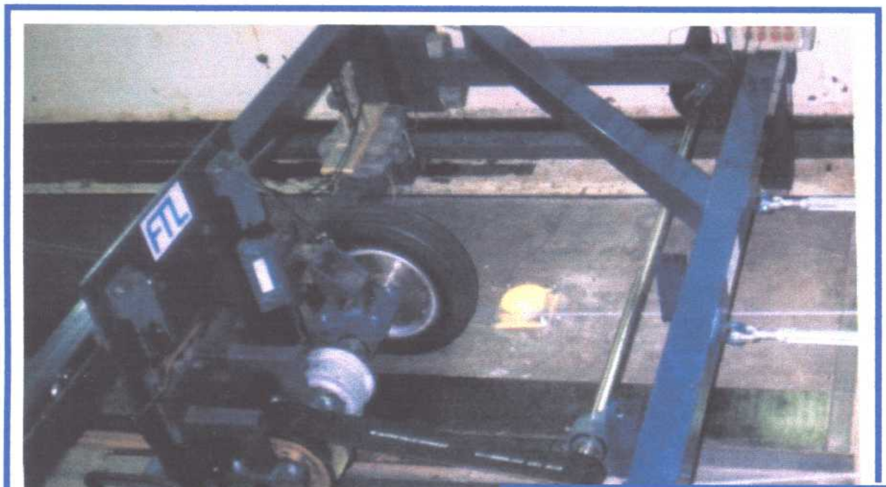


Plate 3.1: Close-up of Trolley Frame and Tire

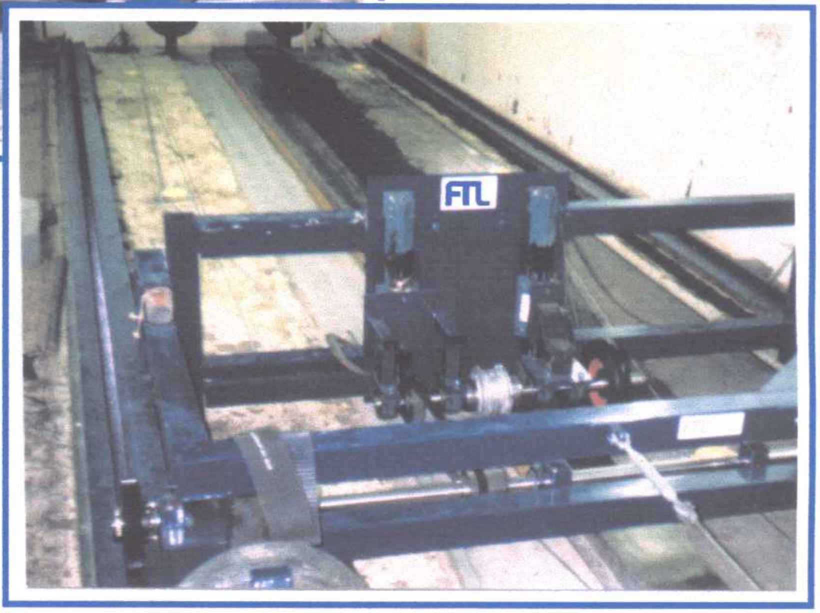


Plate 3.2: Test Tracks and Trolley

4. BRAKING FRICTION TESTS

4.1 Objectives

Two types of braking friction tests were conducted with the following objectives:

- Winter Surface Braking Friction Tests:

(a) To investigate the influence of tire type and pressure on the measured friction coefficient for:

    (i) bare and dry asphalt and ice surfaces;
    (ii) a wide range of contaminated surfaces. The parameters varied included the contaminant type (i.e., liquid vs. solid, and chemical), the application rate, and the substrate (asphalt and ice).
    (iii) temperatures of -2°C and -10°C.

(b) To compare the friction factors produced when potassium formate is present on various surfaces with those produced by other liquid contaminants.

- Load and Pressure Study: To investigate the effect of vertical load, tire inflation pressure and tire contact pressure on the measured friction factor for bare ice and frozen snow at -10°C.

4.2 Winter Surface Braking Friction Tests: Data Summary

The measured friction factors are summarized in Tables 4.1 to 4.5.

Table 4.1: Friction Factors Measured on Ice and Asphalt

Tire (legend at end of Table 4.5)	Tests on Ice			Tests on Asphalt		
	Bare and Dry	Wetted	Bare and Dry	Bare and Dry	Wetted	Bare and Dry
	Temp: -2°C	Temp: -2°C	Temp: -10°C	Temp: -2°C	Temp: -2°C	Temp: -10°C
No. 1	0.083	0.063	0.11	0.6	0.56	0.62
No. 2	0.076	0.05	0.096	0.61	0.56	0.60
No. 3	0.075	0.050	0.082	0.57	0.51	0.58
No. 4	0.089	0.060	0.092	0.55	0.50	0.54
No. 5	0.07	0.035	0.089	0.54	0.47	0.52
No. 6	0.10	0.06	0.12	0.54	0.53	0.55

Table 4.2: Friction Factors Measured with Liquids on Ice Surface

Tire (legend at end of Table 4.5)	Temp. (°C)	Potassium Acetate		Type II (Octagon)	Potassium Formate	
		Appl'n. Rate		Appl'n. Rate	Appl'n. Rate	
		20 ml/m^2	40 ml/m^2	16 ml/m^2	20 ml/m^2	40 ml/m^2
No. 1	-2	0.086	0.087	0.09	0.093	0.098
No. 2	-2	0.084	0.11	0.096	0.105	0.096
No. 3	-2	0.103	0.095	0.11	0.098	0.088
No. 4	-2	0.085	0.111	0.11	0.095	0.115
No. 5	-2	0.115	0.07	0.08	0.09	0.079
No. 6	-2	0.094	0.115	0.094	0.105	0.12
No. 1	-10	0.085	0.088	0.089	0.091	0.10
No. 2	-10	0.093	0.078	0.11	0.10	0.090
No. 3	-10	0.11	0.12	0.11	0.10	0.12
No. 4	-10	0.092	0.097	0.11	0.12	0.13
No. 5	-10	0.11	0.078	0.08	0.096	0.085
No. 6	-10	0.12	0.128	0.10	0.11	0.13

Table 4.3: Friction Factors Measured with Liquids on Asphalt Surface

Tire (legend at end of Table 4.5)	Temp. (°C)	Potassium Acetate		Type II (Octagon)	Potassium Formate	
		Appl'n. Rate		Appl'n. Rate	Appl'n. Rate	
		20 ml/m^2	40 ml/m^2	16 ml/m^2	20 ml/m^2	40 ml/m^2
No. 1	-2	0.57	0.55	0.54	0.55	0.57
No. 2	-2	0.55	0.57	0.52	0.56	0.56
No. 3	-2	0.47	0.45	0.50	0.48	0.47
No. 4	-2	0.43	0.42	0.43	0.46	0.43
No. 5	-2	0.29	0.31	0.32	0.35	0.36
No. 6	-2	0.44	0.42	0.45	0.42	0.43
No. 1	-10	0.54	0.52	0.51	0.54	0.55
No. 2	-10	0.57	0.56	0.53	0.55	0.56
No. 3	-10	0.47	0.43	0.45	0.46	0.49
No. 4	-10	0.40	0.37	0.35	0.33	0.39
No. 5	-10	0.27	0.25	0.28	0.21	0.29
No. 6	-10	0.40	0.38	0.40	0.44	0.48

Table 4.4: Friction Factors Measured with Ottawa TC Sand Applied on Ice

Tire (legend at end of Table 4.5)	Temp. (°C)	Sand Application Rate (g/m^2)			
		50	100	200	400
No. 1	-2	0.095	0.11	0.14	0.18
No. 2	-2	0.10	0.13	0.17	0.19
No. 4	-2	0.12	0.14	0.17	0.19
No. 5	-2	0.085	0.12	0.15	0.16
No. 6	-2	0.13	0.15	0.18	0.19
No. 1	-10	0.12	0.13	0.15	0.17
No. 2	-10	0.11	0.13	0.15	0.15
No. 4	-10	0.10	0.12	0.14	0.16
No. 5	-10	0.095	0.11	0.14	0.15
No. 6	-10	0.13	0.14	0.15	0.16

Table 4.5: Friction Factors Measured with Urea Applied on Ice and Asphalt

Tire (legend at end of Table 4.5)	Urea Applied on Ice		Urea Applied on Asphalt	
	Temp : -2°C	Temp : -10°C	Temp : -2°C	Temp : -10°C
	Rate : 146 g/m^2	Rate : 305 g/m^2	Rate : 146 g/m^2	Rate : 305 g/m^2
No. 1	0.101	0.16	0.53	0.58
No. 2	0.118	0.155	0.511	0.56
No. 3	Not Tested	Not Tested	0.45	0.5
No. 4	0.095	0.1	0.33	0.45
No. 5	0.1	0.11	0.3	0.41
No. 6	0.14	0.21	0.44	0.37

Tire Legend:
No. 1: Type VII 26 x 6.6 aircraft tire inflated to 1550 kPa (225 psi)
No. 2: Falcon aircraft tire inflated to 930 kPa (135 psi)
No. 3: Saab friction tester (SFT) aero tire inflated to 690 kPa (100 psi)
No. 4: Saab friction tester (SFT) smooth ASTM tire inflated to 210 kPa (30 psi)
No. 5: Locked truck tire inflated to 240 kPa (35 psi)
No. 6: PIARC tire inflated at 145 kPa (21 psi)

4.3 Winter Surface Braking Friction Tests: Friction on Ice and Asphalt

4.3.1 Effect of Tire Type and Pressure

Figures 4.1 to 4.9 show the measured friction factors with respect to tire pressure and tire type for the cases tested. The effect of tire type and pressure depends on the surface (i.e., asphalt vs. ice), and the type of material (i.e., liquid vs. solid) applied on the ice and asphalt, as summarized in Table 4.6.

In most cases, the lowest friction factors were measured with the locked truck tire. This probably reflects the fact that the other tires were all tested at a fixed slip ratio in the range of 12 to 15 percent (Section 2), which is closer to the peak value.

Table 4.6: Summary of Observed Trends

Type of Material on Substrate	Substrate: Asphalt	Substrate: Ice
None (Bare & Dry)	Friction increases with tire pressure	Friction independent of tire type and pressure
Solid	Not tested	Similar trends for all tires tested
Liquid	Friction increases with tire pressure	Friction independent of tire type and pressure

On asphalt, the tire type and pressure is clearly a very important factor as the friction factor steadily reduced with lower tire pressures, especially when liquids were present on the asphalt (Figures 4.2 and 4.3). Lower friction factors were also measured with the lower pressure tires on bare and dry asphalt (Figure 4.1).

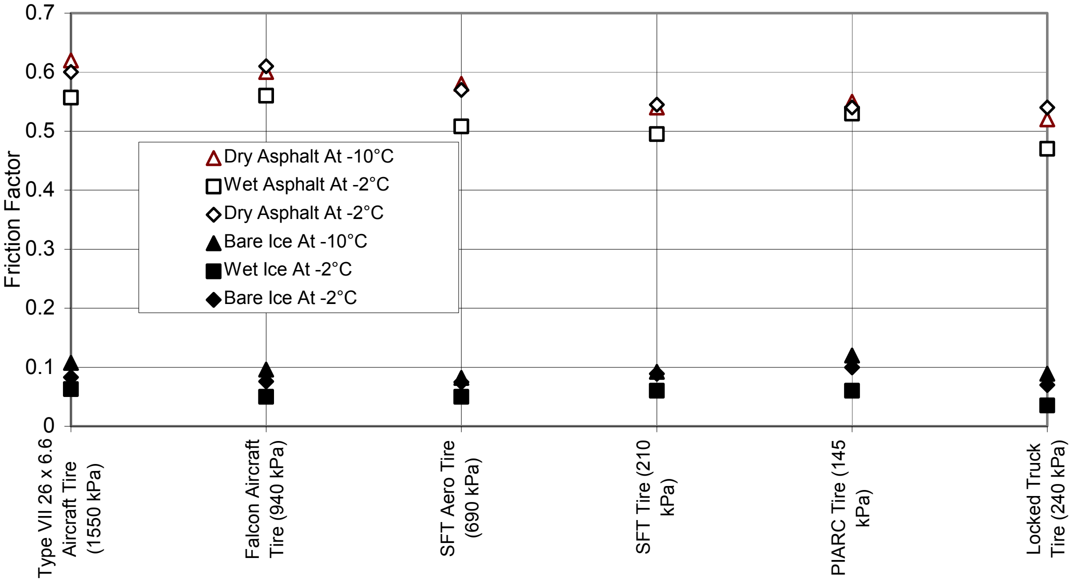


Figure 4.1: Friction Factors on Ice and Asphalt

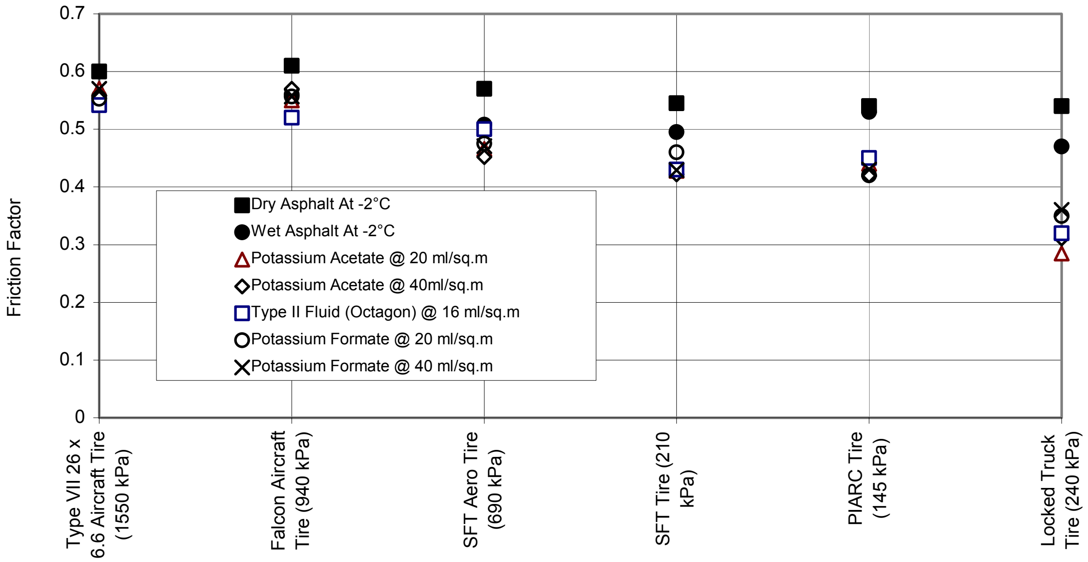


Figure 4.2: Friction Factors with Liquids on Asphalt - Test Temperature: -2°C

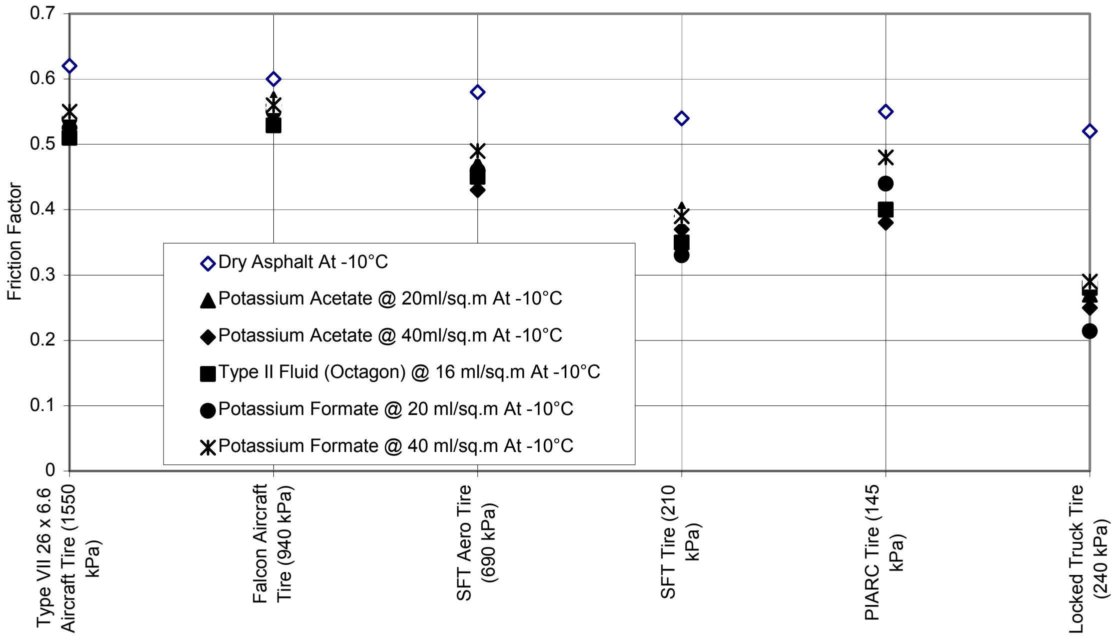


Figure 4.3: Friction Factors with Liquids on Asphalt - Test Temperature: -10°C

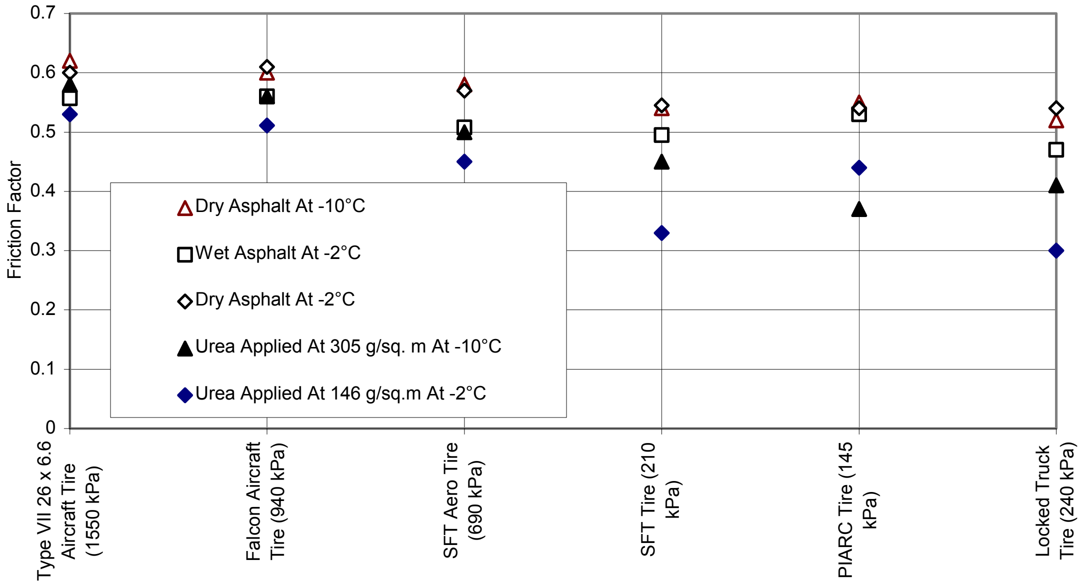


Figure 4.4: Friction Factors with Urea on Asphalt

The friction factors on ice, and on ice with liquids on it, appear to be controlled mainly by the ice, and the materials on it, which act as the sacrificial surface during these cases. Consequently, the measured friction factors for bare ice, and for ice with liquids on it, are independent of tire type and pressure. However, it should be noted that the friction factors measured with the high pressure (1550 kPa) aircraft tire show considerably less variation than do those measured with the lower pressure tires for the range of cases tested (Figures 4.5 and 4.6). This has important implications for correlating the friction factors measured with ground vehicle and aircraft tires as the lower pressure ground vehicle tires indicate changes in friction factor (for the ranges of liquids tested) that are not “seen” by high pressure aircraft tires.

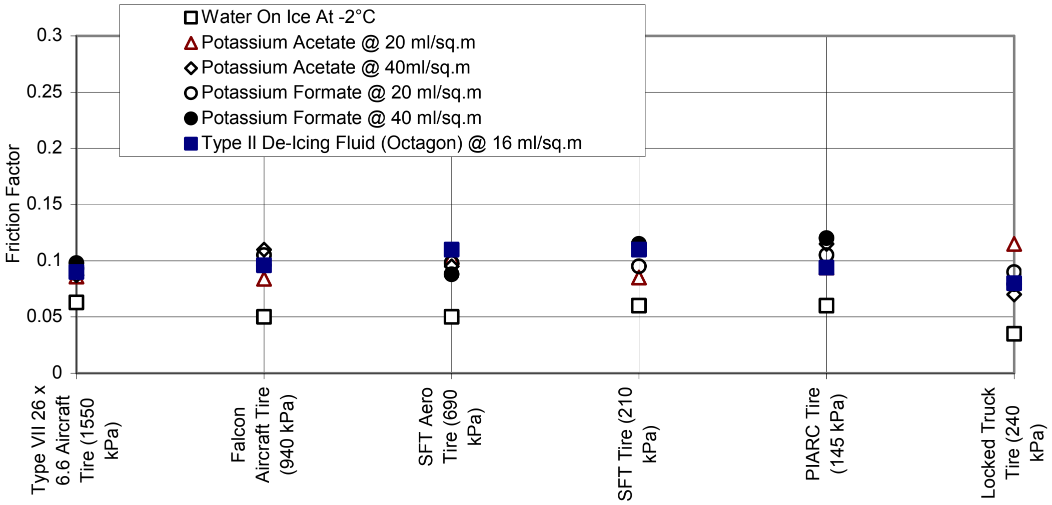


Figure 4.5: Friction Factors with Liquids on Ice – Test Temperature: -2°C

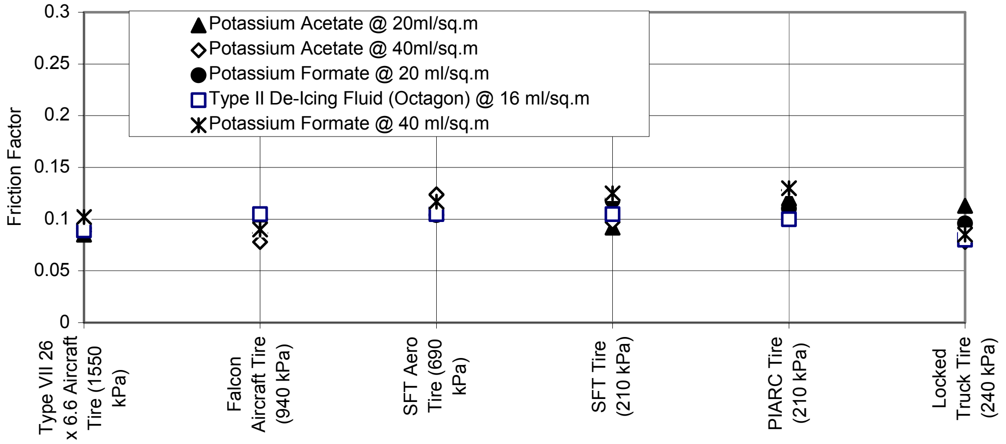


Figure 4.6: Friction Factors with Liquids on Ice – Test Temperature: -10°C

The friction factors for sand on ice increase with the sand application rate for all of the tires tested (Figures 4.7 and 4.8). The friction increases produced by adding sand to the ice surface were generally similar for each tire, as the range of variation in friction factor was up to about 0.05 for the five tires over the full range of sand application rates tested (Figures 4.7 and 4.8).

Subsequent field and laboratory tests have shown that the friction factor is strongly dependent on the vertical and the tire contact pressure (e.g., [4]). Unfortunately, general statements cannot be made with the laboratory test data collected in this program because: (a) the vertical load and tire inflation pressure were not varied parametrically; and, (b) the tire footprint areas were not measured.

