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Evaluation of the Sand Properties Affecting Sand Selection for Airside Applications

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16. Abstract

Extensive laboratory and field tests were carried out to investigate traction enhancement provided by sand applications on ice and packed snow. The key results related to sand specifications for airside applications on snow and ice surfaces are presented.

The most significant recommendations for revisions to Transport Canada's current sand specifications are:

- **The sand size distribution specification.** A Minimum Acceptable Sand and a Preferred Sand should be specified. The proposed