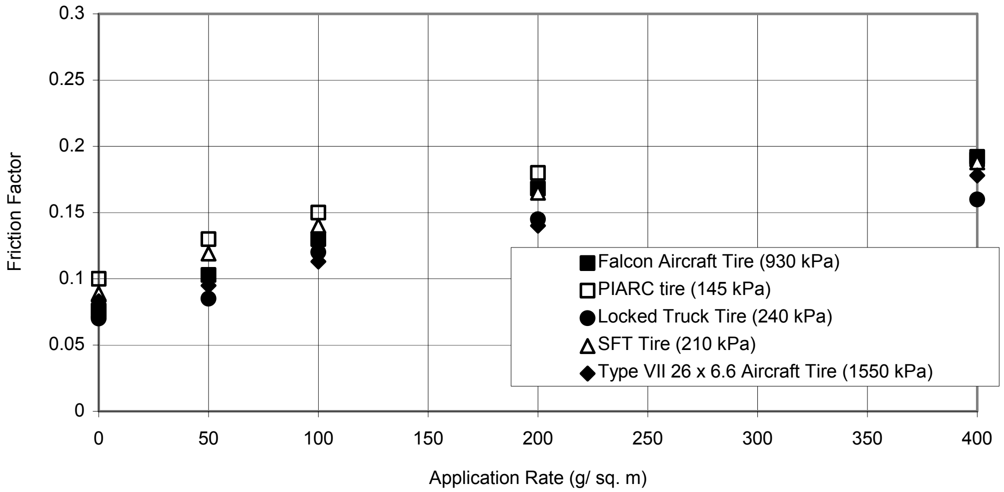


Figure 4.7: Friction Factors with Ottawa TC Sand on Ice - Test Temperature: -2°C

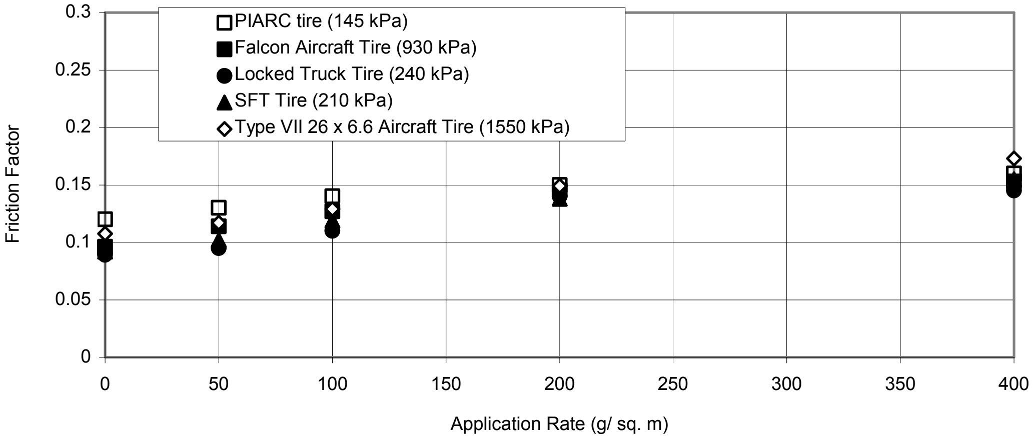


Figure 4.8: Friction Factors with Ottawa TC Sand on Ice – Test Temperature: -10°C

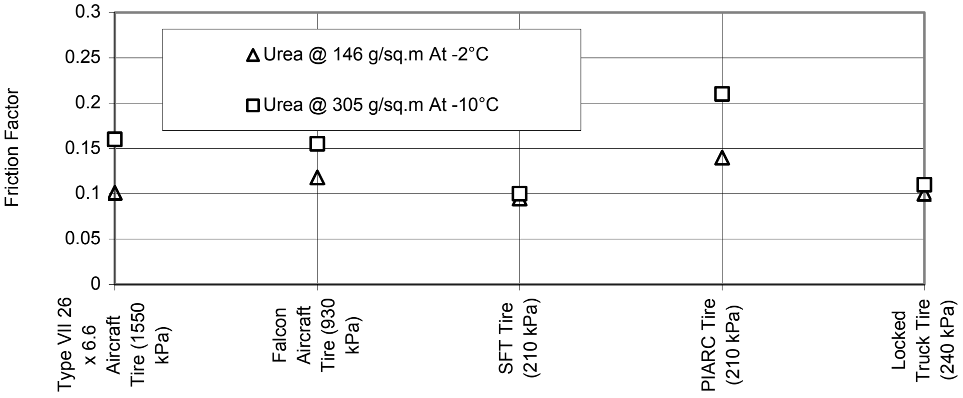


Figure 4.9: Friction Factors with Urea on Ice

4.3.2 Winter Surface Braking Friction Tests: Liquids on Asphalt

As expected, liquids on asphalt cause a reduction in the friction factor with respect to the bare and dry value (Figures 4.1 to 4.3). The tests show that:

(a) Effect of fluid type - The effect of fluid type depends on the tire type and pressure. For the high-pressure aircraft tire, the friction is similar for all liquids tested. However, for the lower pressure tires, potassium acetate, potassium formate and the Octagon Type II de-icing fluid all produced lower friction coefficients than those for a wetted surface (Figures 4.2 and 4.3). This variation (between the high and low pressure tires) is likely attributable to the higher viscosity of the de-icing fluids in comparison to water.

(b) Effect of application rate for potassium acetate and potassium formate - A variation in application rate from 20 to 40 ml/m^2 (0.5 to 1.0 US gallon/1000 ft^2, respectively) does not affect the measured friction factors significantly (Figures 4.2 and 4.3).

(c) The effect of potassium formate vs other liquids - The friction factors measured when potassium formate was present on the asphalt were similar to those measured with potassium acetate and the Octagon Type II de-icing fluid on asphalt (Figures 4.2 and 4.3). Potassium formate caused lower friction than a water-wetted surface, which is similar to the trends observed for potassium acetate and the Octagon Type II de-icing fluid.

(d) Effect of temperature - Lower friction was measured at -10°C than at -2°C, especially for the lower pressure tires (compare Figures 4.2 and 4.3). This variation (with respect to temperature) is likely due to an increase in fluid viscosity at lower temperatures.

4.3.3 Winter Surface Braking Friction Tests: Urea on Asphalt

The effect of urea on the measured friction is dependent on the tire type and pressure and on the temperature, as the urea was partially dissolved in a slurry at -2°C, whereas it remained solid at -10°C. Consequently, at -2°C, it reduced the friction significantly with respect to the values for a bare and dry or a wet asphalt surface, especially for the lower pressure tires (Figure 4.4). The higher pressure tires did not “see” this reduction to the same extent, as higher friction factors were measured with them. This variation (with respect to tire pressure) likely reflects better contact with the asphalt for the higher pressure tires.

At -10°C, the urea prills remained solid and were crushed into a powder by the high pressure (1550 kPa) tire. This condition produced a drop in friction in comparison to bare and dry asphalt (Figure 4.4). This action (of crushing the prills) did not occur to the same extent for the lower pressure tires and they recorded lower friction than for the high pressure tires.

4.3.4 Winter Surface Braking Friction Tests: Liquids on Ice

None of the de-icing fluids tested caused a significant change in the friction factor, compared to the value for a bare and dry ice surface (Figures 4.5 and 4.6). However, water on the ice reduced the friction by about 50%, compared to the value for a bare and dry ice surface (Figure 4.5).

4.3.5 Winter Surface Braking Friction Tests: Sand on Ice

All of the tires recorded an increase in friction factor with increasing application rate. Furthermore, the general trends were similar for each tire as the curves “track” each other (Figures 4.7 and 4.8).

However, the friction factor magnitudes varied with the tire type as higher friction was measured with the higher pressure tires. This probably reflects better contact and bonding between the sand, the ice, and the tire at higher contact pressures.

The friction factors were higher at -2°C than at -10°C for all rates and tires (Figures 4.7 and 4.8). This reflects the fact that the ice is softer at -2°C, which allows for better contact and bonding between the sand, the ice, and the tire.

4.3.6 Winter Surface Braking Friction Tests: Urea on Ice

As for the tests done on asphalt, the effect of urea was dependent on the tire type and pressure, and on the temperature, as the urea was partially dissolved in a slurry at -2°C whereas it remained solid at -10°C. Consequently, at -2°C, the friction was similar to that for a bare and dry ice surface, or for ice with de-icing chemicals on it for all tires (Figure 4.9).

At -10°C, the prills remained solid, adding texture to the ice surface. As a result, the higher pressure tires recorded an increase in friction, in comparison to a bare and dry ice surface (Figure 4.9). The lower pressure tires did not “see” a similar increase in friction, probably due to poorer contact at the tire-urea-ice interface.

4.4 Load and Pressure Study

4.4.1 Data Summary

These tests were done using the Type VII 26.6 x 6.6 aircraft tire. The measured friction factors and tire footprint areas are summarized in Tables 4.7 and 4.8, respectively.

Table 4.7: Load and Pressure Study Data Summary

Surface	Temp (°C)	Load (kN)	Inflation Pressure (kPa)	Friction Factor
Ice	-10	6.73	940	0.15
		13.47	940	0.11
		20.35	940	0.079
		6.73	550	0.16
		13.94	550	0.11
		19.78	550	0.089
		6.82	210	0.15
		13.71	210	0.11
		19.86	210	0.071
Frozen Snow	-10	6.72	940	0.16
		14.19	940	0.13
		19.32	940	0.12
		6.94	550	0.16
		13.95	550	0.12
		19.93	550	0.13
		6.78	210	0.17
		14.35	210	0.13
		19.26	210	0.12

Table 4.8: Gross and Net Tire Footprint Areas

Surface	Temp (°C)	Load (kN)	Inflation Pressure (kPa)	Gross Contact Area (cm^2)	Net Contact Area (cm^2)
Frozen Snow	-10	6.27	940	77	60
		13.43	940	127	104
		19.40	940	172	137
		6.32	550	89	71
		13.38	550	183	146
		19.00	550	219	178
		6.27	210	163	128
		13.03	210	246	198
		18.90	210	387	325

4.4.2 Results

The friction factors on ice and frozen snow both reduce with increasing load for each inflation pressure (Figures 4.10 and 4.11, respectively). The friction factor was not related to the inflation pressure for either substrate.

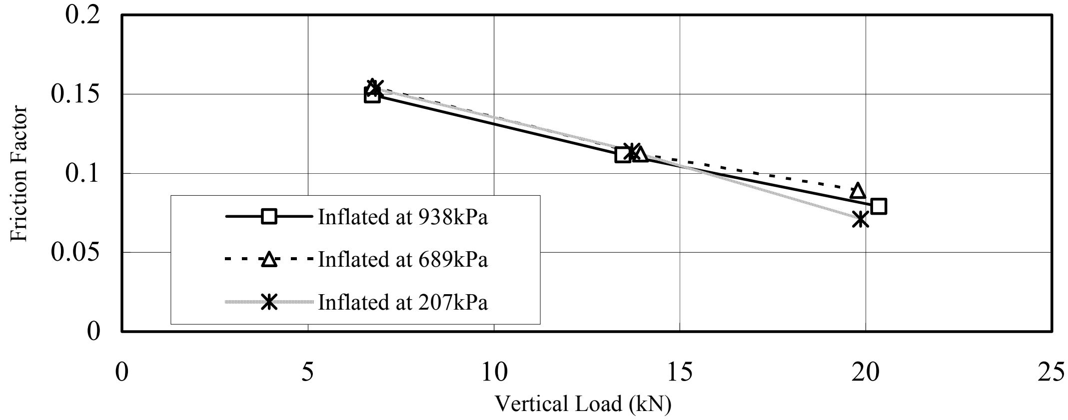


Figure 4.10: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire Surface Tested: Bare Ice; Test Temp.: -10°C

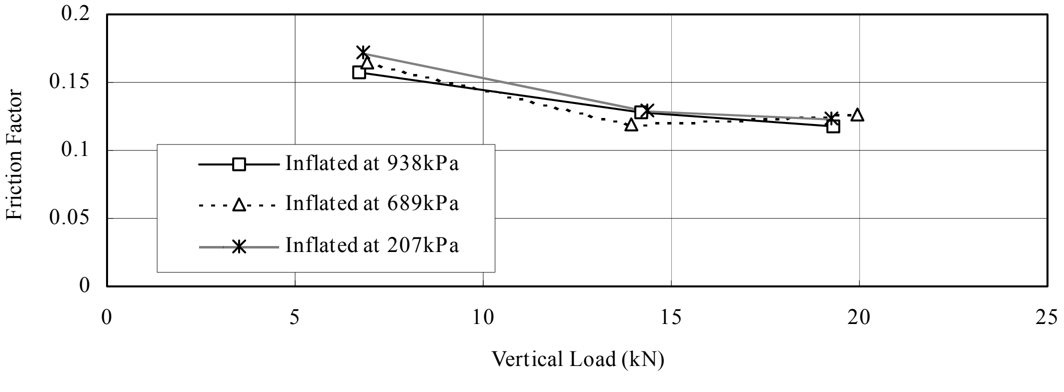


Figure 4.11: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire Surface Tested: Frozen Snow; Test Temp.: -10°C

These results are similar to those obtained during the "Load and Pressure" Study conducted at the 1998 North Bay field trials using the National Aeronautics Space Administration's (NASA) Instrumented Tire Test Vehicle (ITTV) [4].

As expected, the gross and net tire footprint areas increase with the vertical load, and they decrease with increasing inflation pressure (Figures 4.12 and 4.13, respectively).

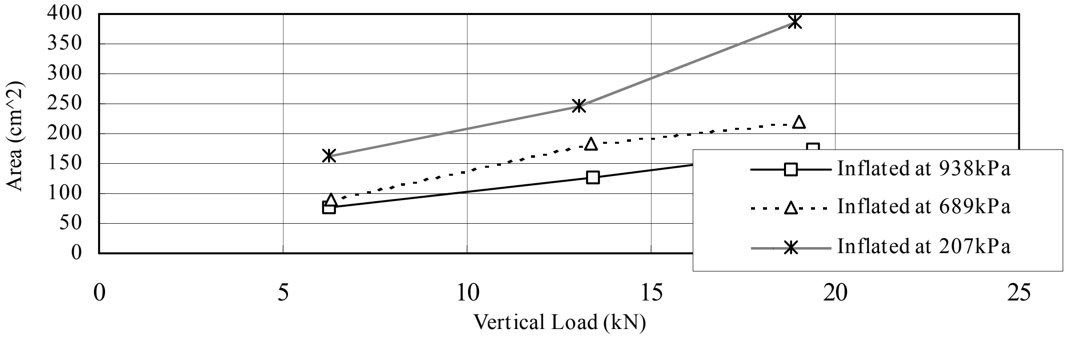


Figure 4.12: Gross Tire Footprint Area for the Type VII 26.6 x 6.6 Aircraft Tire Substrate: Frozen Snow; Test Temp.: -10°C

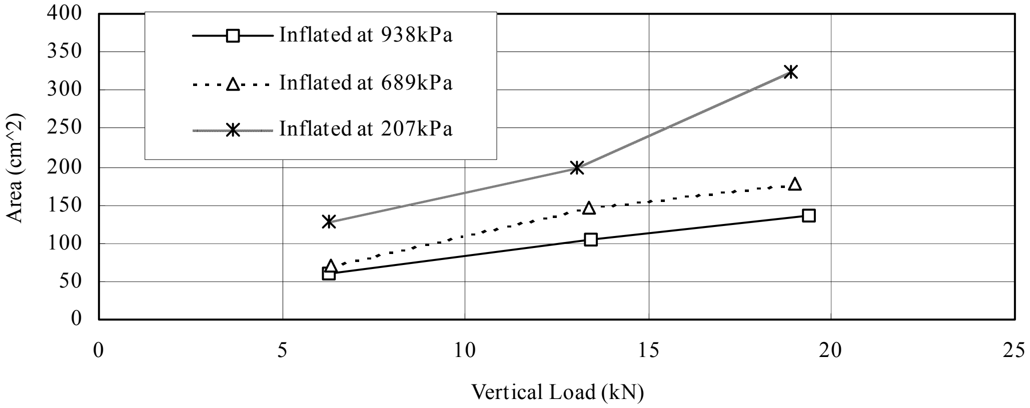


Figure 4.13: Net Tire Footprint Area for the Type VII 26.6 x 6.6 Aircraft Tire Substrate: Frozen Snow; Test Temp.: -10°C

The gross and net contact pressures were calculated for each test case. For each inflation pressure tested, the friction reduces as the gross contact pressure is increased on both the ice and the frozen snow (Figures 4.14 and 4.15, respectively).

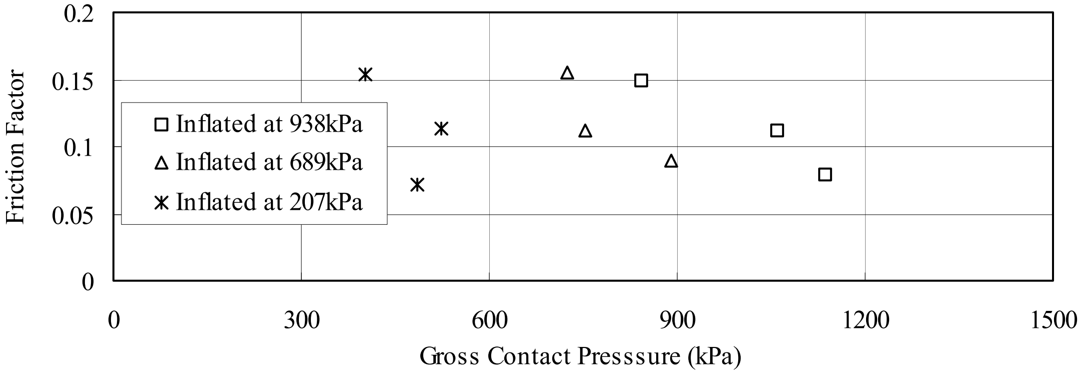


Figure 4.14: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire. Surface Tested: Bare Ice; Test Temp.: -10°C

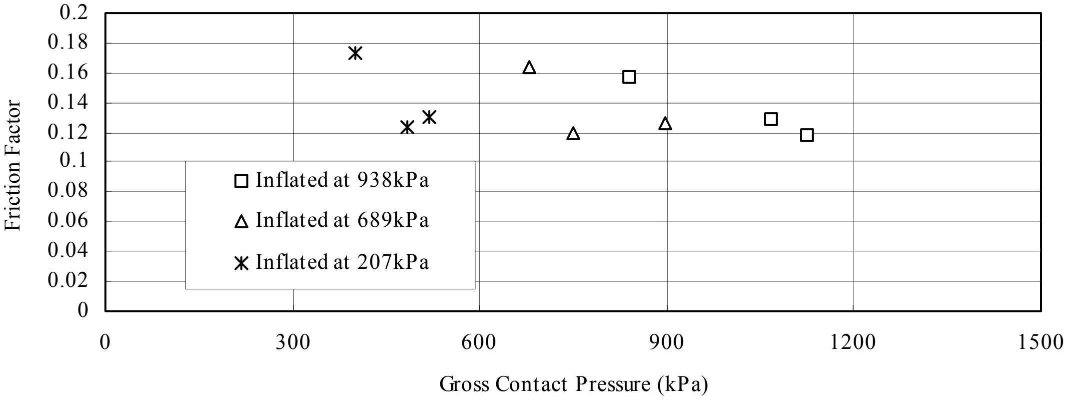


Figure 4.15: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire. Surface Tested: Frozen Snow; Test Temp.: -10°C

The effect of the net contact pressure on the friction on ice and frozen snow is shown on Figures 4.16 and 4.17, respectively. Similar trends are indicated since, for each inflation pressure tested, the friction reduces as the net contact pressure is increased on both ice and frozen snow.

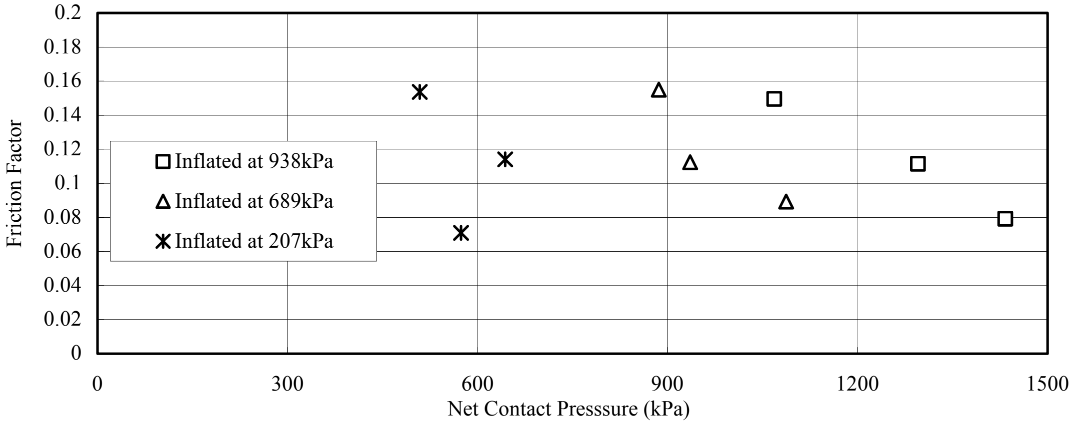


Figure 4.16: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire. Surface Tested: Bare Ice; Test Temp.: -10°C

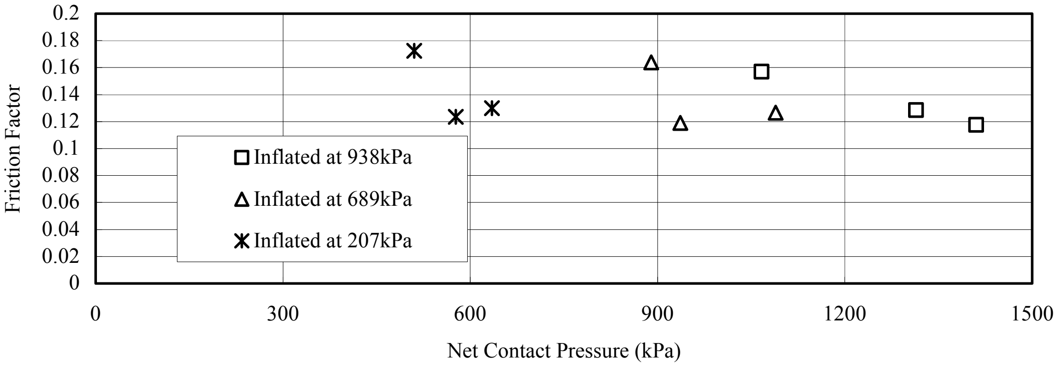


Figure 4.17: Load and Pressure Study Results Using the Type VII 26.6 x 6.6 Aircraft Tire. Surface Tested: Bare Ice; Test Temp.: -10°C

5. SAND FRICTION TESTS AND INVESTIGATION

5.1 Introduction and Objectives

- Laboratory Tests: Two types of sand friction tests were carried out, as follows:

(a) Local Sand Tests – Seven sands locally available at airports were tested on ice at temperatures of -5° and -15°C over a range of application rates. The objective of these tests was to compare the friction provided by these sands with a sand meeting the Transport Canada specification (termed TC Sand).

These test results are presented in section 5.2. They are also compared with the results of the local sand tests conducted in the previous program [1].

(b) Parametric Sand Friction Tests – These tests were conducted to investigate the effects of sand grain size, angularity, and area coverage on the friction produced.

The effects of these parameters were isolated by sieving the three local sands tested into four different grain size ranges. The sand produced for each grain size range was applied on ice and frozen snow at temperatures of -5° and -15° C at a number of rates.

These test results are presented and discussed in sections 5.3 to 5.6.

- The Production of a Sand Advisory Circular – This was produced using the laboratory test data as well as many other sources of published information. The Sand Advisory Circular has been published under separate cover [2].

5.2 Local Sand Friction Tests

5.2.1 Description of Local Sands Tested

The size gradations of the sands as they were received are provided in Appendix A. Each of the sands was sieved with a no. 4 sieve, and the material passing it was used for testing. The Sault Ste. Marie coarse sand, the two Waterloo-Guelph crushed limestone materials, the Windsor sand, and the Norway sand were all very close to or within the TC specification (Table 5.1). The Kapuskasing fine sand, and the North Bay MTO sand were much finer than TC sand, and contained a wider range of grain sizes (Table 5.1). For completeness, the size gradations of the other local sands tested previously [1] are copied in Appendix B. These other local sands were also passed through a no. 4 sieve before testing, and the plots in Appendix B show the size gradations before this was done. The resulting size gradations for the sands are plotted in Section 5.4 (Figure 5.14), which presents analyses done using the sand friction data.

The angularity of the sands tested was documented using the visual inspection techniques specified in ASTM D 2488-93 [5]. See also Figure 5.1. Table 5.2 summarizes these results for the sands tested in this program as well as those tested previously [1].

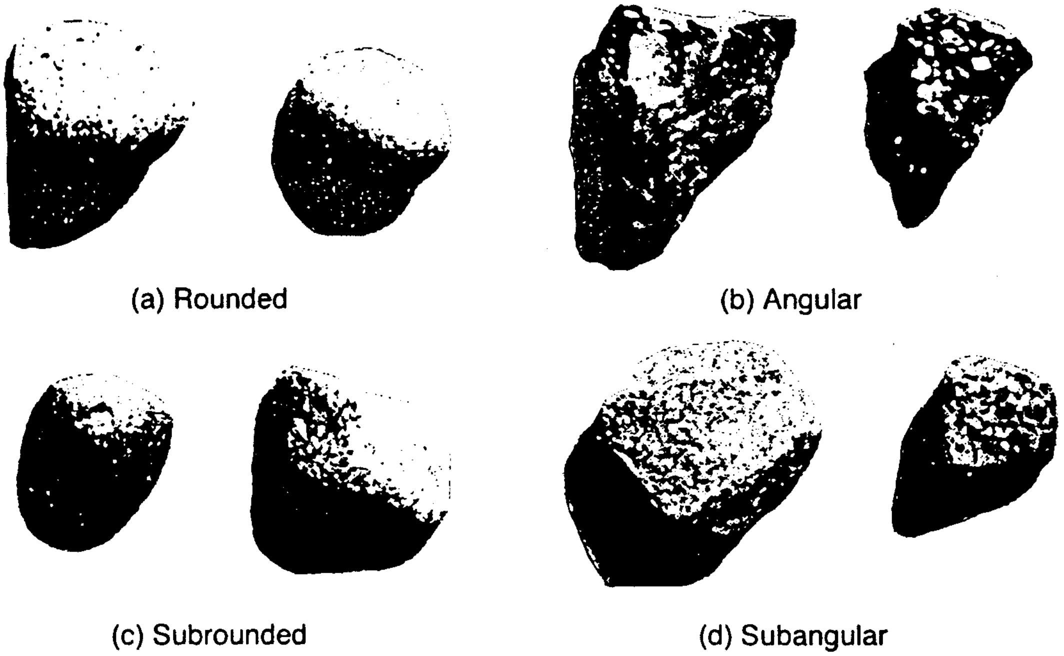


Figure 5.1: Typical Angularity of Sand Grains by Classifications (after [5])

In subsequent sections, attempts are made to investigate friction trends with respect to the weighted-average grain size of the sand, the area coverage, and the angularity index (defined subsequently). Consequently, these parameters are also listed in Table 5.2 for all of the sands tested in this program as well as the previous one [1].

Table 5.1: Local Sand Description: Comparison to TC Size Specification

Sand Source & Description Used	Comparison to Transport Canada Size Specification	
	Sizes (i.e.,Coarser Vs Finer)	Size Range
• **Sands Tested Previously [1]:**		
Red Lake Airport - Pit - Run	All particles finer	Wider size range
New Liskeard - Earlton Airport Sand	All particles finer	Wider size range
Timmins Airport Sand	All particles finer	Much wider size range
Kapuskasing Airport Sand	All particles finer	Much wider size range
S.S. Marie Airport - MTO Sand	All particles finer	Much wider size range
S.S. Marie - Crushed Rock(sand-gravel-sandstone)	Mainly Falls Within Transport Canada Specification	
Churchill Airport - Gravel Pit Beach	All particles finer	Much wider size range
Churchill Airport - Gravel Pit	All particles finer	Much wider size range
Churchill Airport - Crushed Rock	Most particles finer	Wider size range
Dryden Airport Sand	All coarser sizes	About the same size range
Ottawa Airport - TC Sand	Falls Within Transport Canada Specification	
Churchill Airport - TC Sand	Falls Within Transport Canada Specification	
Sudbury Airport Sand	Falls Within Transport Canada Specification	
Flin Flon Airport Sand	Mainly Falls Within Transport Canada Specification	
Manitoulin Isl. Airport - Crushed Screenings	Mainly Falls Within Transport Canada Specification	
Lynn Lake Airport Sand	Mainly Falls Within Transport Canada Specification	
• **Sands Tested In This Project:**		
Sault Ste. Marie Coarse Sand	Near the fine edge of the TC Specification	
Waterloo-Guelph Crushed Limestone 1	Within TC Specification	
Waterloo-Guelph Crushed Limestone 2	Mainly within TC Specification	
North Bay MTO Sand	Mostly finer sizes	Much wider size range
Windsor Airport Sand	At coarse edge of TC Specification	
Kapuskasing Fine Sand	Mostly finer sizes	Much wider size range
Norway	Follows coarse edge of TC Specification	

Table 5.2: Local Sand Description Summary

Sand Source & Description	Coverage (%) At 100 g/m^2	Material Angularity Description Using ASTM D 2488-93				Avg. Grain Size (mm)
		% Rounded	% SubRounded	% Subangular	% Angular	
Red Lake Airport - Pit - Run	10.6	70	20	10	0	0.52
New Liskeard - Earlton Airport Sand	5.5	10	30	50	10	0.99
Timmins Airport Sand	16.9	90	5	5	0	0.3
Kapuskasing Airport Sand	7.3	90	10	0	0	0.75
S.S. Marie Airport - MTO Highway Sand	14.9	80	10	10	0	0.37
S.S. Marie Airport - Crushed Rock(sand-gravel-sandstone)	5.5	10	10	30	50	0.87
Churchill Airport - Gravel Pit Beach	10.7	90	5	5	0	0.52
Churchill Airport - Gravel Pit	14	90	10	0	0	0.39
Churchill Airport - Crushed Rock	2.8	0	0	20	80	1.7
Dryden Airport Sand	2.0	0	0	50	50	2.76
Ottawa Airport - TC Sand	4.1	0	0	20	80	1.34
Churchill Airport - TC Sand	2.7	0	10	60	30	2.02
Sudbury Airport Sand	3.4	0	0	10	90	1.64
Flin Flon Airport Sand	4.6	0	40	60	0	1.20
Manitoulin Isl. Airport - Crushed Screenings	3.7	0	0	10	90	1.45
Lynn Lake Airport Sand	3.4	10	40	40	10	1.44
Sault Ste. Marie Coarse Sand	5.5	0	30	70	0	1.01
Waterloo-Guelph Crushed Limestone 1	3.4	0	0	20	80	1.61
Waterloo-Guelph Crushed Limestone 2	3.0	0	10	70	20	1.83
North Bay MTO Sand	19.5	60	30	10	0	0.28
Windsor Airport Sand	2.6	0	0	10	90	2.18
Kapuskasing Fine Sand	19.3	90	10	0	0	0.29
Norway	2.5	0	0	20	80	2.27

5.2.2 Test Results: Friction Factors on Ice

At -5°C, the friction factor increased from a value for bare ice of 0.12 to a maximum of about 0.25 over the range of sand types and application rates tested (Figure 5.2). At -15°C, the friction factor increased from a value for bare ice of 0.14 to a maximum of about 0.24 over the range of sand types and application rates tested (Figure 5.3). These friction factor increases are similar to those measured for the other local sands tested previously [1].

For both test temperatures (i.e., -5° and -15°C), the friction increases with the application rate up to about 300 g/m^2 (Figures 5.2 and 5.3, respectively). At higher rates, the friction tends to "level off", indicating that less friction increase is provided by sand applications at the higher rates. This trend is similar to that observed previously [1].

For completeness, the data plots produced in the previous program [1] from tests on ice and frozen snow at the two test temperatures (i.e., -5° and -15°C) are copied in Appendix D.

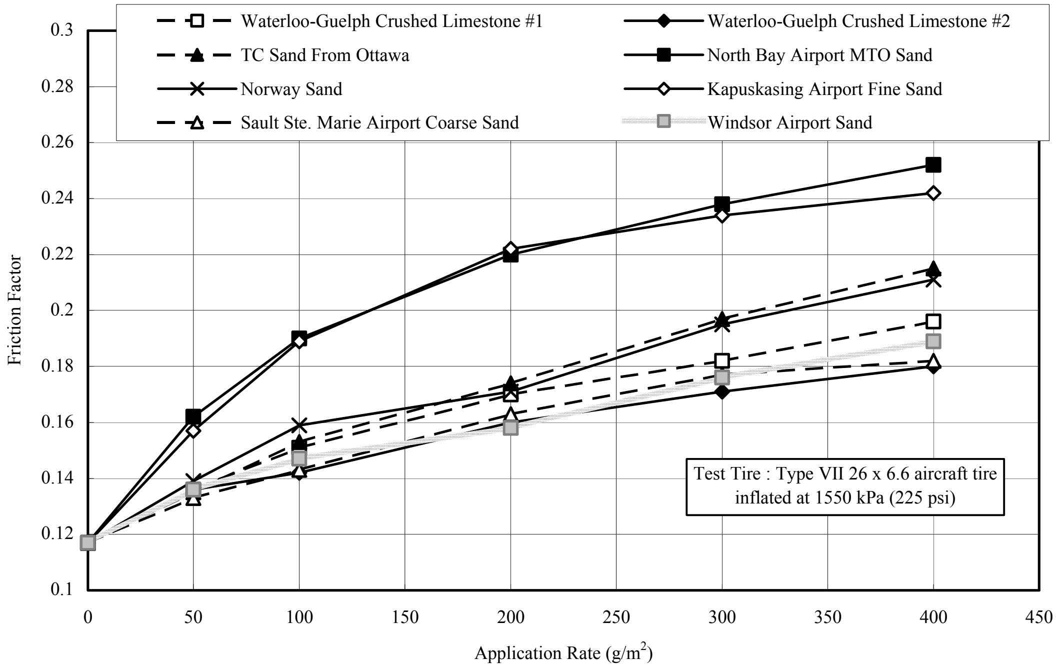


Figure 5.2: Local Airport Sands Applied on Ice at –5°C

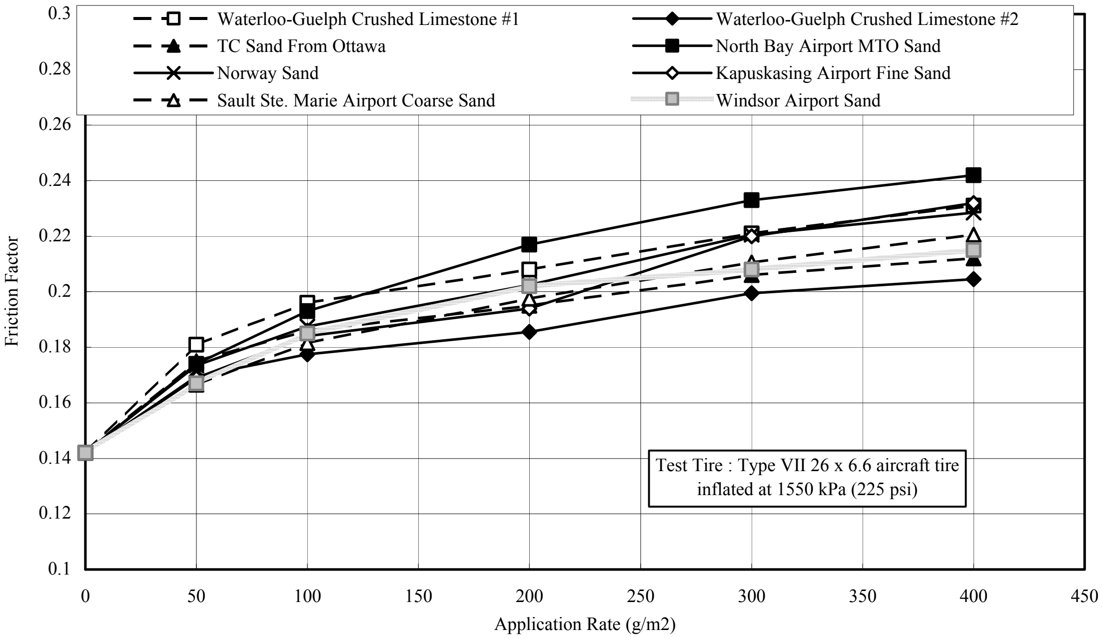


Figure 5.3: Local Airport Sands Applied on Ice at –15^{o}C

5.2.3 Test Results: Relative Rankings of the Local Sands

The local sands are ranked with respect to the friction factors they produced <u>on ice</u> at -5° and -15°C in Tables 5.3 and 5.4, respectively. For completeness, the rankings have been done for all sands tested, including those tested in the previous program [1].

For completeness, the relative rankings produced in the previous test program with respect to the friction factors on <u>frozen snow</u> at -5° and -15°C are reproduced (from [1]) in Tables 5.5 and 5.6, respectively.

The sands producing higher and lower friction <u>on ice</u> are summarized below:

- Sands within the top third ranking for both application rates:

<u>Test Temperature: -5°C</u>	<u>Test Temperature: -15°C</u>
Churchill gravel pit beach	Churchill gravel pit beach
Red Lake	Red Lake
Kapuskasing – sand	Kapuskasing – sand
North Bay MTO	New Liskeard-Earlton
Timmins	Flin Flon
Kapuskasing – Fine Sand	Sault Ste. Marie – Crushed Rock
Sault Ste. Marie – MTO	

- Sands within the bottom third ranking for both application rates:

Test Temperature: -5°C	Test Temperature: -15°C
Churchill – crushed rock	Ottawa TC sand
Flin Flon	Churchill TC sand
Manitoulin Isl. – crushed screenings	Dryden
Sudbury	Sault Ste. Marie – coarse sand
	Windsor
	Waterloo-Guelph – Crushed Limestone 2

These results suggest that:

(a) fine vs coarse – in general, the finer sands tended to produce higher friction while the coarser materials tended to provide lower friction.

(b) effect of temperature – a clear trend is not evident. Some sands provided superior performance at both temperatures, while for others, their ranking (and hence performance) varied with temperature (see above summary).

Table 5.3: Rankings Based on the Friction Produced on Ice at -5°C

Application Rate: 50 g/m^2		**Application Rate: 100 g/m^2**	
Sand: Airport & Description	Rank	Sand: Airport & Description	Rank
Churchill - Gravel pit beach	1	Red Lake – Pit-Run	1
Red Lake - Pit-Run	2(tie)	Churchill – Gravel pit beach	2
Timmins - Sand	2(tie)	Kapuskasing - Fine Sand	3(tie)
North Bay - MTO sand	4	North Bay - MTO sand	3(tie)
Kapuskasing - Sand	5	Timmins – Sand	5(tie)
Kapuskasing - Fine Sand	6(tie)	Kapuskasing - Sand	5(tie)
Sault Ste. Marie - MTO sand	6(tie)	Lynn Lake - Sand	7(tie)
Lynn Lake - Sand	8	Sault Ste. Marie - MTO sand	7(tie)
Churchill - Gravel Pit	9	Churchill – Gravel Pit	7(tie)
Sault Ste. Marie - Crushed Rock	10	Sault Ste. Marie - Crushed Rock	10
Waterloo-Guelph : Crushed Limestone 1	11(tie)	New Liskeard-Earlton - Sand	11(tie)
New Liskeard-Earlton - Sand	11(tie)	Dryden	11(tie)
Waterloo-Guelph : Crushed Limestone 2	13(tie)	Norway	13
Norway	13(tie)	Waterloo-Guelph: Crushed Limestone 1	14
Sault Ste. Marie - Coarse sand	15(tie)	Ottawa - TC Sand	15(tie)
Windsor - Sand	15(tie)	Churchill - TC Sand	15(tie)
Dryden	17	Flin Flon - Sand	15(tie)
Churchill - Crushed Rock	18(tie)	Windsor	18
Flin Flon - Sand	18(tie)	Waterloo-Guelph: Crushed Limestone 2	19
Ottawa - TC Sand	20(tie)	Sudbury - Sand	20(tie)
Churchill - TC Sand	20(tie)	Manitoulin Island - Crushed Screenings	20(tie)
Sudbury - Sand	22	Sault Ste. Marie - Coarse sand	20(tie)
Manitoulin Island - Crushed Screenings	23	Churchill - Crushed Rock	23

Table 5.4: Rankings Based on the Friction Produced on Ice at -15°C

Application Rate: 50 g/m^2			**Application Rate: 100 g/m^2**	
Sand: Airport & Description	Rank		Sand: Airport & Description	Rank
Red Lake - Pit-Run	1		Red Lake - Pit-Run	1
New Liskeard-Earlton - Sand	2		New Liskeard-Earlton - Sand	2 (tie)
Sault Ste. Marie - Crushed Rock	3		Sault Ste. Marie – Crushed Rock	2 (tie)
Kapuskasing - Sand	4		Flin Flon – Sand	4
Flin Flon - Sand	5		Timmins - Sand	5
Churchill - Gravel Pit	6		Churchill - Gravel Pit	6
Waterloo-Guelph: Crushed Limestone 1	7		Sudbury	7 (tie)
Churchill - Gravel pit beach	8		Kapuskasing - Sand	7 (tie)
Timmins - Sand	9		Manitoulin Island - Crushed Screenings	9 (tie)
Manitoulin Island - Crushed Screenings	10 (tie)		Churchill - Gravel pit beach	9 (tie)
North Bay - MTO sand	10 (tie)		Lynn Lake - Sand	11(tie)
Norway	10 (tie)		Waterloo-Guelph : Crushed Limestone 1	11(tie)
Sault Ste. Marie – MTO sand	13 (tie)		Churchill - Crushed Rock	11(tie)
Churchill - Crushed Rock	13 (tie)		Sault Ste. Marie - MTO sand	14(tie)
Lynn Lake - Sand	13 (tie)		North Bay - MTO sand	14(tie)
Kapuskasing - Fine Sand	16 (tie)		Ottawa - TC Sand	16
Waterloo-Guelph: Crushed Limestone 2	16 (tie)		Norway	17
Sudbury	16 (tie)		Windsor	18(tie)
Windsor	19 (tie)		Kapuskasing - Fine Sand	18(tie)
Sault Ste. Marie - Coarse sand	19 (tie)		Sault Ste. Marie - Coarse sand	20
Ottawa - TC Sand	21		Dryden	21
Churchill - TC Sand	22		Waterloo-Guelph: Crushed Limestone 2	22
Dryden	23		Churchill - TC Sand	23

The sands producing higher and lower friction on frozen snow are summarized below:

- Sands above the median ranking for both application rates:

Test Temperature: -5°C	Test Temperature: -15°C
Churchill gravel pit	Churchill gravel pit
New Liskeard-Earlton	New Liskeard-Earlton
Flin Flon	Churchill TC sand
Churchill gravel pit beach	

- Sands below the median ranking for both application rates:

Test Temperature: -5°C	Test Temperature: -15°C
Ottawa TC sand	Ottawa TC sand
Dryden	Dryden
Churchill TC sand	Lynn Lake
Manitoulin Isl – crushed screenings	

These result are somewhat similar to those for ice as they suggest that:

(a) fine vs coarse – in general, the finer sands tended to produce higher friction while the coarser materials tended to provide lower friction.

(b) effect of temperature – a clear trend is not evident. Some sands provided superior performance at both temperatures, while for others, their ranking (and hence performance) varied with temperature (see above summary).

The factors controlling the friction produced are investigated further in Section 5.2.5.

Table 5.5: Rankings Based on the Friction on Frozen Snow at -5°C

Application Rate: 50 g/m^2		**Application Rate: 100 g/m^2**	
Sand: Airport & Description	Rank	Sand: Airport & Description	Rank
Churchill Airport - Gravel Pit Beach	1	Red Lake Airport Sand	1
Churchill Airport - Gravel Pit	2	New Liskeard - Earlton Airport Sand	2(tie)
New Liskeard - Earlton Airport Sand	3(tie)	Flin Flon Airport Sand	2(tie)
Flin Flon Airport Sand	3(tie)	Churchill Airport - Gravel Pit Beach	2(tie)
Churchill Airport - Crushed Rock	5(tie)	Churchill Airport - Gravel Pit	2(tie)
Lynn Lake Airport	5(tie)	Lynn Lake Airport	6
Red Lake Airport Sand	7(tie)	Dryden Airport Sand	7(tie)
Dryden Airport Sand	7(tie)	Churchill Airport - Crushed Rock	7(tie)
Ottawa Airport - TC Sand	9	Ottawa Airport - TC Sand	9
Churchill Airport - TC Sand	10	Manitoulin Island - Crushed Screenings	10(tie)
Manitoulin Island - Crushed Screenings	11	Churchill Airport - TC Sand	10(tie)

Table 5.6: Rankings Based on the Friction on Frozen Snow at -15°C

Application Rate: 50 g/m^2		**Application Rate: 100 g/m^2**	
Sand: Airport & Description	Rank	Sand: Airport & Description	Rank
Churchill Airport - Gravel Pit	1	Churchill Airport - TC Sand	1 (tie)
Churchill Airport - Gravel Pit Beach	2(tie)	Churchill Airport - Gravel Pit	1 (tie)
New Liskeard - Earlton Airport Sand	2(tie)	Manitoulin Island - Crushed Screenings	3(tie)
Churchill Airport - Crushed Rock	2(tie)	Red Lake Airport Sand	3(tie)
Churchill Airport - TC Sand	5	New Liskeard - Earlton Airport Sand	3(tie)
Manitoulin Island - Crushed Screenings	6	Flin Flon Airport Sand	3(tie)
Flin Flon Airport Sand	7	Churchill Airport - Gravel Pit Beach	7(tie)
Red Lake Airport Sand	8	Churchill Airport - Crushed Rock	7(tie)
Dryden Airport Sand	9	Lynn Lake Airport	9
Lynn Lake Airport	10	Dryden Airport Sand	10
Ottawa Airport - TC Sand	11	Ottawa Airport - TC Sand	11

5.2.4 Quantities Required for the Various Sands to Provide the Same Friction

The test results have shown that all of the sands provided an increase in friction when applied on ice and frozen snow. Within limits, the same friction level could be obtained from each sand by applying more or less of it onto the surface.

The local sands were compared with respect to the relative application rates required for ice and frozen snow. The application rate ratio ($\text{Rate}_{\text{ratio}}$) was defined using equation 5.1, and determined for each sand. See Table 5.7. For completeness, the results obtained during the previous test program [1] are also included in Table 5.7.

$$\text{Rate}_{\text{ratio}} = \text{Rate}_{\text{local for TC sand at 100 g/sq.m}} \;/\; 100 \text{ g/sq.m} \qquad [5.1]$$

where: $\text{Rate}_{\text{local for TC sand at 100 g/sq.m}}$ = the application rate required for the local sand of interest to produce the same friction factor as Ottawa TC sand applied at 100 g/sq.m

Most of the sands provided better performance than did the Ottawa TC sand since they produced the same friction factor at lower application rates.

The attributes of sands producing higher and lower friction are investigated further in Section 5.2.5.

Table 5.7: Application Rate Comparison

Sand Source & Description	Application Rate Ratios (defined by equation 5.1)			
	Surface: Ice		Surface: Frozen Snow	
	Temp: -5°C	Temp: -15°C	Temp: -5°C	Temp: -15°C
Red Lake Airport - Pit - Run	0.28	0.29	0.65	0.62
New Liskeard - Earlton Sand	0.67	0.44	0.46	0.25
Timmins Airport Sand	0.37	0.67	Not Tested	Not Tested
Kapuskasing Airport Sand	0.43	0.50	Not Tested	Not Tested
S.S. Marie Airport - MTO Sand	0.45	0.93	Not Tested	Not Tested
S.S. Marie Airport - Crushed Rock	0.54	0.49	Not Tested	Not Tested
(sand-gravel-sandstone)				
Churchill Airport - Gravel Pit Beach	0.32	0.73	0.38	0.35
Churchill Airport - Gravel Pit	0.48	0.71	0.38	0.25
Churchill Airport - Crushed Rock	1.30	0.86	0.82	0.40
Dryden Airport Sand	0.70	1.14	0.91	0.83
Ottawa Airport - TC Sand	Not Applicable - Used As The Basis Of Comparison			
Churchill Airport - TC Sand	1.00	1.56	1.27	0.40
Sudbury Airport Sand	1.19	0.79	Not Tested	Not Tested
Flin Flon Airport Sand	0.74	0.58	0.46	0.52
Manitoulin Isl - Crushed Screenings	1.20	0.80	1.25	0.31
Lynn Lake Airport Sand	0.46	0.86	0.73	0.81
Sault Ste. Marie Coarse Sand	1.35	1.60	Not Tested	Not Tested
Waterloo-Guelph Crushed Limestone 1	0.97	0.75	Not Tested	Not Tested
Waterloo-Guelph Crushed Limestone 2	1.45	2.30	Not Tested	Not Tested
North Bay MTO Sand	0.38	0.90	Not Tested	Not Tested
Windsor Airport Sand	1.25	1.22	Not Tested	Not Tested
Kapuskasing Fine Sand	0.42	1.60	Not Tested	Not Tested
Norway	0.75	1.60	Not Tested	Not Tested

5.2.5 Analysis: Factors Affecting the Friction Produced

The effect of the following factors was investigated:

(a) The area coverage – As described in [1], for the same application rate, the finer sands cover a much greater percentage of the surface than do the coarser ones. This was identified in the previous work [1] as a significant parameter affecting the measured results. The area coverage was calculated with the same techniques used previously. The area coverage varied by a factor of about 10 for the local sands tested (Table 5.2).

(b) The grain size – This was investigated using the weighted-average grain size (calculated from the measured grain size distributions) as an index. The weighted average grain size ranged from 0.28 mm to 2.8 mm (Table 5.2).

(c) The angularity of the sand grains – The local sands were classified using the visual inspection techniques specified in ASTM D 2488-93 [5]. See also Figure 5.1. All of the local sands contained a range of material angularities (Table 5.2). The "angularity index" (A_I) was defined using equation 5.2 and trends were investigated with respect to it.

$$\begin{aligned} A_I = {} & \%\ \text{Rounded} \bullet \text{Weighting Factor}_{\text{Rounded}} + \\ & \%\ \text{Sub-Rounded} \bullet \text{Weighting Factor}_{\text{Sub-Rounded}} + \\ & \%\ \text{Sub-Angular} \bullet \text{Weighting Factor}_{\text{Sub-Angular}} + \\ & \%\ \text{Angular} \bullet \text{Weighting Factor}_{\text{Angular}} \end{aligned} \qquad [5.2]$$

where: % Rounded, % Sub-Rounded, % Sub-Angular, and % Angular = the percentages of rounded, sub-rounded, sub-angular, and angular particles defined using ASTM D 2488-93 [5], respectively.

$\text{Weighting Factor}_{\text{Rounded}}$, $\text{Weighting Factor}_{\text{Sub-Rounded}}$, $\text{Weighting Factor}_{\text{Sub-Angular}}$ and $\text{Weighting Factor}_{\text{Angular}}$ = the weighting factors applied for rounded, sub-rounded, sub-angular, and angular particles, respectively (values taken to be 1.0, 2.0, 3.0, and 4.0, respectively).

The angularity index ranges from a minimum of 100 (for a sand comprised entirely of rounded particles) to 400 (for a material comprised entirely of angular particles).

The effect of area coverage on the friction produced by sand applications on ice and frozen snow is shown in Figures 5.4 and 5.5, respectively.

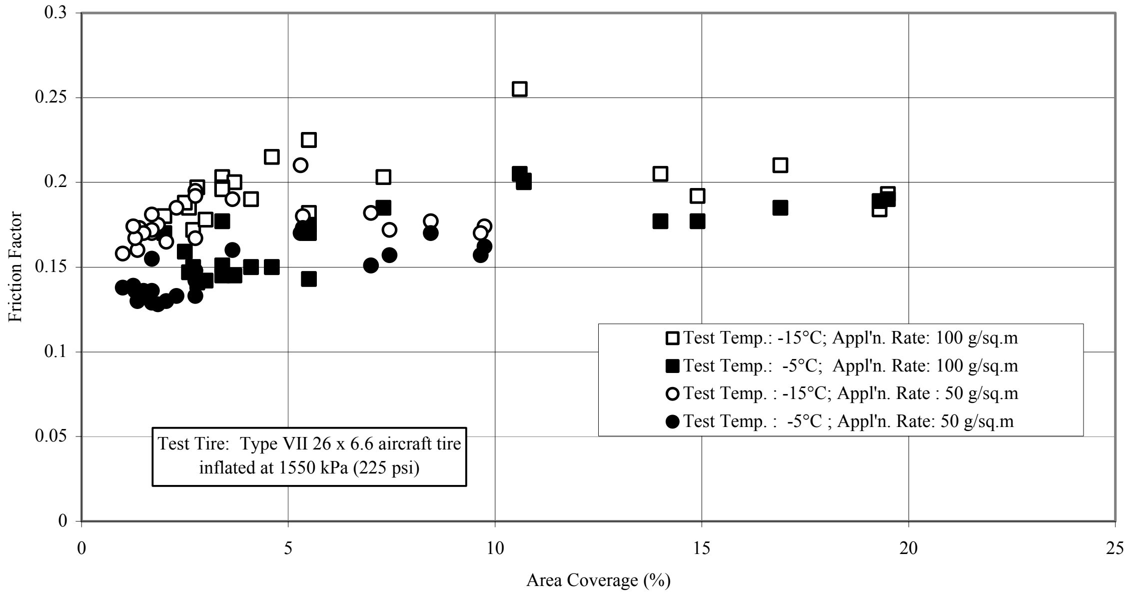


Figure 5.4: Friction Factor on Ice: Effect of Area Coverage

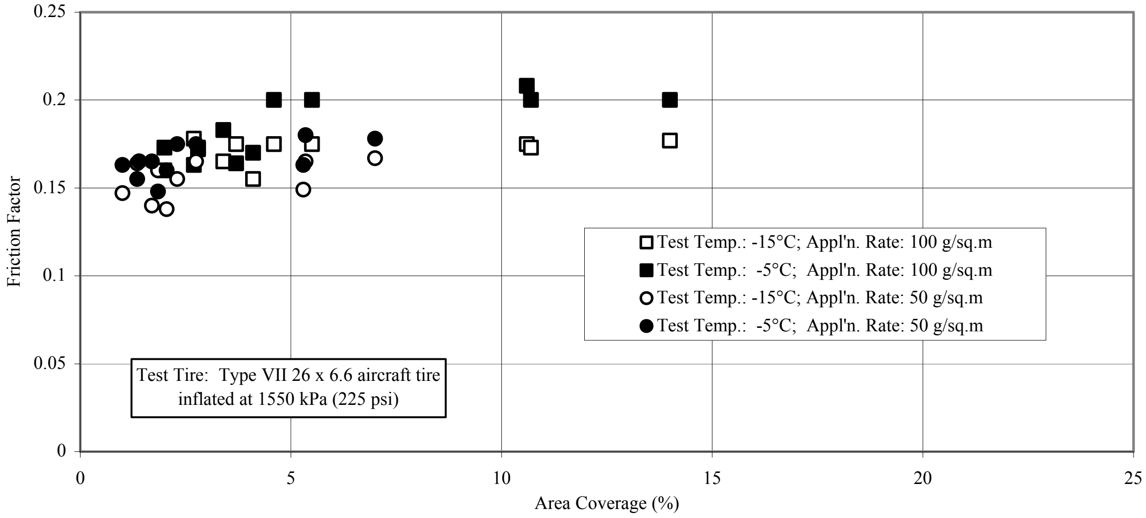


Figure 5.5: Friction Factor on Frozen Snow: Effect of Area Coverage

For both frozen snow and ice, the friction factor increases with the area coverage for coverages up to about 7%. At higher area coverages, the friction factor “levels off” indicating that it is not sensitive to the area coverage above that (Figures 5.4 and 5.5).

The effect of weighted-average grain size on the friction produced by sand applications on ice and frozen snow is shown in Figures 5.6 and 5.7, respectively.

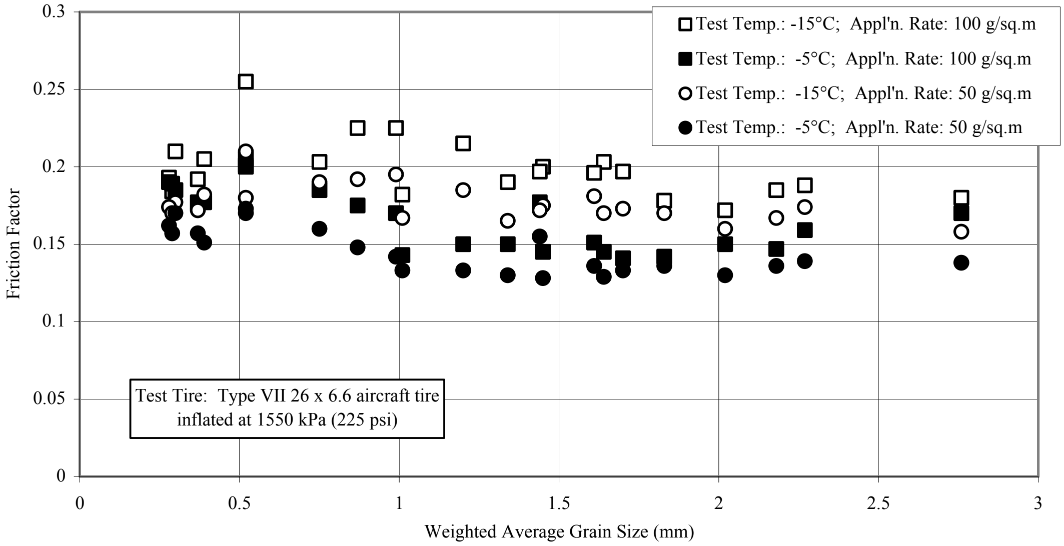


Figure 5.6: Friction Factor on Ice: Effect of Average Grain Size

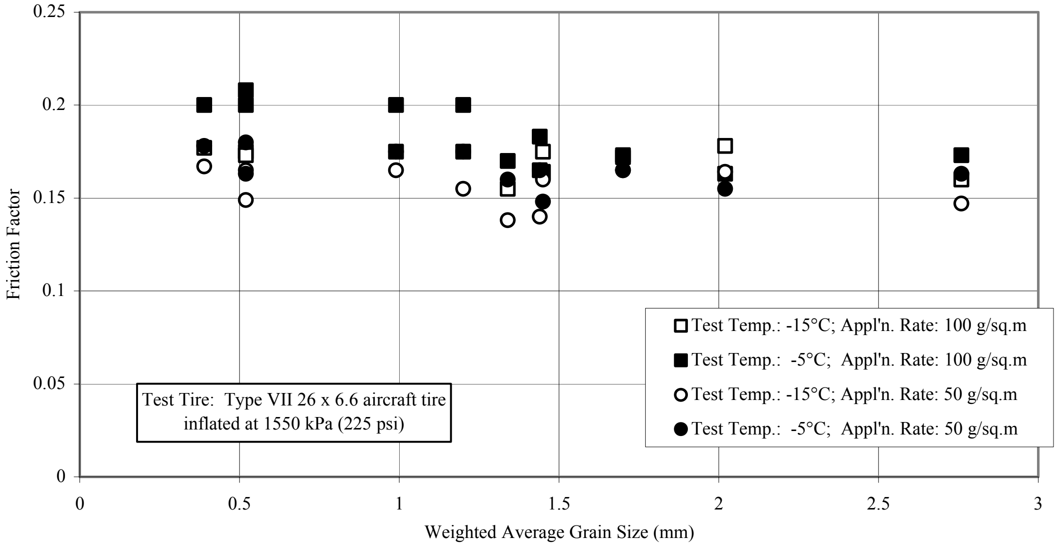


Figure 5.7: Friction Factor on Frozen Snow: Effect of Average Grain Size

The friction factor appears to decrease slightly with increasing grain size, which is opposite to the expected trend. However, direct comparisons are not possible because the area coverage was also changed, being largest for the smaller grain sizes. The effect of grain size is investigated directly in Section 5.3.

The effect of the angularity index (defined using equation 5.2) is shown in Figures 5.8 and 5.9, for sand applications on ice and frozen snow respectively.

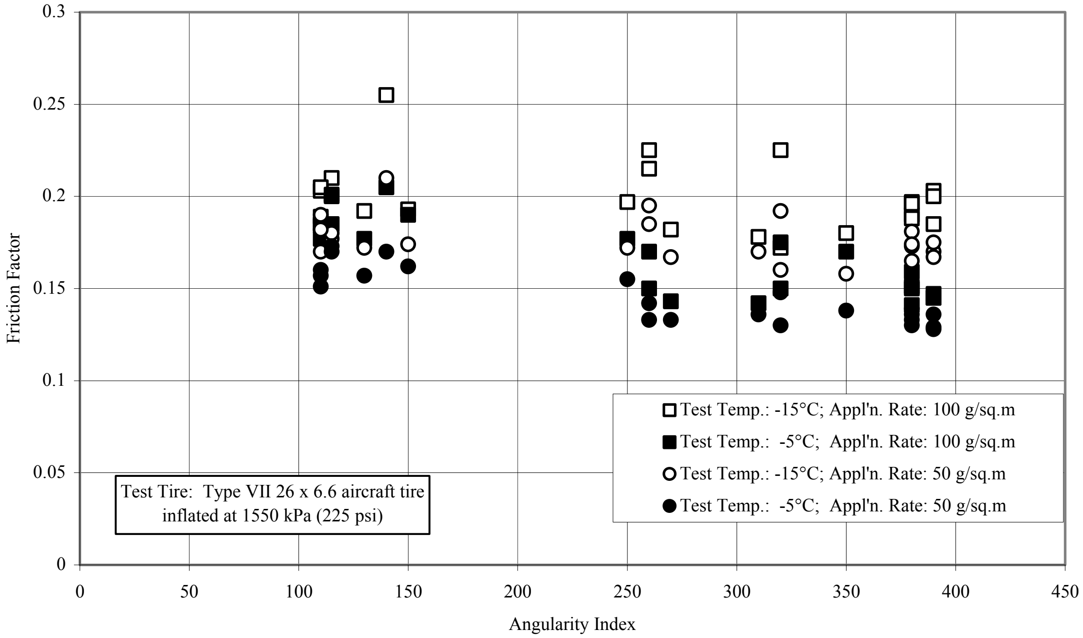


Figure 5.8: Friction Factor on Ice: Effect of Angularity

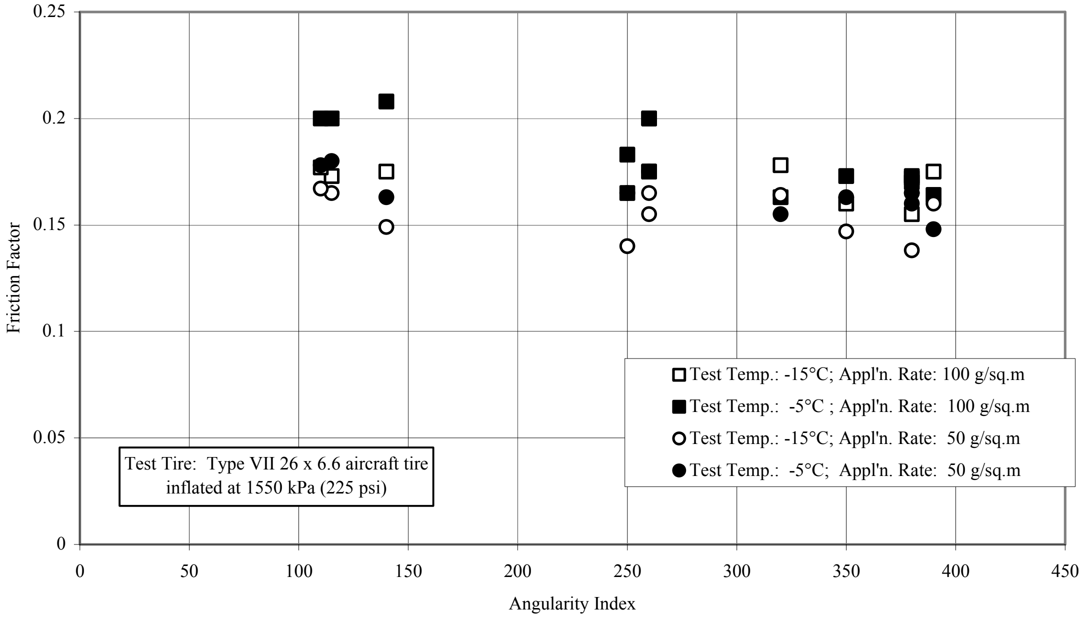


Figure 5.9: Friction Factor on Frozen Snow: Effect of Angularity

The friction factor appears to decrease with increasing angularity, which is opposite to the expected trend. However, direct comparisons are not possible because the area coverage was also changed, being largest for the sands with smaller, more-rounded grains. The effect of angularity is investigated directly in Section 5.3.

5.3 Parametric Sand Friction Tests Using the Aircraft Tire

5.3.1 Objectives

The parametric sand friction tests were conducted to obtain better understanding of the factors controlling sand friction on frozen snow and ice. The test matrix (described in Section 2.2) was selected to:

(a) isolate and quantify the effects of area coverage, sand grain size, and sand grain angularity with respect to the friction produced by sand applications;

(b) compare the results for bare ice and for frozen snow surfaces;

(c) compare the results for temperatures of -5° and -15°C;

(d) compare the results for the Type VII 26 x 6.6 aircraft tire (at 1550 kPa) and the low-pressure SFT tire (at 210 kPa). This section presents the results obtained using the aircraft tire. The results obtained with the low-pressure SFT tire are presented in Section 5.6.

The sand angularity was varied by testing three sands with grains that ranged in shape from primarily angular to primarily rounded (i.e., the Ottawa TC sand, the Flin Flon airport sand, and the Red Lake airport sand, respectively). The Angularity Indexes for these respective sands were 380, 260, and 140, respectively (Table 2.8, in Section 2).

The area coverage was varied independently from the grain size by:

(a) sieving each sand into four grain size ranges (i.e., <1.18 mm; 1.18 to 2.0 mm; 2.0 to 2.4 mm; and 2.4 to 4.0 mm); and,

(b) testing each sieved size bin at application rates ranging from 50 to 400 g/m^2. To provide comparative baseline data, the whole size gradation was tested for each sand for each condition (i.e., substrate, temperature and tire type) as well.

This procedure varied the area coverage as summarized in Table 5.8.

Table 5.8: Area Coverage Variation during the Test Program

Size Range (mm)	Area Coverage Range (%) for Application Rates Ranging from 50 to 400 g/m^2		
	Red Lake Sand	Ottawa TC Sand	Flin Flon Sand
< 1.18	8.7 to 70.0	12.8 to 102	7.4 to 59.4
1.18 to 2.0	1.8 to 14.0	1.8 to 14.0	1.8 to 14.0
2.0 to 2.4	1.3 to 10.1	1.3 to 10.1	1.3 to 10.1
2.4 to 4.0	0.9 to 7.0	0.9 to 7.0	0.9 to 7.0
Whole Dist'n.	5.3 to 42.4	2.1 to 16.5	2.3 to 18.6

5.3.2 Results Using the Type VII 26 x 6.6 Aircraft Tire: Effect of Application Rate

Sample results showing the effect of application rate are presented for ice and frozen snow in Figures 5.10 and 5.11, respectively. A complete set of these plots for all cases tested (i.e., grain size ranges; substrates [ice and frozen snow]; and temperatures [-5° and -15°C]) are contained in Appendices F, G, and H for the Red Lake sand, the Ottawa TC sand, and the Flin Flon airport sands, respectively.

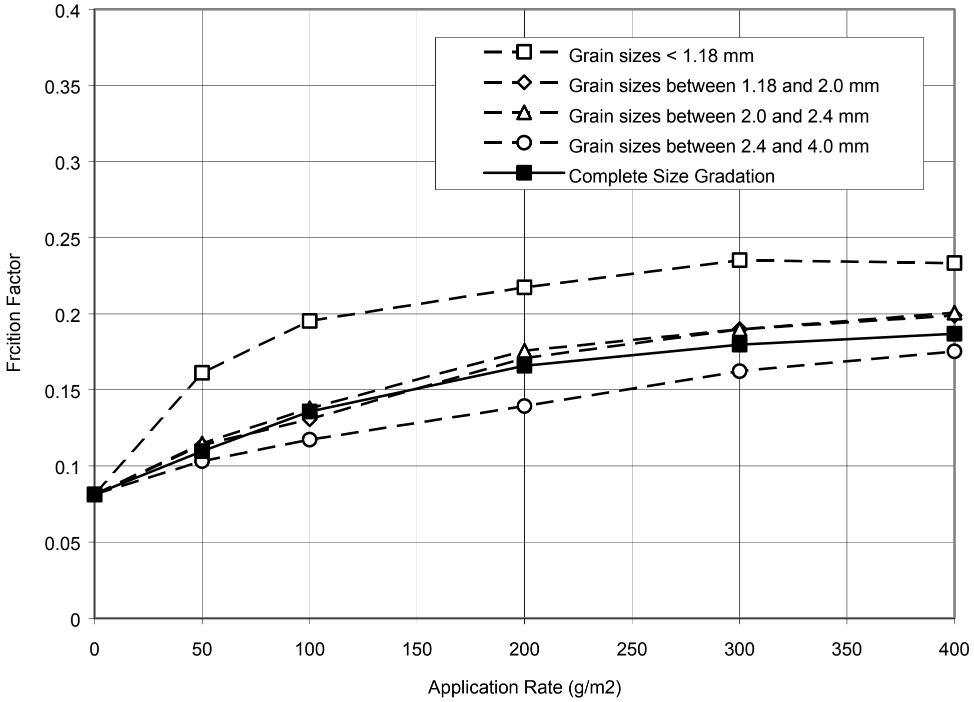


Figure 5.10: Sample Results: Effect of Application Rate for Red Lake Sand Applied on Ice at -5°C

For bare ice and for each grain size range tested, the friction factor increased with the application rate up to about 200 to 300 g/m^2, and then it tended to "level off", indicating that little or no further increase in friction was provided by applying sand at higher rates. The data show clearly that for the same application rate, the friction increased as the grain size decreased (Figure 5.10). The friction measured for the whole size gradation lies within the range measured for the grain size ranges tested. This trend reflects the effect of area coverage as the smaller grains provided greater area coverage than the larger ones for the same application rate. The effect of area coverage is discussed in the next section.

The trends for frozen snow are generally similar to those for bare ice (Figure 5.11).

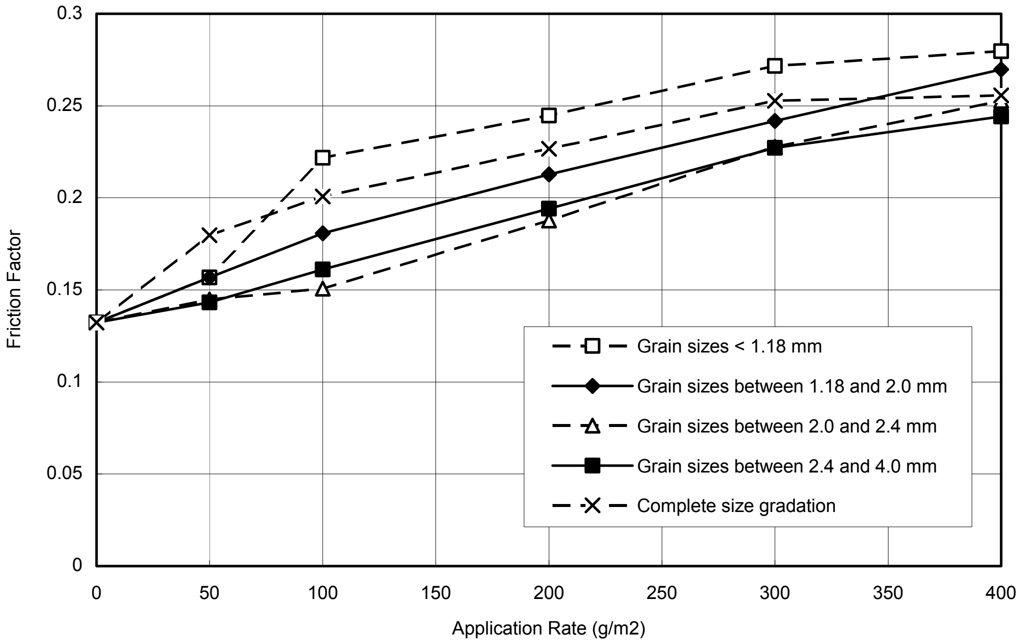


Figure 5.11: Sample Results: Effect of Application Rate for Red Lake Sand Applied on Frozen Snow at -5°C

5.3.3 Results Using the Type VII 26 x 6.6 Aircraft Tire: Effect of Area Coverage

Sample results showing the effect of area coverage are presented for ice and frozen snow in Figures 5.12 and 5.13, respectively. A complete set of these plots for all cases tested (i.e., grain size range; substrate [ice and frozen snow]; and temperature [-5° and -15°C]) are contained in Appendices F, G, and H for the Red Lake sand, the Ottawa TC sand, and the Flin Flon airport sands, respectively.

The area coverage is clearly important as the friction factor increases with area coverage for both bare ice and frozen snow. However, the results also indicate that the grain size is important as, for the same area coverage, higher friction was produced by the larger grain sizes (Figures 5.12 and 5.13). This is discussed further in Section 5.4.

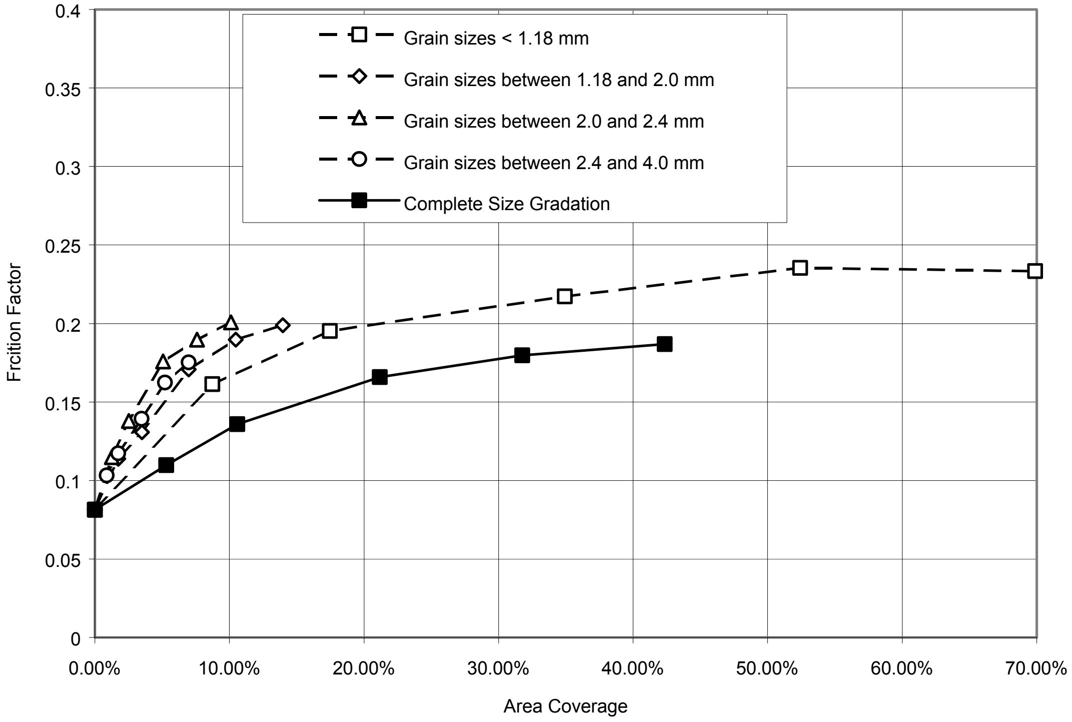


Figure 5.12: Sample Results: Effect of Area Coverage for Red Lake Sand Applied on Ice at -5°C

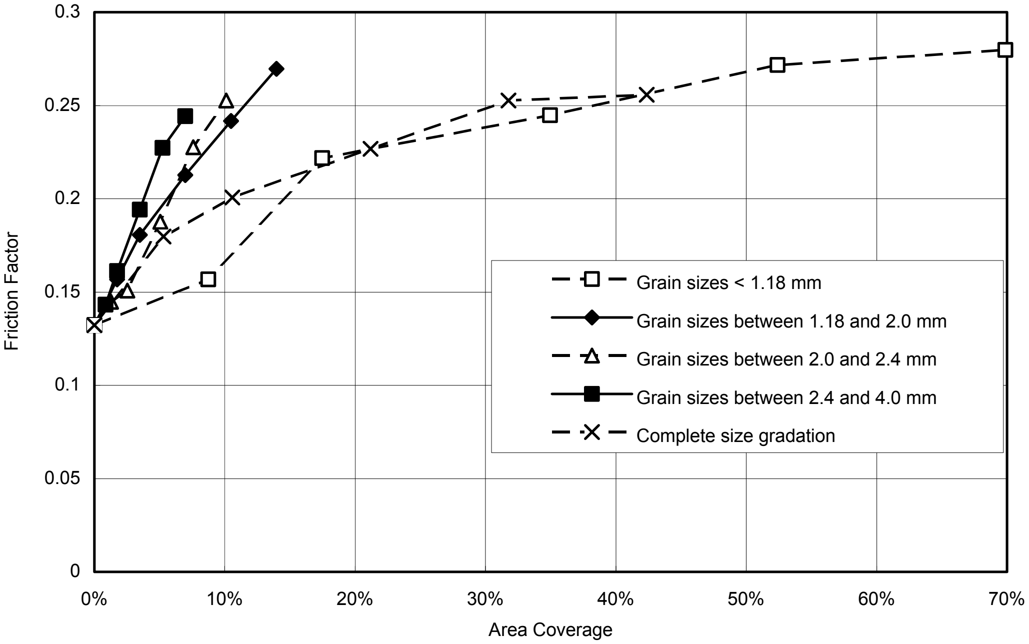


Figure 5.13: Sample Results: Effect of Area Coverage for Red Lake Sand on Frozen Snow at -5°C

5.4 Analysis: Friction Factors Measured with the Aircraft Tire

5.4.1 The Development of a Sand Friction Equation

Numerical modelling was conducted to develop a predictor equation for the friction measured by the Type VII 26 x 6.6 aircraft tire using the results from both the local sand tests and the parametric sand tests. Many different modelling approaches were tried, keeping in mind the following criteria:

(a) Input data and parameters in the analysis - The analyses should only require basic data as inputs. This is an obvious requirement for ensuring that the predictor is usable. It was decided to develop the predictor(s) using only the area coverage, the weighted-average grain size and the Angularity Index as parameters as the results showed that they all affected the friction produced.

The area coverage and the weighted-average grain size can be calculated from the measured sand size distributions. For the analyses presented here, the following assumptions were made to calculate the area coverage and the weighted-average grain size:

(i) all sand grains are spherical;
(ii) the specific gravity of all sand grains is 2.7.

The Angularity Index was calculated for each sand using equation 5.2.

Thus, the input data required to use the analysis approach are the measured sand size distribution, and the results of a visual angularity classification made using ASTM D 2488-93 [5].

(b) The general form of the predictor - Because the test data showed that the friction increase provided by sand applications (termed $\Delta\ \mu$) was relatively insensitive to the initial (i.e., unsanded) value for the bare ice or frozen snow surface (termed μ_{Ice} or $\mu_{Froz\ Snow}$, respectively), the analyses were developed with the general form shown in equations 5.3 and 5.4.

- Bare Ice Surface: $\mu_{After\ Sanding} = \mu_{Ice} + \Delta\ \mu$ [5.3]
- Frozen Snow Surface: $\mu_{After\ Sanding} = \mu_{Froz\ Snow} + \Delta\ \mu$ [5.4]

The approach that provided the best fit to the data was to:

(i) treat the effect of changes in area coverage and grain size on friction, termed $f(\Delta\mu_{A\_cov})$ and $f(\Delta\mu_{Grain\ Size})$, respectively, as independent parallel processes.

(ii) treat the effect of a change in sand angularity on friction, termed

$f(\Delta\mu_{\text{Angularity}})$, as a modifier.

This approach produces the general equation below:

$$1/\Delta\mu = f(\Delta\mu_{\text{Angularity}}) \bullet [\, 1/ f(\Delta\mu_{\text{A\_cov}}) + 1/ f(\Delta\mu_{\text{Grain Size}}) \,] \qquad [5.5]$$

(c) Frozen snow vs bare ice - because the trends observed on frozen snow and bare ice were generally similar to each other, the predictor was developed to be applicable to both frozen snow and bare ice. This simplifies its usage as the user is not required to distinguish between these two surfaces.

(d) -5°C vs. -15°C - because the friction increases produced by sand applications were much larger at -5°C than at -15°C (by a factor of about 2), separate predictors were developed for these two temperatures.

The results of best-fit analyses for the test data at -5°C and at -15°C are summarized in equations 5.6 and 5.7, respectively.

- Temperature: -5°C : $\Delta\mu = (A_I / 100)^{0.1} / [(1.2/A_c) + (0.8/ G_s^2)]$ [5.6]
- Temperature: -15°C : $\Delta\mu = (A_I / 100)^{0.1} / [(2.4/A_c) + (1.6/ G_s^2)]$ [5.7]

where: A_I = the angularity index (defined using equation 5.2)
A_c = the area coverage, expressed as a decimal value
G_s = the weighted-average grain size, in mm

The input parameter ranges that equations 5.6 and 5.7 are considered to be applicable for are summarized below:

- Angularity index: 110 to 390
- Application rate: 50 to 400 g/m^2
- Sand size distribution (local sand tests only): as per Table 5.2, and Appendices A and B. See also Figure 5.14 which shows a plot of all the size gradations together.
- Sand Sizes:
  - Local sand tests: weighted-average grain size : 0.29 to 2.76 mm (Table 5.2)
  - Parametric sand tests: < 1.18 mm to 4.0 mm
- Substrate: Bare ice and frozen snow
- Temperature: -5°C and -15°C

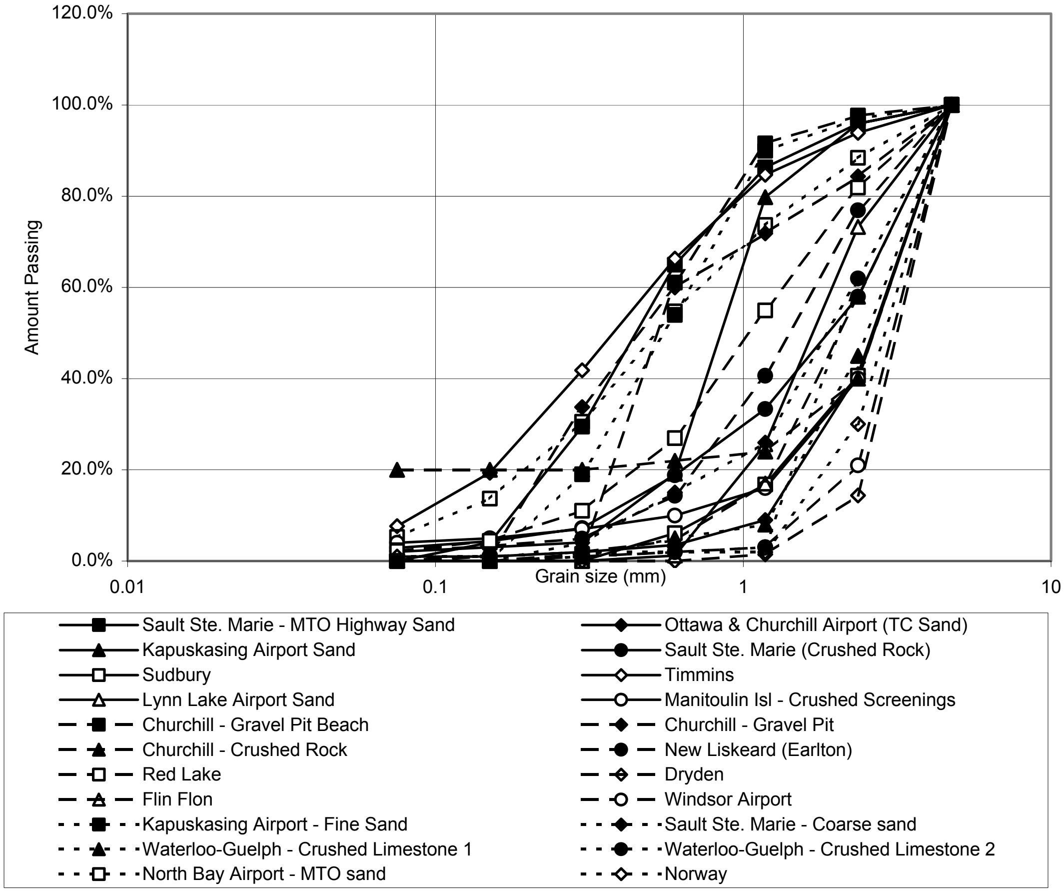


Figure 5.14: Grain Size Distributions after All Material Coarser than Sieve No. 4 Was Removed

The predicted and measured friction factors at -5°C and at -15°C are compared in Figures 5.15 and 5.16, respectively. The results from the parametric tests and the local sand tests compare well with each other. The predicted friction coefficients are slightly less than the measured values as the average ratio between them for the -5°C and -15°C tests is 0.96 and 0.99, respectively. The variation between the predicted and measured friction factors is similar for each temperature, and most of the predicted values are within about +/- 20 % of the measured values (Table 5.9).

Table 5.9: Correlation between the Measured and Predicted Friction Factors

Temp (°C)	% Agreement - defined as the percentage of data points for which the predicted values are within the measured values to the tolerances specified below		
	+/- 10 %	+/- 20 %	+/- 30 %
-5	52	81	97
-15	57	84	98

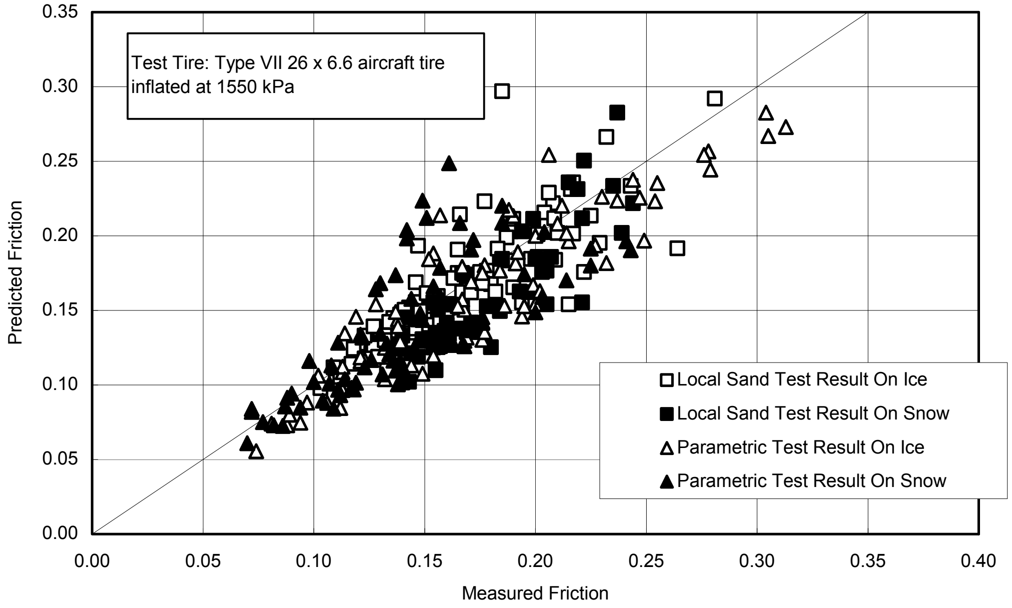


Figure 5.15: Comparison: Measured vs. Predicted Friction for Sand Applied on Frozen Snow and Ice at –5°C

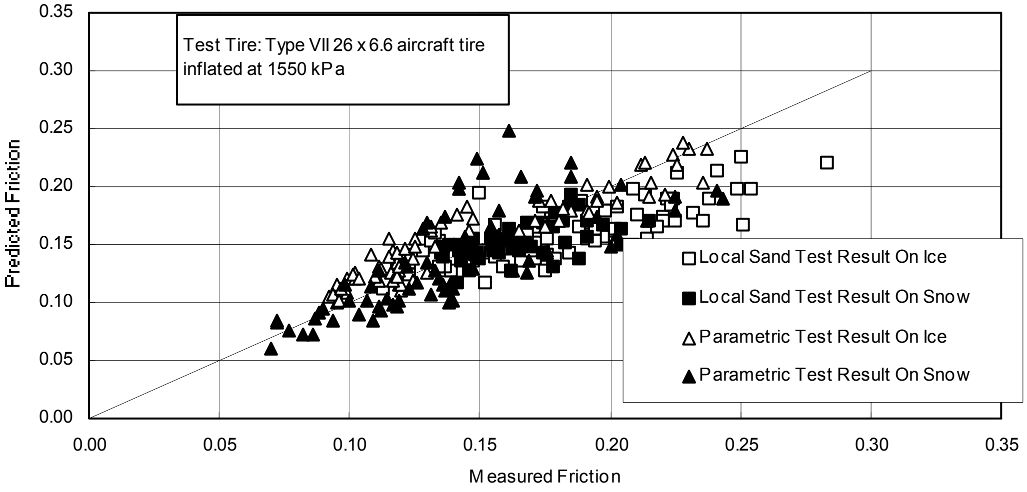


Figure 5.16: Comparison: Measured vs. Predicted Friction for Sand Applied on Frozen Snow and Ice at –15°C

5.4.2 Trends Predicted by the Sand Friction Equations

The trends predicted by equations 5.6 and 5.7 were investigated by conducting sensitivity analyses over the ranges of input parameters tested in the laboratory programs. The effects of area coverage, grain size, and angularity index are shown in Figures 5.17, 5.18, and 5.19, respectively.

The area coverage is clearly the most important parameter as, as for the ranges of input parameters tested in the laboratory programs, variations in area coverage produce much larger friction changes than do the respective variations in grain size and angularity index. Compare Figures 5.17 to 5.19. The friction change (i.e., "Δ μ") increases with the area coverage non-linearly. At low area coverages, Δ μ increases rapidly with the area coverage. However, less friction increase is provided at higher area coverages by further increases in area coverage (Figure 5.17).

The friction increase also increases with the grain size in a non-linear manner (Figure 5.18). Increases in grain size at the low end produce relatively large increases in friction. However, much less friction increase is provided at higher grain sizes by further increases in grain size.

The angularity has a small effect on the friction as it increases slightly with increasing angularity index (Figure 5.19).

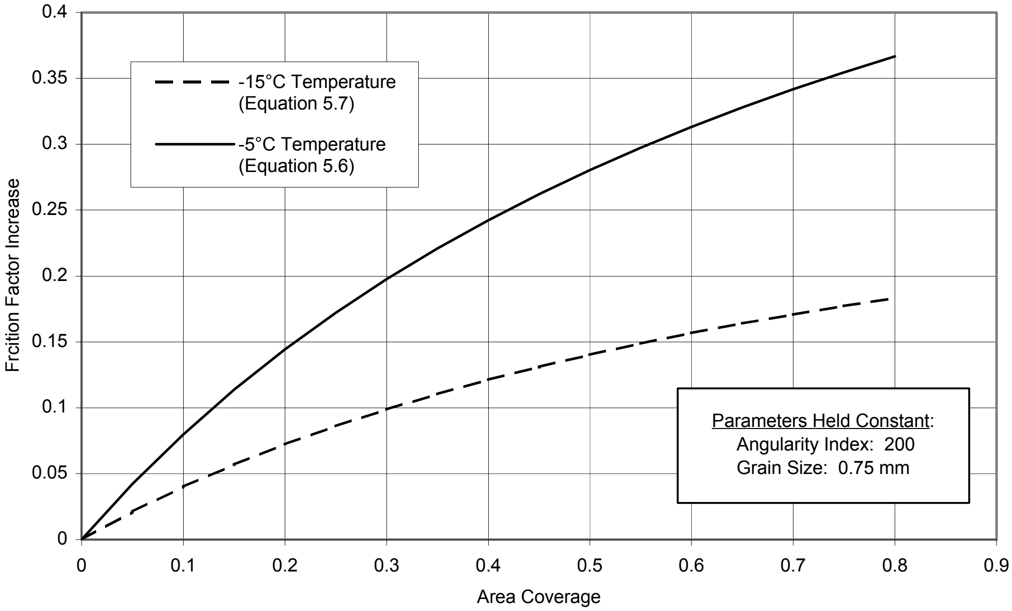


Figure 5.17: Trend Predicted by Equations 5.6 and 5.7: Effect of Area Coverage

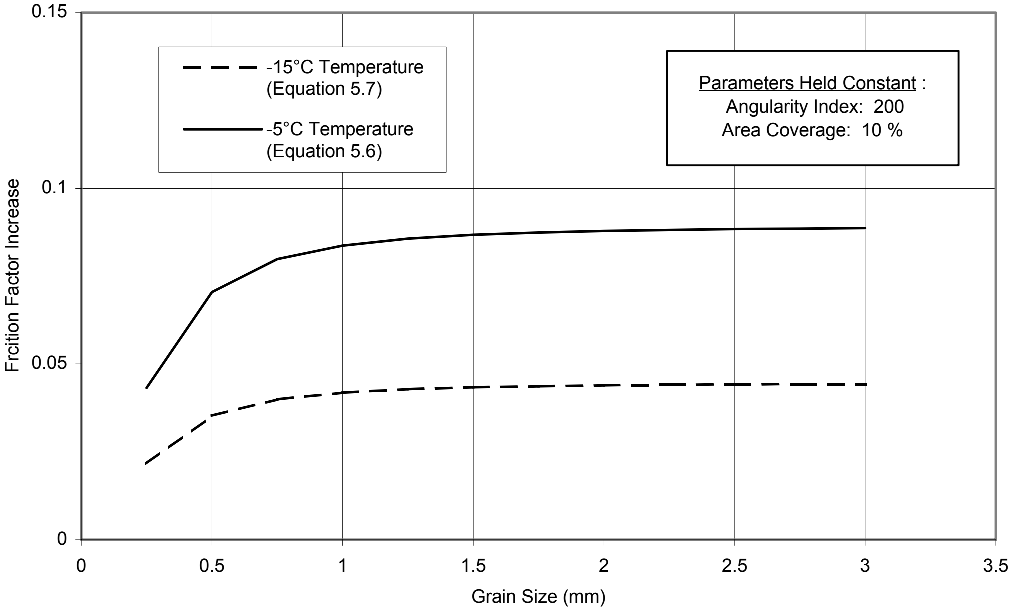


Figure 5.18: Trend Predicted by Equations 5.6 and 5.7: Effect of Grain Size

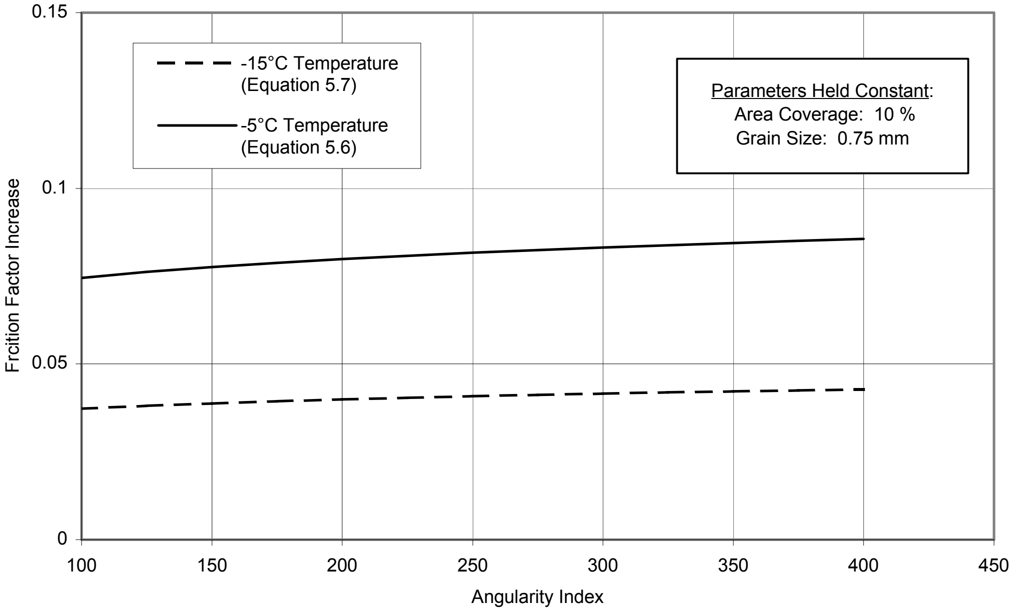


Figure 5.19: Trend Predicted by Equations 5.6 and 5.7: Effect of Angularity Index

5.5 Analyses Using the Sand Friction Equation

5.5.1 Predicted Relative Performance of the Local Sands Tested

Equations 5.6 and 5.7 were used to compare the expected performance of the local sands tested at -5°C and -15°C (Figure 5.20). To investigate the effect of the size distribution as well, the sands were ranked from fine to coarse at the "50% passing" level, and they are plotted in this order in Figure 5.20.

Sand applications at –5°C are predicted to produce greater friction increases than at -15°C, which reflects the results observed during the test program.

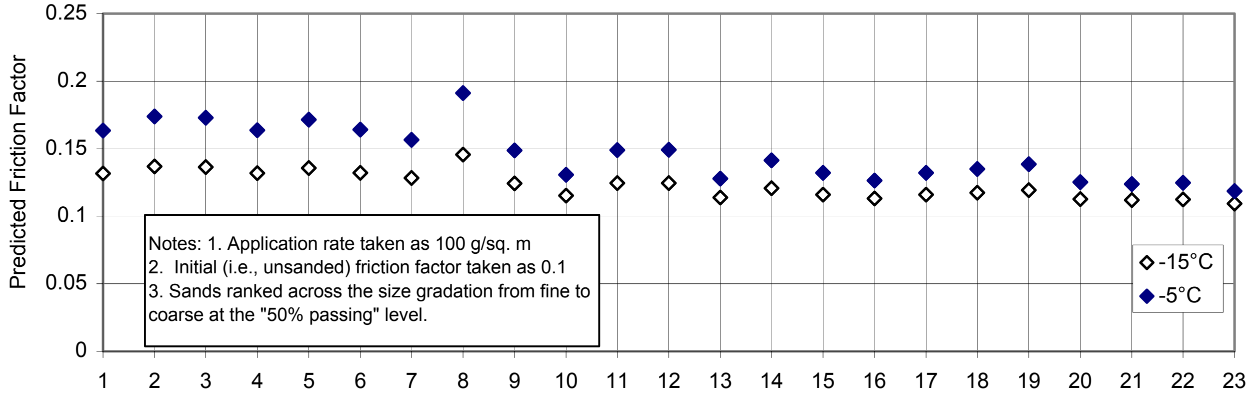
With respect to the sand size distribution, the results generally show that the friction is expected to decrease as the sand becomes coarser. This reflects the reduction in area coverage that occurs as the sands become coarser (for the same application rate).

The Red Lake sand is predicted to provide the highest friction at both temperatures, and it is an outlier to the overall trend for the local sands. The Red Lake sand has a relatively large amount of fine material throughout its distribution, which provides it with higher relative area coverage. For example, the area coverage provided by the Red Lake sand was nearly double that of the New Liskeard sand (Table 5.2) although the amount passing at the 50% level was similar for them (Figures 5.14 and 5.20).

This result is supported by the results of the test programs as the Red Lake sand was consistently ranked highly with respect to the friction produced (Section 5.2).

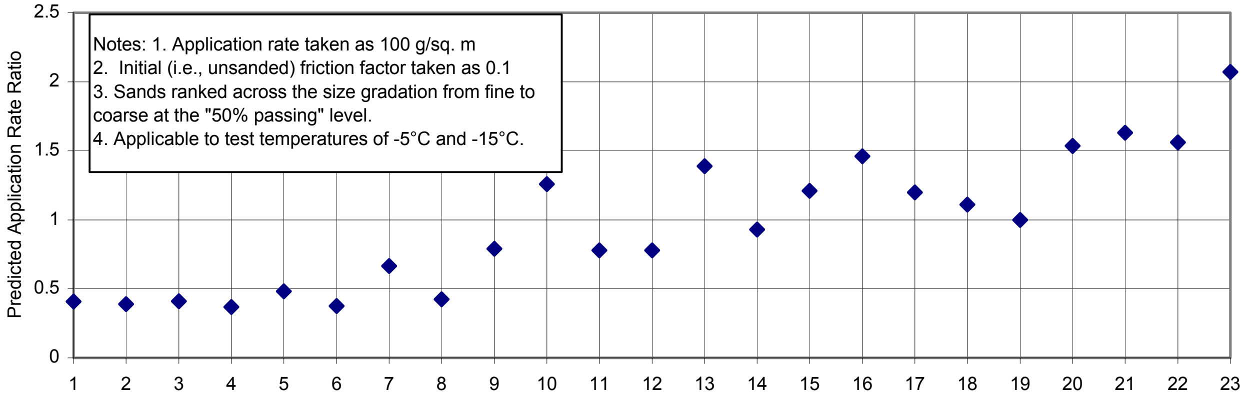
Equations 5.6 and 5.7 were also used to compare the sands with respect to the application rates required to achieve the same friction as Ottawa TC sand. The application rate ratio (i.e., $\mathrm{Rate}_{\mathrm{ratio}}$ – see equation 5.1 for definition) is plotted for all sands in Figure 5.21. The application rate ratio increases steadily as the sands become coarser (Figure 5.21).

Much smaller quantities of the finer sands are required to provide the same friction as Ottawa TC sand. For the coarser sands, more material must be applied to achieve the same friction as Ottawa TC sand.



Notes: 1. Application rate taken as 100 g/sq. m
2. Initial (i.e., unsanded) friction factor taken as 0.1
3. Sands ranked across the size gradation from fine to coarse at the "50% passing" level.

Figure 5.20: Predicted Friction Across the Size Gradation at –5^{o}C and –15^{o}C



Notes: 1. Application rate taken as 100 g/sq. m
2. Initial (i.e., unsanded) friction factor taken as 0.1
3. Sands ranked across the size gradation from fine to coarse at the "50% passing" level.
4. Applicable to test temperatures of -5°C and -15°C.

Figure 5.21: Predicted Relative Application Rates Required for the Local Sands

Legend

1 Timmins
2. Sault Ste. Marie-MTO Highway Sand
3. Churchill – Gravel Pit
4. North Bay Airport – MTO Sand
5. Churchill – Gravel Pit Beach
6. Kapuskasing Airport – Fine Sand
7. Kapuskasing Airport Sand
8. Red Lake
9. New Liskeard (Earlton)
10. Lynne Lake Airport Sand
11. Sault Ste. Marie – Course Sand
12. Sault Ste. Marie – Crushed Rock
13. Waterloo-Guelph – Crushed Limestone 2
14. Flin Flon
15. Waterloo-Guelph – Crushed Limestone 1
16. Churchill – Crushed Rock
17. Sudbury
18. Manitoulin Isl – Crushed Screenings
19. Ottawa TC Sand
20. Churchill Airport (TC Sand)
21. Norway
22. Windsor Airport
23. Dryden

5.5.2 Current Sand Size Specifications and their Expected Friction

The size distributions for airport runway sand specified by Transport Canada (TC)[6] and the Federal Aviation Administration (FAA) [7] are compared in Figure 5.22. Appendix E shows the size distributions specified for highways and roads by other organizations.

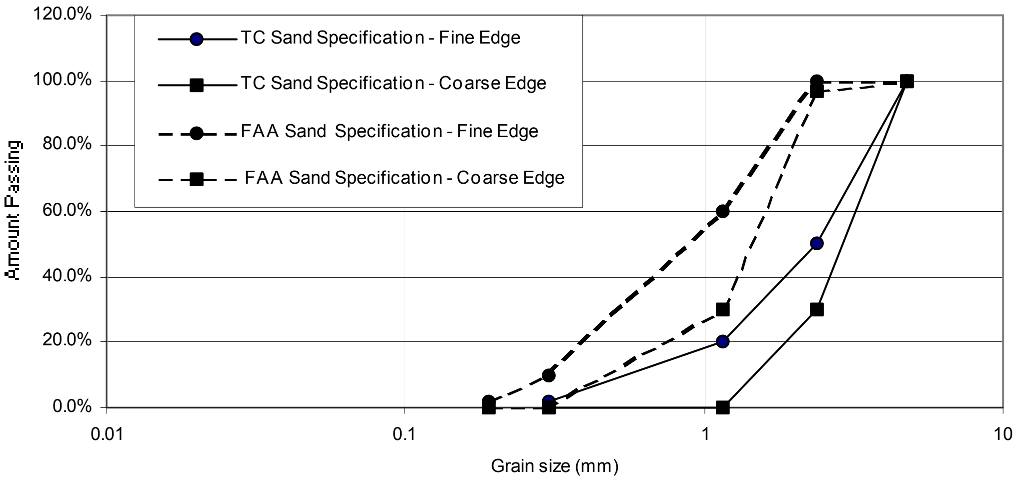


Figure 5.22: Grain Size Distributions Specified by Transport Canada and the FAA

Figure 5.22 shows that the FAA's size specification requires finer sand than does the TC size specification. Equations 5.6 and 5.7 were used to investigate the expected variation in friction between these two specifications, and across the range of each of them.

The friction is predicted to reduce steadily from the fine edge of the FAA specification to the coarse edge of the TC specification at both -5°C and -15°C (Figures 5.23 and 5.24). This reflects the effect of area coverage, which decreases steadily over this range of size gradations.

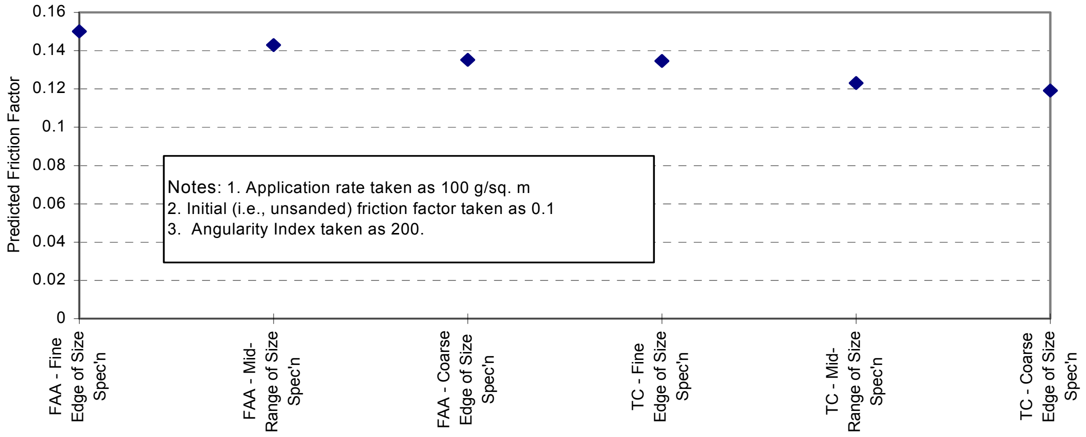


Figure 5.23: Predicted Friction for Various Size Specifications at –5°C: Mid-Range Sand Angularity for All Sands

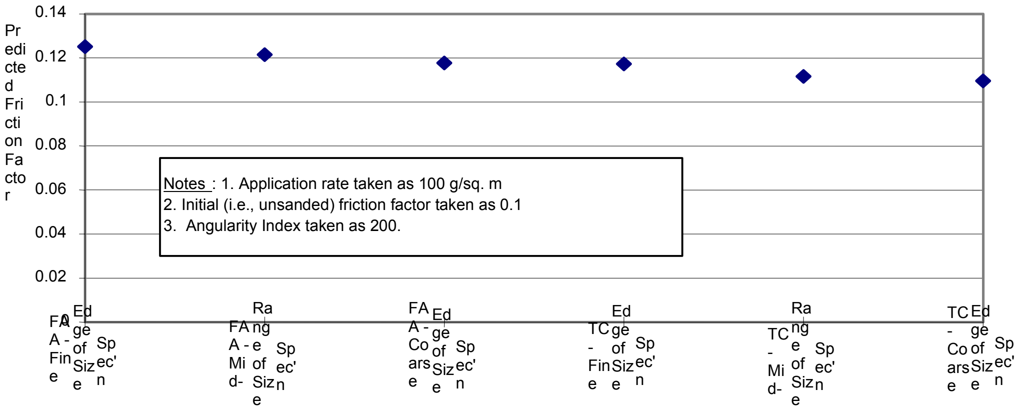
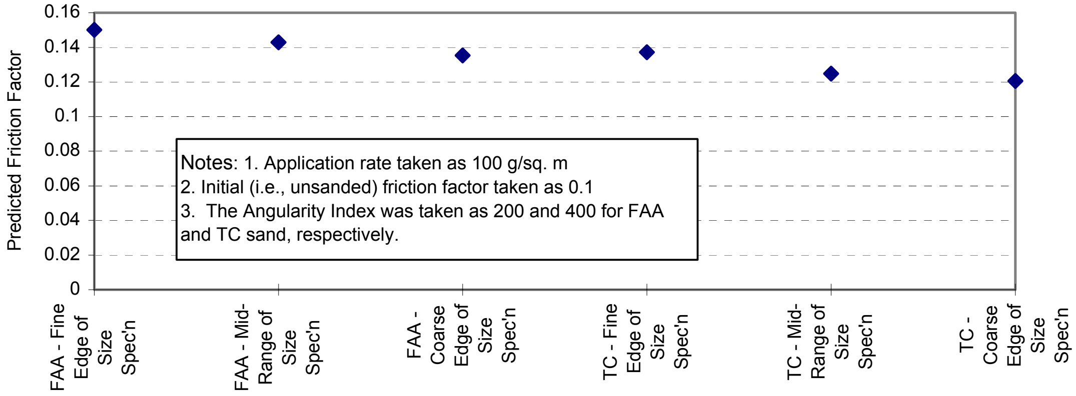


Figure 5.24: Predicted Friction for Various Size Specifications at –15°C: Mid-Range Angularity for All Sands

The comparisons shown in Figures 5.23 and 5.24 presume that the angularity of the sands was equal for all size gradations. (An angularity index of 200 was assumed, which reflects an mid-range grain angularity.) It is quite possible that materials prepared to meet the TC specification will be more angular than those meeting the FAA specification (which is finer). TC sand is often prepared by crushing rock.

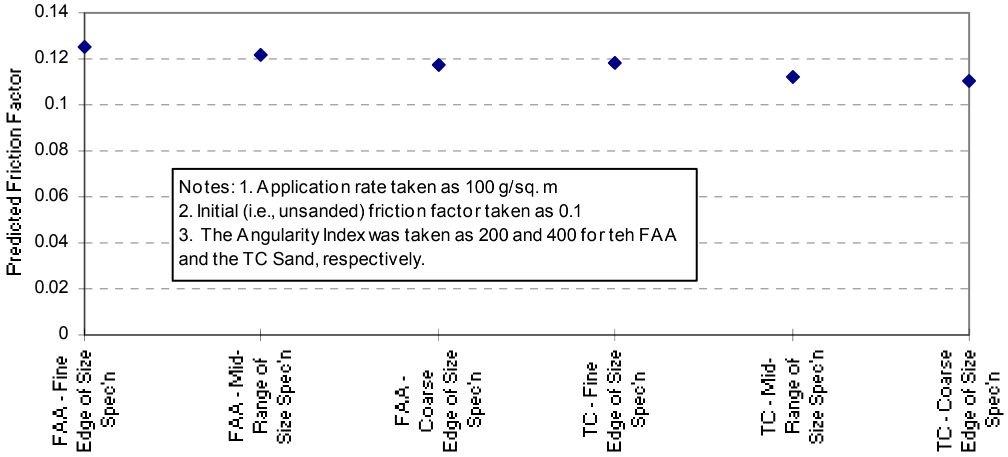
The effect of this variation was investigated using equations 5.6 and 5.7. The friction was predicted for FAA sand with a mid-range angularity (angularity index of 200) and for an extreme angular TC sand (angularity index of 400, which is the maximum possible value).

The analyses suggest that this potential variation in angularity will not affect the results significantly for either of the two test temperatures. The friction is predicted to decrease steadily across the range from fine to coarse reflecting the reduction in area coverage that takes place (Figures 5.25 and 5.26).



Notes: 1. Application rate taken as 100 g/sq. m
2. Initial (i.e., unsanded) friction factor taken as 0.1
3. The Angularity Index was taken as 200 and 400 for FAA and TC sand, respectively.

Figure 5.25: Predicted Friction for Various Size Specifications at –5°C: Angular TC Sand vs. Smoother FAA Sand



Notes: 1. Application rate taken as 100 g/sq. m
2. Initial (i.e., unsanded) friction factor taken as 0.1
3. The Angularity Index was taken as 200 and 400 for teh FAA and the TC Sand, respectively.

Figure 5.26: Predicted Friction for Various Size Specifications at –15°C: Angular TC Sand vs. Smoother FAA Sand

5.6 Sand Friction Tests Using the Low-Pressure SFT Tire

5.6.1 Objectives and General Scope

A total of 120 tests were carried out using the low-pressure (207 kPa) SFT tire to investigate the correlation between this tire and the Type VII 26.6 x 6.6 aircraft tire for:

- two different sands – the Ottawa TC and the Red Lake sands were tested.
- two different temperatures (i.e., -5°C and -15°C)
- two different substrates (i.e., frozen snow and bare ice)
- five different application rates (i.e., 50, 100, 200, 300, and 400 g/m^2)
- three different grain size ranges (i.e., < 1.18 mm, between 2.4 and 4.0 mm, and the whole size gradation)

5.6.2 Presentation of Results

Plots showing the effect of application rate on the measured friction are provided in Appendices I and J for the Red Lake and Ottawa TC sands, respectively. Figures 5.27 and 5.28 show sample results for applications of Red Lake sand on ice and frozen snow, respectively.

The friction factor increases with the application rate for low rates. At higher rates, the friction factor tends to level off, indicating that little benefit was obtained (in terms of increased friction) by applying more sand. This is similar to the trends observed with the Type VII 26.6 x 6.6 aircraft tire.

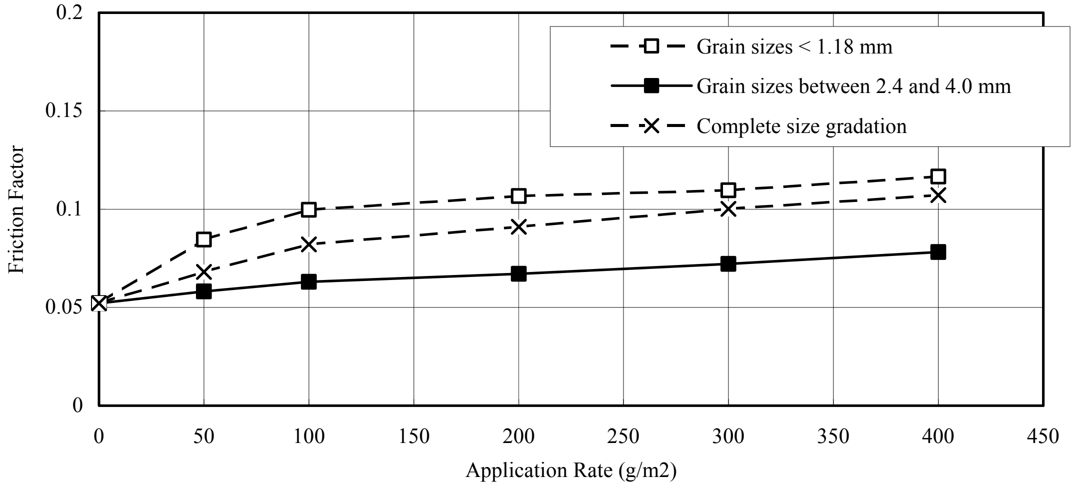


Figure 5.27: Sample Results: Red Lake Airport Sand Applied on Ice at –5°C Friction Factors measured Using the Low-Pressure (210 kPa) SFT Tire

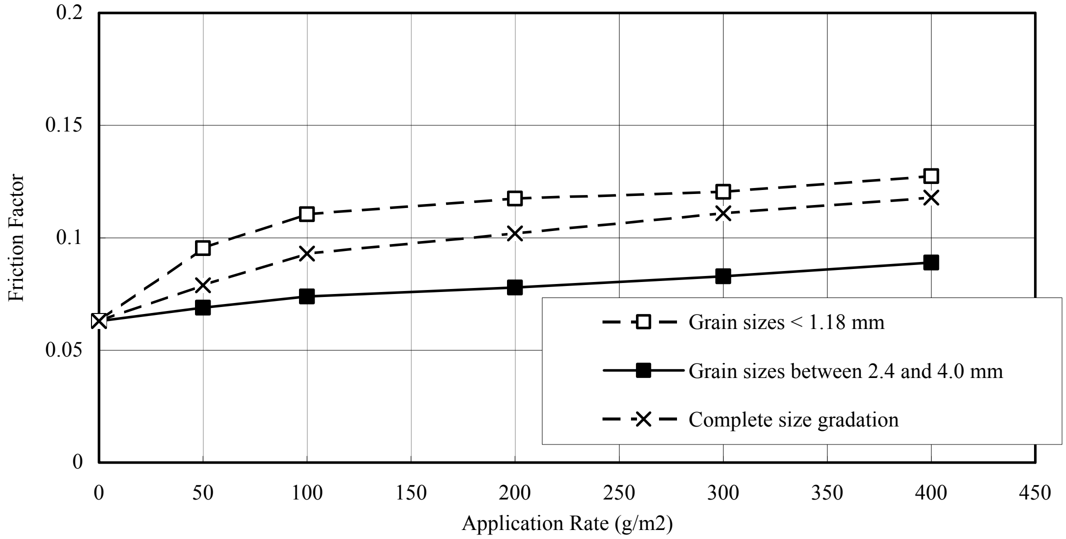


Figure 5.28: Sample Results: Red Lake Airport Sand Applied on Frozen Snow at –5°C Friction Factors Measured Using the Low Pressure (210 kPa) SFT Tire

The effect of area coverage was investigated, and a complete set of plots is provided for the tests done with the Red Lake and Ottawa TC sands in Appendices I and J, respectively. Figures 5.29 and 5.30 show sample results for applications of Red Lake sand on ice and frozen snow, respectively.

The friction factor is strongly related to the area coverage as it increases with the area covered. For the sample cases presented in Figures 5.29 and 5.30, the results obtained for the three grain sizes lie on top of each other, which indicates that, for these cases, the friction factor is primarily controlled by the area coverage. However, the reader is cautioned that this trend was not universal, as for other cases, the results obtained from the different grain sizes tested varied significantly (Appendices I and J). This result indicates that other factors, such as the grain size and the sand angularity, are important. These results are similar to those obtained with the Type VII 26.6 x 6.6 aircraft tire.

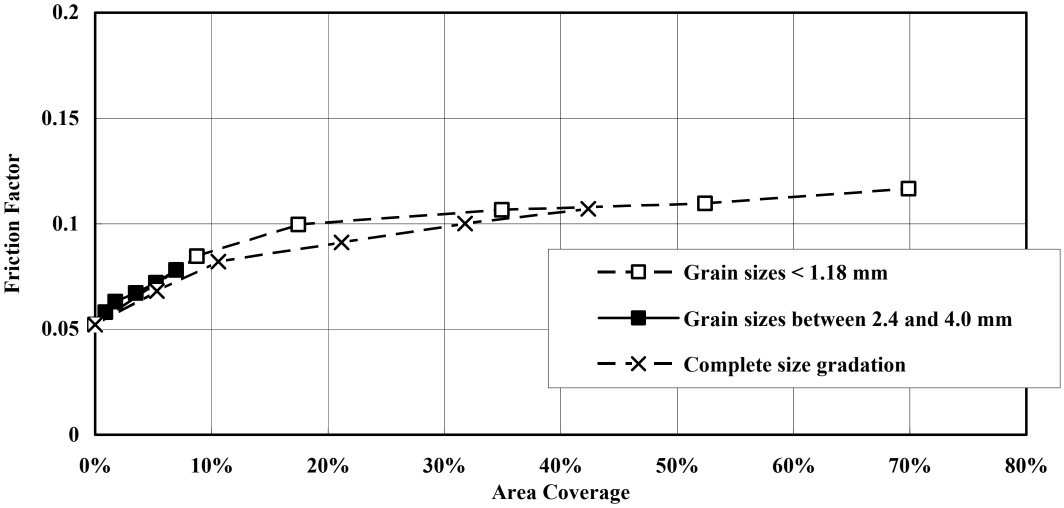


Figure 5.29: Sample Results: Red Lake Airport Sand Applied on Ice at –5°C Friction Factors Measured Using the Low Pressure (210 kPa) SFT Tire

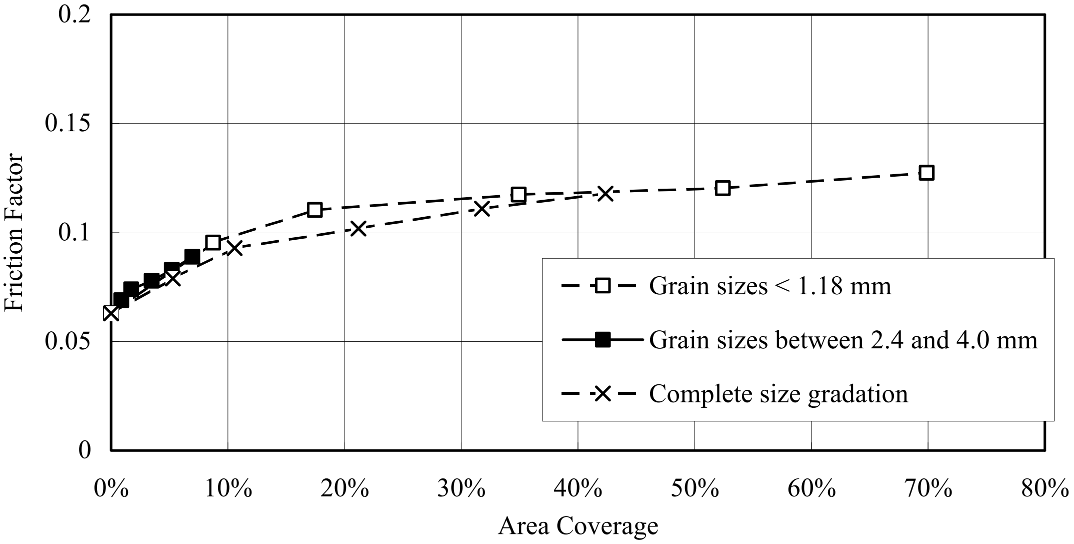


Figure 5.30: Sample Results: Red Lake Airport Sand Applied on Frozen Snow at –5°C Friction Factors Measured Using the Low Pressure (210 kPa) SFT Tire

5.6.3 Comparison with Results Obtained Using the Type VII 26.6 x 6.6 Aircraft Tire

The friction factors measured with the Type VII 26.6 x 6.6 aircraft tire are compared with those obtained using the low-pressure SFT tire for the Red Lake and the Ottawa TC sands in Figures 5.31 and 5.32, respectively. The average ratios between the friction factors measured with the Type VII 26.6 x 6.6 aircraft tire and the low-pressure SFT tire (i.e., $\mu_{\text{Type VII 26.6 x 6.6 aircraft tire}}$ and $\mu_{\text{low-pressure SFT tire}}$, respectively) are summarized in Table 5. 10.

Table 5.10: Average Ratios (i.e., $\mu_{\text{Type VII 26.6 x 6.6 aircraft tire}} / \mu_{\text{low-pressure SFT tire}}$)

Red Lake Sand				Ottawa TC Sand		
	Frozen Snow	Ice			Frozen Snow	Ice
-5° C	2.12	1.96		-5° C	1.33	1.34
-15° C	2.03	1.94		-15° C	1.39	1.84

For both sands, higher friction was measured with the Type VII 26.6 x 6.6 aircraft tire than with the low-pressure SFT tire. For the Red Lake sand, the average ratios between the two friction factors were similar for both frozen snow and ice for both temperatures. For the Ottawa TC sand, the tests done using the Type VII 26.6 x 6.6 aircraft tire on ice at -15°C resulted in proportionately higher friction than was observed for the other cases (Table 5.10).

The Red Lake data fall into two general data groups (Figure 5.31). For the tests done using the whole sand gradation, the friction factors measured using the Type VII 26.6 x 6.6 aircraft tire were similar in magnitude to those measured with the low-pressure SFT tire for both frozen snow and ice, and for both test temperatures. For the tests done using the sand that was sieved into sizes less than 1.18 mm, and into the 2.4-4.0 mm size range, higher friction was measured using the Type VII 26.6 x 6.6 aircraft tire.

This grouping was not observed with the tests done using Ottawa TC sand as the relationship between the friction factors measured with the two tires was generally similar for each sand size range tested (Figure 5.32).

These results indicate that the relationship between the friction factors measured by the Type VII 26.6 x 6.6 aircraft tire and the low-pressure SFT tire is not consistent. Further testing and analyses are required to establish the relationship. Because the results obtained using the aircraft tire are considered more likely to be representative of the relative sand performance “seen” by an aircraft, the low-pressure SFT results are not analysed further here.

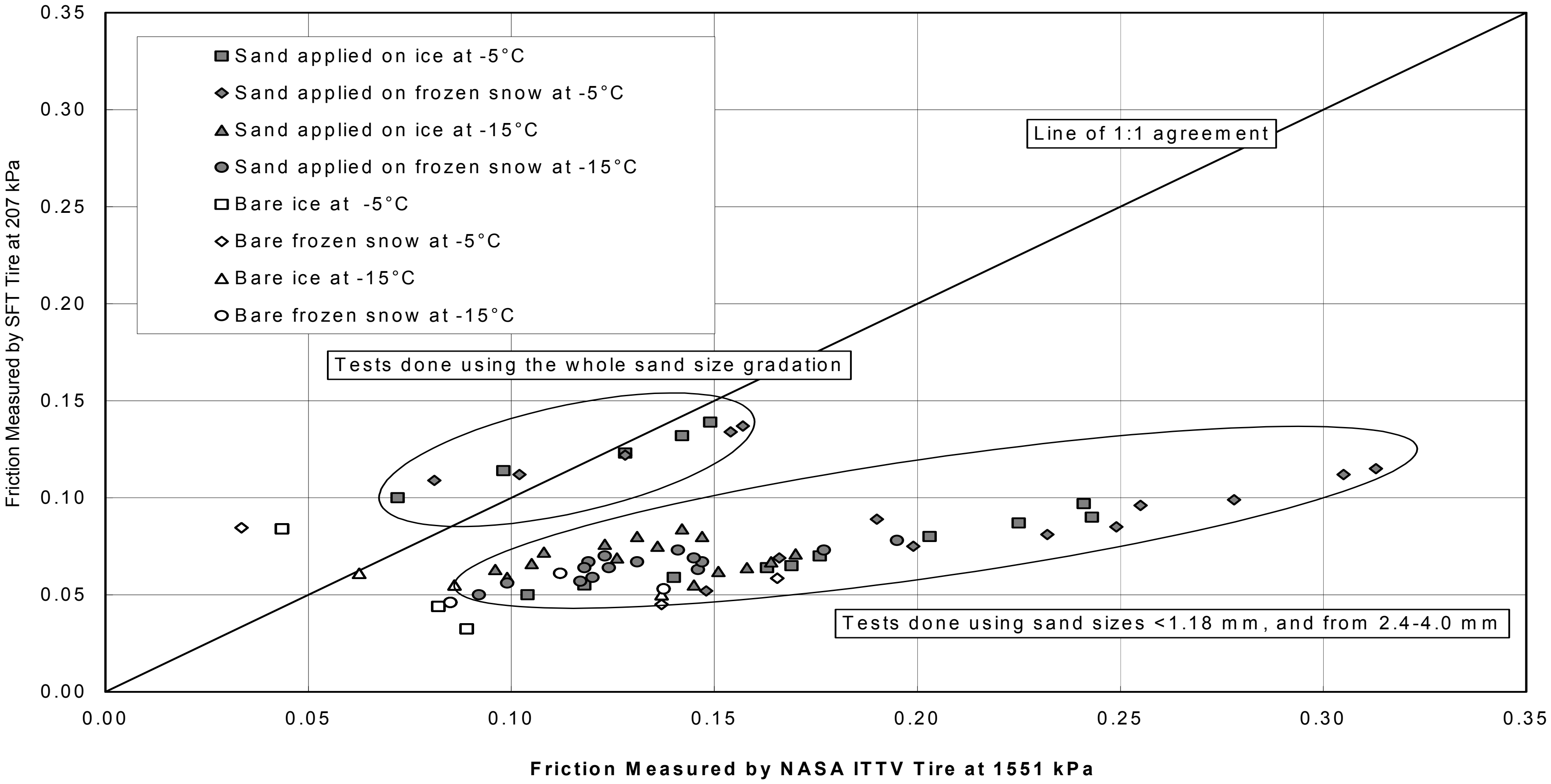


Figure 5.31: Red Lake Airport Sand Applied on Frozen Snow and Ice

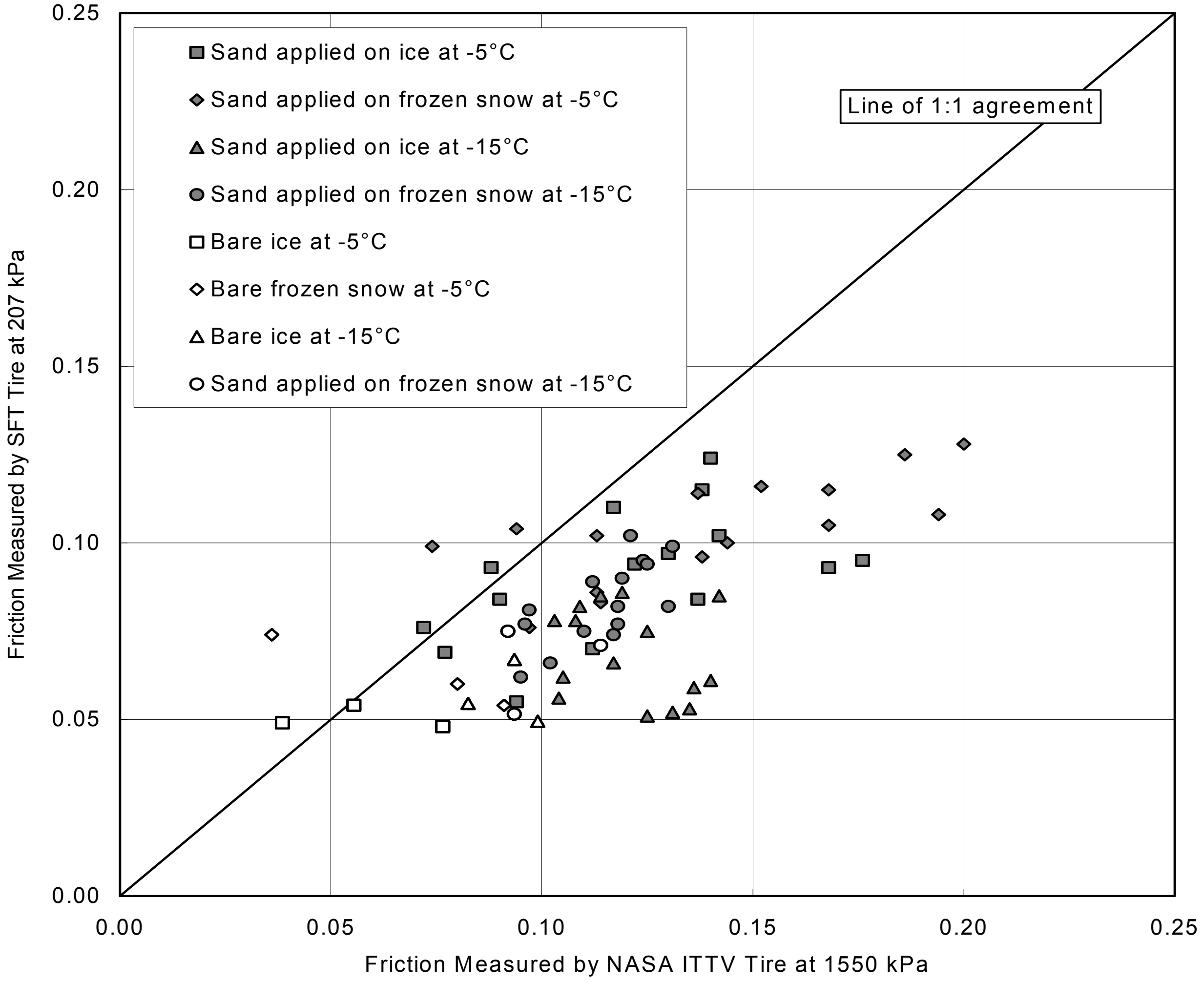


Figure 5.32: Ottawa Airport TC Sand on Frozen Snow and Ice

6. FREEZING RAIN TESTS

6.1 Objectives

The objectives of the freezing rain tests were:

(a) to investigate procedures for freezing rain testing;

(b) to evaluate the performance of various ice control chemicals at a number of application rates.

6.2 Test Procedure and Setup

6.2.1 Test Procedures

A number of test procedures and parameters were tried before finalizing the procedure used in the program.

The test procedure used in the previous program [1] was reviewed. In summary, the previous procedure consisted of the following steps:

(a) Apply the de-icing chemical on a bare concrete surface and then commence the freezing rain system. The friction was measured immediately after application of the chemical.

(b) Expose the test surface to freezing rain for 20 minutes. Depending on the ice conditions, the test surface was "plowed" using a scraper comprised of a plow blade section fixed in position at appropriate angles using a jig. The plow blade was loaded with deadweights such that the vertical load was similar to that for plows operating on the runway.

The friction was measured before "plowing" and after "plowing".

In cases where relatively little ice was present on the surface, no "plowing" was done and only the friction was measured.

(c) Expose the test surface to another 20 minutes of freezing rain and repeat step
(d) This sequence was repeated until the test surface was fully ice-covered.

The above test procedure suffered from a number of problems including the following:

(a) The decision whether or not to "plow" was a subjective one, that greatly affected subsequent test results as the action of "plowing" removed a large part of the de-icing chemical from the test surface. Usually, ice built up much faster once "plowing" had been done.

At airports, the de-icing chemical would probably be re-applied in these cases. Furthermore, it is likely that plowing would be avoided in these cases at airports as much as possible to ensure that the chemical is present on the runway for as long as possible.

(b) A significant amount of time (about 10-15 minutes) was required to “plow” the surface and to measure the friction factor. Although the freezing rain system was de-activated for this time period, the test surface was still exposed to sub-freezing temperatures during this time. This caused ice to form on the test surface in some cases, which affected the test results.

As a result, the data obtained during the previous test program [1] contained a large amount of scatter.

Small-scale freezing rain tests have been conducted in the laboratory at the Université du Québec à Chicoutimi ([8], [9]), and these results were also referred to in developing a test procedure. These tests showed that the initial “wetness” of the surface had an important effect on the chemical’s performance as it affected the degree to which freezing precipitation, water and solutions were absorbed into the texture of the test surface. This introduced repeatability problems because this is difficult to control and standardize. This highlighted the need for a good reference surface. As a result, the test program at the Université du Québec á Chicoutimi ([8], [9]) included tests on polymer-concrete high-friction reference panels. These reference panels were found to provide satisfactory results [8].

This problem (of scatter introduced by variations in the initial “wetness” of the concrete) was also observed during the previous test program conducted by FTL [1]. Consequently, it was decided to conduct freezing rain tests on two substrates :

(a) the same concrete surface used during the previous program [1].

(b) a steel plate with a non-skid coating commonly used on aircraft carriers. This coating is described in section 3 and Appendix C. This surface was impervious to water and was much easier to clean between tests (than the concrete). The coated steel plates were cleaned by vacuuming and allowing them to dry for a one-day period between tests.

The scenario to be simulated in the test program was also considered. The test procedure was developed to simulate the following case:

(a) A freezing rain storm commences and de-icing chemical is applied just before the storm starts. Because the runway is likely to be wet in this case, the test surface was wetted before applying the de-icing chemical.

(b) Aircraft continue to land on the runway at regular intervals. This was simulated by running the tire along the test track regularly. To assist in developing the test procedure, baseline tests were conducted at intervals ranging from 1 to 10 minutes (described in section 6.3). After this, it was decided to standardize the interval at 5 minutes.

It was also felt that the surface temperature would provide useful information for evaluating the test procedure and results. Consequently, it was decided to measure this parameter over the duration of each test.

The following test procedure was selected and used:

(a) Apply de-icing chemical on the test surface before any exposure to freezing rain. Measure the friction factor and temperature of the surface.

(b) Commence the freezing rain system.

(c) Measure the friction factor and temperature of the surface at regular intervals. The time interval was standardized at 5 minutes for all tests done with de-icing chemicals. This was continued until the test surface was fully covered with ice.

6.2.2 Test Setup

The tests were conducted using the same freezing rain system used previously [1]. The rainfall rate was set at 5 mm/hr for all tests.

All tests were done using the Type VII 26 x 6.6 aircraft tire inflated at 1550 kPa (225 psi).

6.3 Results: Presentation of Raw Data and Test Observations

6.3.1 Baseline Data

Baseline data were obtained by conducting tests with no chemical on the surface. Because the data collected on the coated, impervious steel plate were considered to be more reliable than those for the concrete surface (discussed in the next section), baseline tests were only done on the coated steel plate.

The baseline data are plotted in Figure 6.1. Tests were conducted at friction measurement intervals of 1, 5 and 10 minutes to investigate the effect of wheel passes (simulating traffic) on the ice formation process and the resulting friction. Similar results were obtained for each measurement interval, as the friction factor steadily reduced with exposure to the freezing rain over the first 20 minutes. At that point, the test surface was fully ice-covered and the friction was unchanged by further exposure to freezing rain.

The surface temperature increased during the first part of the test (when an ice cover was forming on the surface). After that, it remained stable.

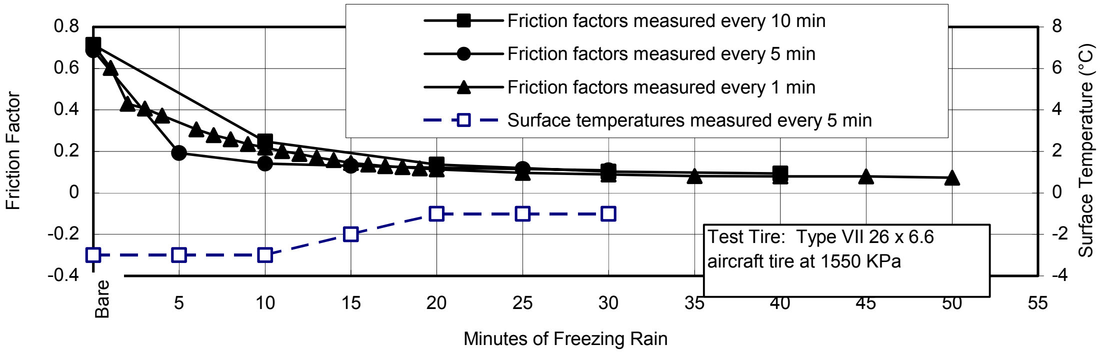


Figure 6.1: Baseline Freezing Rain Tests on a Textured Steel Plate: No Chemical Applied

Because the results were similar for each friction measurement time interval, this test parameter was selected based on convenience. All tests with the de-icing chemicals were done at a measurement interval of 5 minutes.

6.3.2 Tests On Concrete

The friction factors measured on the concrete surface for urea and potassium acetate are plotted versus time of exposure to the freezing rain in Figures 6.2 and 6.3, respectively.

The results from the tests done on the coated steel plate are presented in the next section. It should be noted that the tests done on concrete are considered to be less reliable because:

> (a) The concrete surface had little micro-texture which caused a large drop in friction to occur when the de-icing chemicals were first put on the surface, and before they were exposed to freezing rain. As a result, the difference in friction between an “iced”’ surface and the initial surface was quite small.
>
> (b) The concrete was not impervious. As a result, it was difficult to clean the surface from test to test. Some water and de-icing chemicals probably remained in the concrete from test to test. As a result, the test results on concrete were not as repeatable as those on the impervious, coated steel plate. This problem was also recognized by Bernardin, [8] who recommended that impervious textured surfaces be used for these tests.

Nevertheless, the results on concrete provide a useful point of comparison for the tests done on the steel plate.

The results on concrete are discussed in section 6.3.4 together with those obtained on the coated steel plate.

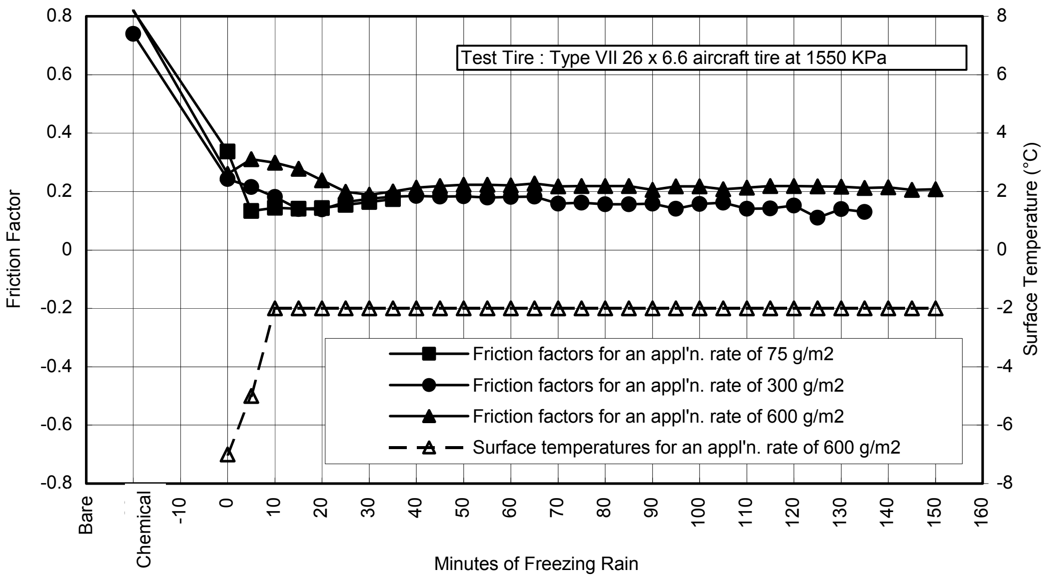


Figure 6.2: Freezing Rain Tests: Urea on Concrete

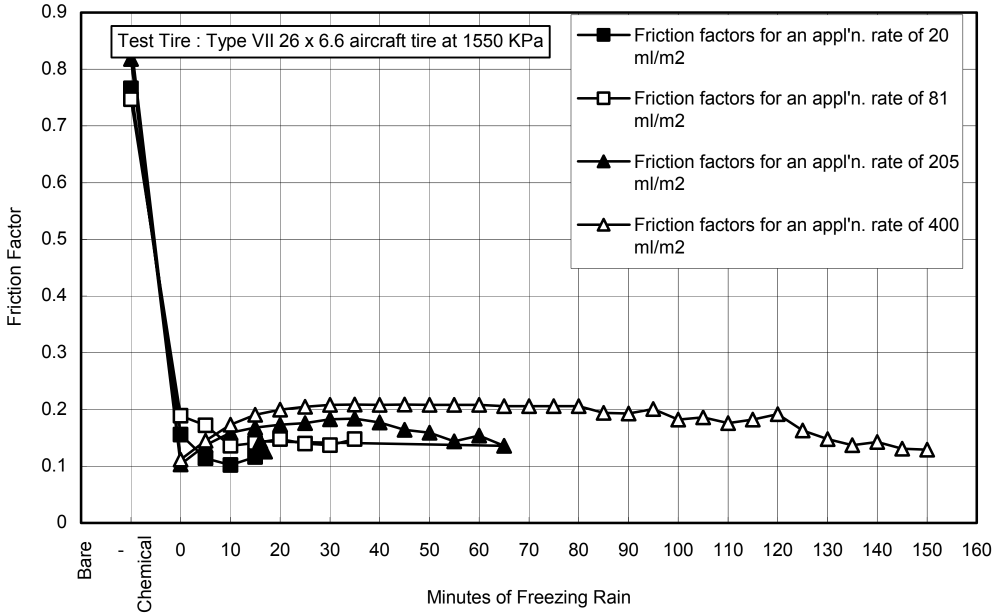


Figure 6.3: Freezing Rain Tests: Potassium Acetate on Concrete

6.3.3 Tests on the Coated Steel Plate

The measured friction factors for the solid de-icing chemicals (i.e., urea, sodium acetate, and sodium formate) and for the liquid ones (i.e., potassium acetate and UCAR) are plotted versus time of exposure to the freezing rain in Figures 6.4, to 6.8, respectively.

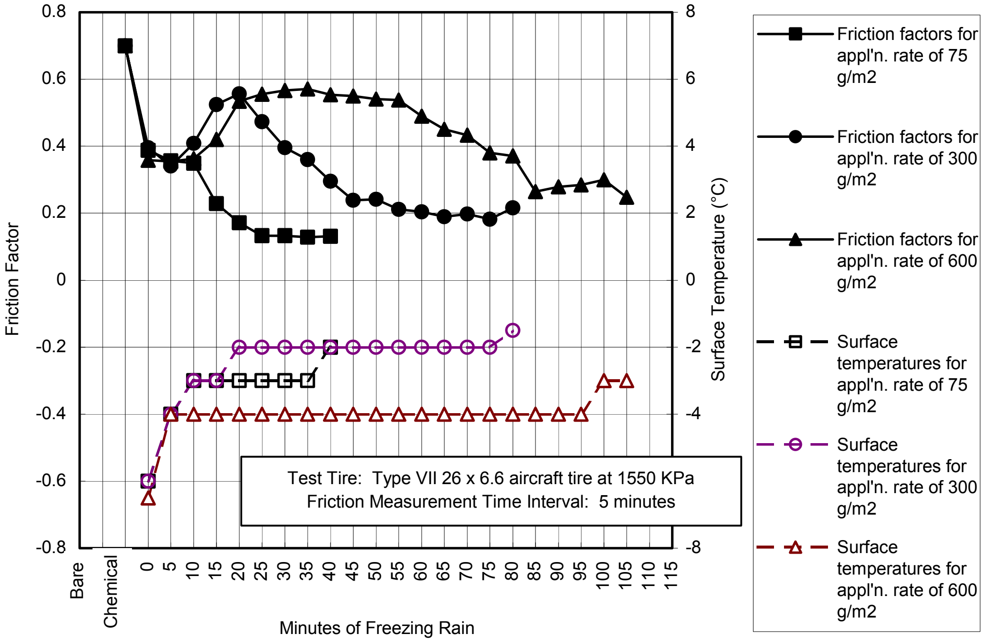


Figure 6.4: Freezing Rain Tests: Urea on Coated Steel Plate

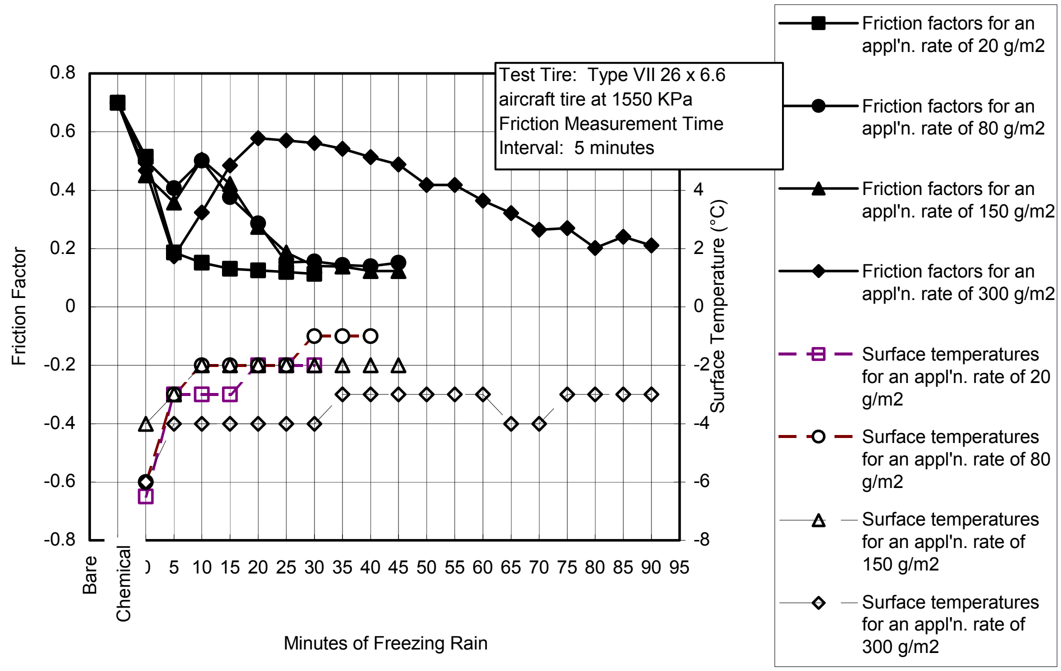


Figure 6.5: Freezing Rain Tests: Sodium Acetate on Coated Steel Plate

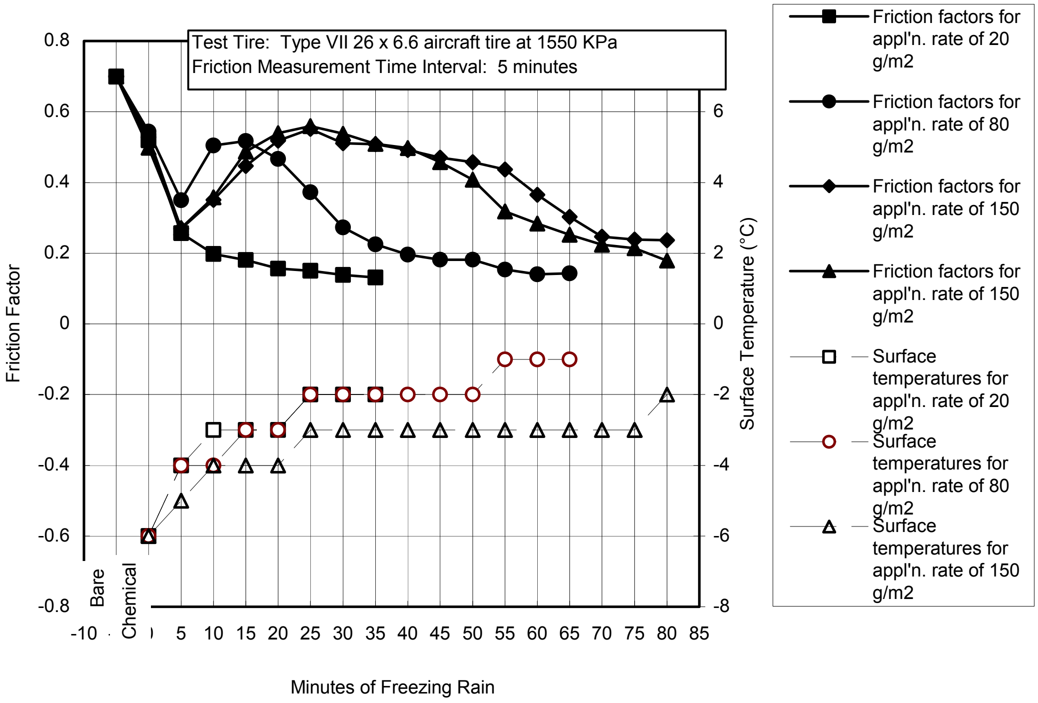


Figure 6.6: Freezing Rain Tests: Sodium Formate on Coated Steel Plate

<u>Note to Figure 6.6</u>: The 150 g/m^2 application rate was tested twice to investigate the repeatability of the test method.

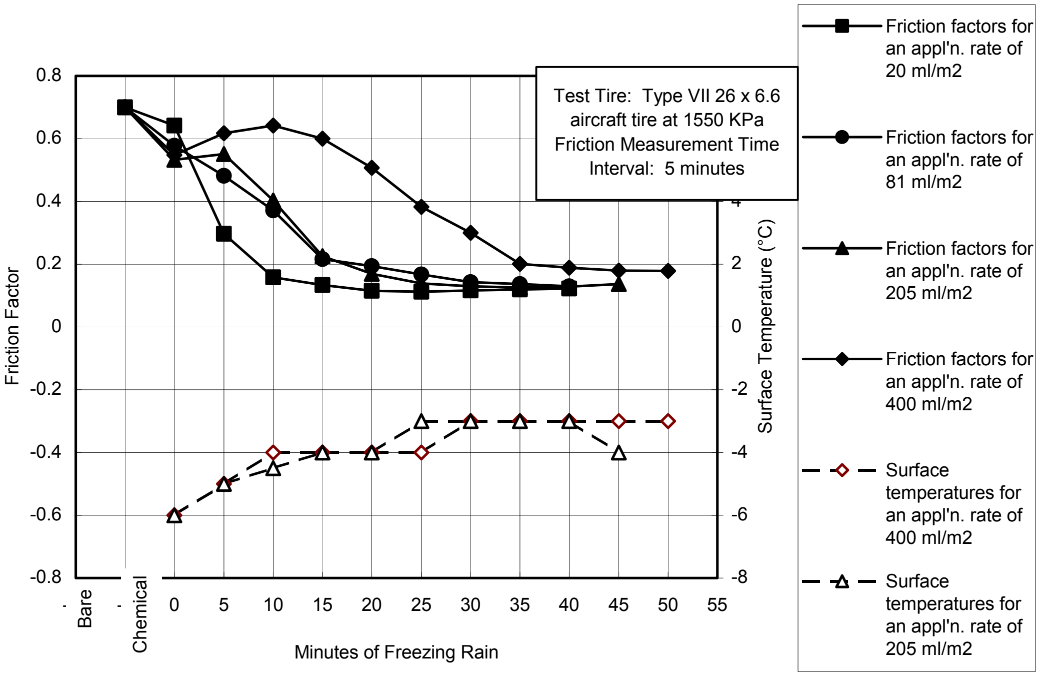


Figure 6.7: Freezing Rain Tests: Potassium Acetate on Coated Steel Plate

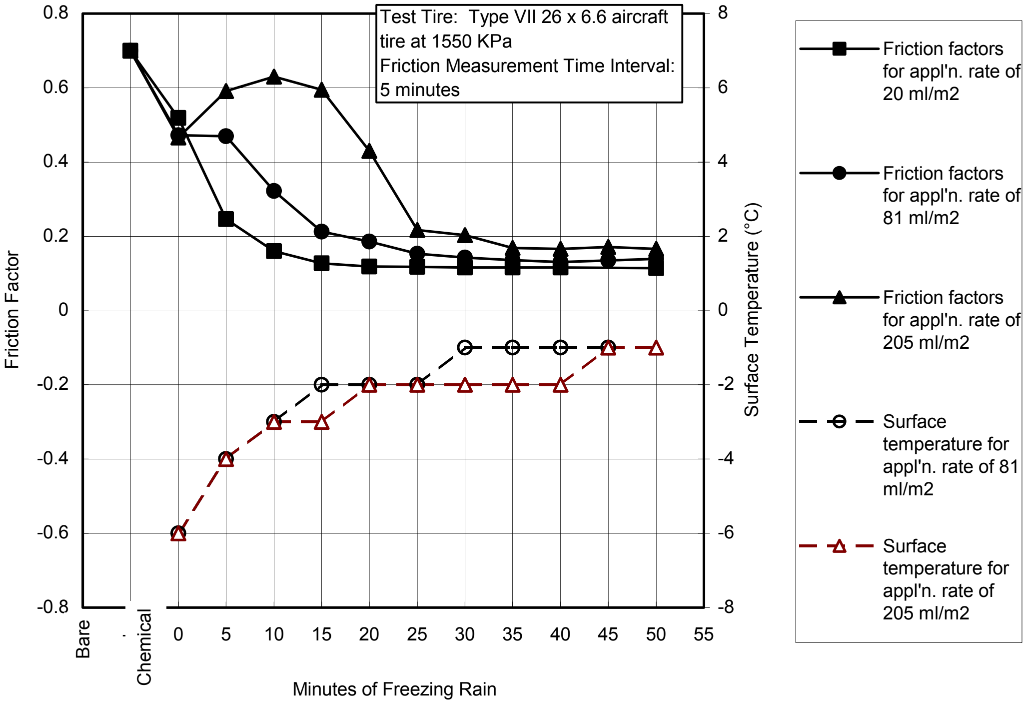


Figure 6.8: Freezing Rain Tests: UCAR on Coated Steel Plate

6.3.4 Summary Test Observations

The same processes were observed for each chemical with respect to ice formation and the measured friction factors on both concrete and the coated steel plate.

All of the chemicals caused a drop in friction, with respect to a bare surface, when they were first applied. (The friction factors for the bare surface, and with chemicals on it but before exposure to freezing rain, are labelled as “bare” and “chemical”, respectively, on Figures 6.2 to 6.8.) The drop in friction measured on the concrete surface (Figures 6.2 and 6.3) was quite large because it had little microtexture. The drop in friction when the chemicals were applied on the coated steel plate was considerably less because it had more micro-texture (Figures 6.4 to 6.8).

The friction produced when the chemicals were exposed to freezing rain was affected greatly by the ice formation process. The ice formation processes were similar for all chemicals and they varied with the application rate:

(a) High and intermediate application rates - at first, freezing rain falling on the surface did not freeze due to the effects of the de-icing chemical. The friction increased as the chemical was diluted by the water on the surface, bringing the condition closer to wet surface.

Eventually, the chemical became dilute enough that some ice formation could occur, which resulted in the formation of slush on the surface. Additional freezing rain caused the formation of more slush, and this material eventually hardened into ice on the test track. The friction dropped steadily over the slush formation process. Once ice had formed, the friction coefficient remained essentially constant with further exposure to freezing rain.

(b) Low application rates - in this case, the falling freezing rain formed ice on the test track immediately, which resulted in low friction. Once ice had formed, the friction coefficient remained essentially constant with further exposure to freezing rain.

As expected, the surface temperature increased over the duration of the test (Figures 6.2 to 6.8). Typically, the surface temperature was about -7°C at the start of each test. Within the first 15 minutes of freezing rain, the temperature increased to about -2° to -3°C. The temperature then stayed relatively constant (at about -2° to -3°C) over the remainder of each test (Figures 6.2 to 6.8).

6.4 Analysis of Protection Times Provided by the Chemicals

The "protection time" was used as an index for comparing the performance of the chemicals tested. Because the tests done on the coated steel plate were considered to be most reliable, these anlayses were only done with the results obtained on the coated steel plate.

The "protection time" was defined as the time that the test surface could be exposed to freezing rain before the friction factor dropped to 0.2 or less. At this point in the test, the surface was usually fully ice-covered.

The protection times provided by the **solid chemicals** increased linearly with the application rate (Figure 6.9).

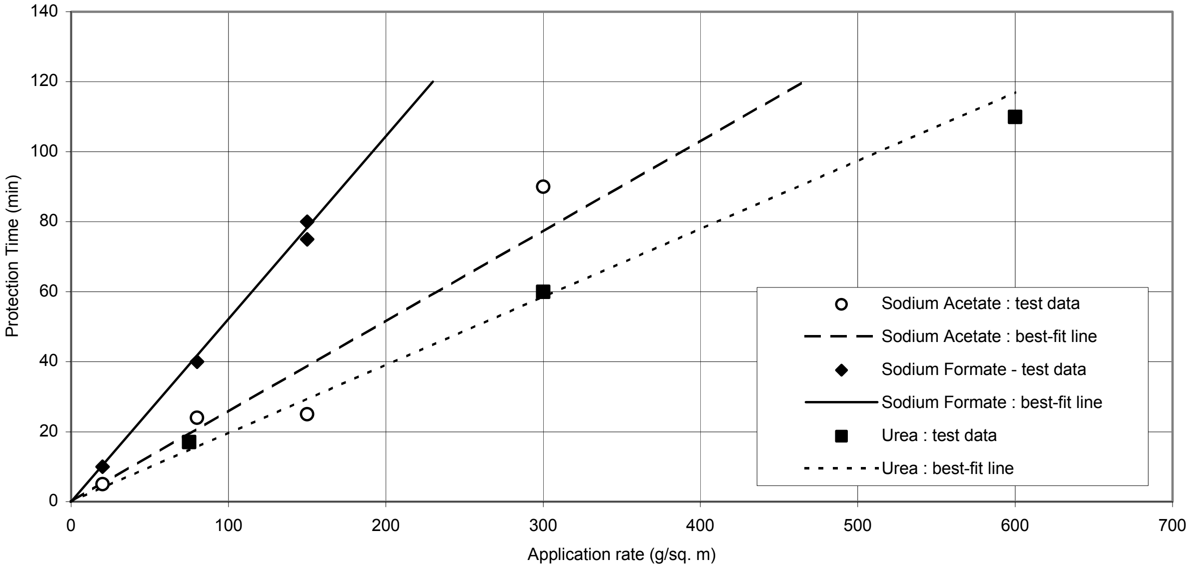


Figure 6.9: Protection Time Provided by Solid Chemicals

The relative application rates required for the three chemicals to provide the same protection times are summarized in Table 6.1. The quantities for sodium acetate and sodium formate required to provide the same protection time as urea were about 70% and 40% of those for urea, respectively.

Table 6.1: Comparison of the Solid De-Icing Chemicals Tested

De-Icing Chemical	Protection Time Application Rate Ratio (see note 1 for def'n)
Urea	Not applicable - used as the basis of comparison
Sodium Acetate	0.7
Sodium Formate	0.4

Note:
1. The Protection Time Application Rate Ratio was defined as follows:

application rate required for the chemical of interest to provide a protection time of 30 minutes/
application rate for urea to provide a protection time of 30 minutes

The protection times provided by the liquid chemicals also increased with the application rate (Figure 6.10). At low application rates (i.e., less than about 40 ml/m^2 [1 US gal/1000 ft^2]), the protection time increased rapidly with application rate. At higher rates, the protection time increased more slowly with the application rate, in a near-linear manner. This variation in trend compared to the solid de-icers (which provided increased protection time as a linear function of the application rate) may be due to the improved ability of the liquid de-icing chemicals to coat the surface in a uniform manner.

The quantity of UCAR required to provide 30 minutes protection time was about 60% of that for potassium acetate (Figure 6.10).

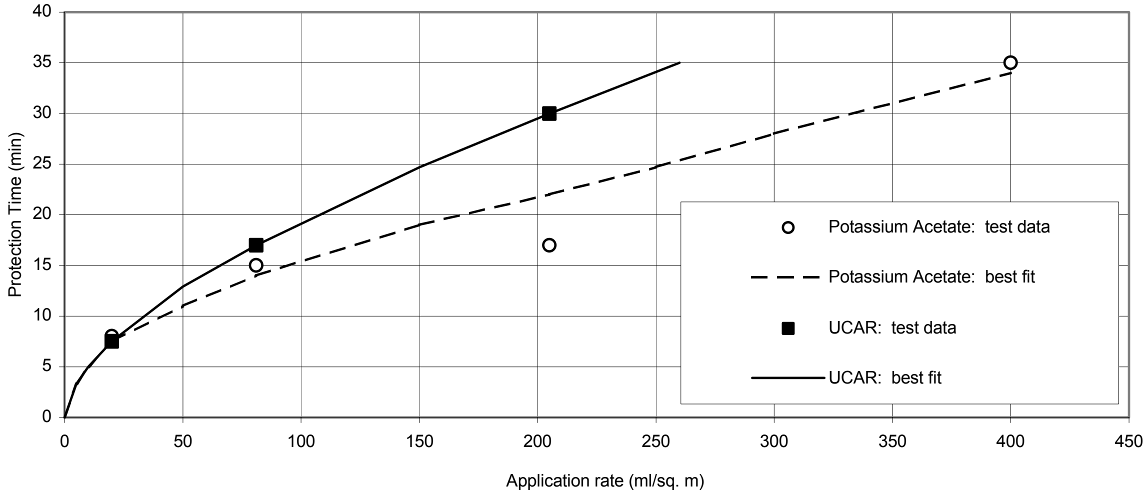


Figure 6.10: Protection Time Provided by Liquid Chemicals

6.5 Assessment of the Test Method and Concluding Remarks

6.5.1 Test Method Repeatability

This was checked using a number of methods.

Some tests were repeated over their full duration, and a result is shown in Figure 6.6 (for sodium formate applied at 150 g/m^2 on the coated steel plate). The ice formation processes and resulting friction factors were very similar for both tests.

The protection times (presented in section 6.4) also provide an indication of the test method's repeatability. The data points for each test are relatively consistent as a function of application rate (Figures 6.9 and 6.10) which suggests that the method provides reasonable repeatability.

6.5.2 Recommendations

A test method has been developed and used to compare the performance of five different de-icing chemicals at several different application rates.

The method appears to give realistic results. Further work should be conducted to:

> (a) Verify the method by comparing the results obtained here with field data. Observations should be made of the ice and slush conditions that occur during freezing rain conditions and these should be compared to the laboratory results. Also, where possible, the relative performance of various de-icing chemicals observed from field applications should be compared with the laboratory test results.
>
> (b) Investigate simpler indexes for predicting the relative performance of various de-icing chemicals in freezing rain. For example, relative comparisons could be done using the chemicals' ice melting performance (measured using SHRP H-205.2 [10]) as an index. Another possibility would be to make comparisons based on the temperature at which solutions of various concentrations of the various chemicals will freeze.
>
> These tests are much simpler to perform, and they may provide an easier, less-costly means for predicting the relative performance of various de-icing chemicals in freezing rain, provided that a good correlation can be developed between these basic properties and their relative performance in freezing rain in large-scale tests (of the type performed here).
>
> (c) Investigate the effect of the impervious test surface that has been used. It is possible that the various chemicals may penetrate the porous surfaces on runways differently, which would affect their overall performance.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary Results and Conclusions

7.1.1 Braking Friction Tests

Tests were done to: (a) compare the friction measured for various tire types on a wide range of winter surfaces; and, (b) investigate the effect of load and pressure on friction.

The effect of tire type and pressure depends on the surface (i.e., asphalt vs ice), and the type of material (i.e., liquid vs solid) applied on the ice and asphalt, as shown below.

Table 7.1: Braking Friction Tests

Type of Material on Substrate	Substrate: Asphalt	Substrate: Ice
None (Bare & Dry)	Friction increases with tire pressure	Friction independent of tire type and pressure
Solid	Not tested	Friction increases with tire pressure
Liquid	Friction increases with tire pressure	Friction independent of tire type and pressure

The observed trends are summarized below:

(a) On asphalt, the friction factor steadily reduced with lower tire pressures, especially when liquids were present on the asphalt. As expected, liquids on asphalt caused a reduction in the friction factor with respect to the bare and dry value. The drop in friction was related to: (i) the fluid type (as more viscous fluids produced lower friction than did a wetted surface, although there were no significant differences among the various de-icing fluids tested); and, (ii) temperature (as lower friction was produced at -10°C than at -2°C). It was not related to the application rate of the fluids over the ranges tested.

(b) The friction factors on ice and on ice with liquids on it, appear to be mainly controlled by the ice and the materials on it, which act as the sacrificial surface during these cases. The friction factors for sand on ice increase with the tire pressure, which is believed to be due to the tendency of higher pressures to cause better bonding between the sand and ice.

(c) The effect of urea on the measured friction is dependent on tire type and pressure and on the temperature, since the urea was partially dissolved in a slurry at -2°C, whereas it remained solid at -10°C.

The “load and pressure” tests were conducted on bare ice and frozen snow at -10°C using the Type VII 26.6 x 6.6 aircraft tire. The friction decreased with the vertical load for both substrates. The friction was not related to the tire inflation pressure as similar results were obtained for the three pressures tested. These results are similar to those from the load and pressure study conducted at the 1998 North Bay field trials [4].

7.1.2 Sand Friction Tests

Tests were conducted to investigate the friction provided by sand applications on ice and frozen snow. The friction increased with the sand application rate for all sands tested. Typically, sand applications at rates up to 400 g/m^2 increased the friction factor from about 0.1 (for bare ice or frozen snow) to a maximum value of 0.25 to 0.3.

Tests were conducted to compare the friction provided by seven sands that are available locally at airports to one that meets the Transport Canada specification [7] (termed Ottawa TC sand). These data were analysed in combination with the results obtained previously [1], in which 16 local sands were tested. The following results were obtained:

(a) The differences in friction factor among all of the sands were small. Despite this, there were large differences in the relative amounts required for one sand to provide the same friction as another. This is due to the fact that relatively large increases in application rate only produce relatively small increases in friction.

(b) Most of the local sands provided better performance than the Ottawa TC sand, since less material was needed to achieve the same friction.

The parameters controlling sand friction were investigated by conducting tests in which the area coverage, the grain size, and the angularity were varied independently. The friction was most strongly related to the surface area covered by the sand, and it increased with the area coverage. Thus, the results generally show that the friction is expected to decrease slightly as the sand becomes coarser. The friction also increased with the grain size and angularity of the sand. Sand applications at -5°C produced greater friction increases than at -15°C. The equations below were developed which provide a reasonable fit to the data, as most of the predicted values were within about +/- 20% of the measured values.

- $\mu_{\text{After Sanding}} = \mu_{\text{Ice or frozen snow}} + \Delta\,\mu$ [7.1]
- Temperature : -5°C : $\Delta\,\mu = (A_I / 100)^{0.1} / [(1.2/A_c) + (0.8/ G_s^2)]$ [7.2]
- Temperature : -15°C : $\Delta\,\mu = (A_I / 100)^{0.1} / [(2.4/A_c) + (1.6/ G_s^2)]$ [7.3]

where : $\mu_{\text{After Sanding}}$ = the friction factor produced by sand on ice or frozen snow
$\mu_{\text{Ice or frozen snow}}$ = the unsanded friction factor of the ice or frozen snow surface
$\Delta\,\mu$ = the friction factor increase produced by sand applications

A_I = the angularity index (defined using equation 5.2)
A_c = the area coverage, expressed as a decimal value
G_s = the weighted-average grain size, in mm

The equations were used to compare the friction expected across the size distributions for airport runway sand specified by Transport Canada (TC)[6] and the Federal Aviation Administration (FAA) [7]. The friction is predicted to reduce slightly across the range from the fine edge of the FAA specification to the coarse edge of the TC specification at both -5°C and -15°C. This reflects the effect of area coverage, which decreases steadily over this range of size gradations.

7.1.3 Freezing Rain Tests

A method was developed to investigate the performance of de-icing chemicals in freezing rain in the laboratory. Potassium acetate, UCAR, sodium acetate, urea, and sodium formate were tested at several application rates. The method appears to give credible results, and it is highly repeatable.

The friction was affected greatly by the ice formation process. The ice formation processes were similar for all chemicals and they varied with the application rate.

At high and intermediate application rates, the surface remained wet at first, causing relatively high friction to be measured. Eventually, slush was produced by the freezing rain, which later hardened into ice on the test track. A steady drop in friction was recorded over the slush and ice formation process.

For low application rates, the freezing rain formed ice on the test track quickly, which resulted in low friction. Once ice had formed, the friction coefficient remained essentially constant with further exposure to freezing rain.

The "protection time" was used as an index for comparing the performance of the various chemicals. (See section 6 for definition). The protection time provided by the solid chemicals increased linearly with the application rate. The quantities required for sodium acetate and sodium formate to provide the same protection time as urea were about 70% and 40% of those for urea, respectively.

The protection times provided by the liquid chemicals also increased with the application rate, although in contrast to the solid de-icers, the trend was non-linear. This variation may be due to the improved ability of the liquid de-icing chemicals to coat the surface in a uniform manner. The quantity of UCAR required to provide 30 minutes protection time was about 60% of that for potassium acetate.

7.2 Recommendations

7.2.1 Braking Friction

The tests have shown that the vertical load and the contact pressure have a large effect on the friction factor on ice and frozen snow. This was also observed during the recent field trials conducted at the North Bay, Ontario airport [4]. This effect should be investigated further to understand the relationship between the friction factor "seen" by an aircraft and that measured by the various ground vehicles.

It is recommended that parametric load and pressure tests be conducted over a wider range of vertical loads, surfaces, temperatures, and tire types.

7.2.2 Sand Friction

No further testing or analyses are recommended.

7.2.3 Performance of De-Icing Chemicals in Freezing Rain

A test method was developed and used to compare the performance of five different de-icing chemicals at several application rates. While the method appears to provide realistic results, further work should be conducted to:

- Verify the method by comparing the results obtained here with field data. Observations should be made of the ice and slush conditions that occur during freezing rain conditions and these should be compared to the laboratory results. Also, where possible, the relative performance of various de-icing chemicals observed from field applications should be compared with the laboratory test results.

- Investigate simpler indexes for predicting the relative performance of various de-icing chemicals in freezing rain. For example, relative comparisons could be done using the chemicals' ice melting performance (measured using SHRP H-205.2 [10]) as an index. Another possibility would be to make comparisons based on the temperature at which solutions of various concentrations of the various chemicals will freeze.

  These tests are much simpler to perform, and they may provide an easier, less costly means for predicting the relative performance of various de-icing chemicals in freezing rain, provided that a good correlation can be developed between these basic properties and their relative performance in freezing rain in large-scale tests (of the type performed here).

- Investigate the effect of the impervious test surface that has been used. It is possible that the various chemicals may penetrate the porous surfaces on runways differently, which would affect their overall performance.

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APPENDIX A

SIZE GRADATIONS OF THE SANDS TESTED PREVIOUSLY [1]

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX B

SIZE GRADATIONS OF THE SANDS TESTED IN THE CURRENT PROGRAM

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX C

DESCRIPTION OF THE ANTI-SKID SURFACE USED FOR THE FEEZING RAIN TESTS

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX D

SAND FRICTION DATA PLOTS OBTAINED FROM THE PREVIOUS TEST PROGRAM [1]

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX E

COMPARISON OF THE TRANSPORT CANADA SIZE SPECIFICATION FOR AIRPORT RUNWAY SAND WITH SAND SIZE SPECIFICATIONS FOR HIGHWAYS AND ROADS

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX F

PARAMETRIC SAND TEST RESULTS

SAND: RED LAKE AIRPORT SAND
TIRE: TYPE VII 26 X 6.6 AIRCRAFT TIRE AT 1550 KPA

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX G

PARAMETRIC SAND TEST RESULTS
SAND: OTTAWA TC SAND
TIRE: TYPE VII 26 X 6.6 AIRCRAFT TIRE AT 1550 KPA

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX H

PARAMETRIC SAND TEST RESULTS
SAND: FLIN FLON AIRPORT SAND
TIRE: TYPE VII 26 X 6.6 AIRCRAFT TIRE AT 1550 KPA

(Not available in electronic format/
Non disponible en format électronique)

APPENDIX I

PARAMETRIC SAND TEST RESULTS

SAND: RED LAKE AIRPORT SAND
TIRE: SFT TIRE AT 210 KPA

***(Not available in electronic format/
Non disponible en format électronique)***

APPENDIX J

PARAMETRIC SAND TEST RESULTS

SAND: OTTAWA TC SAND
TIRE: SFT TIRE AT 210 KPA

(Not available in electronic format/
Non disponible en format électronique)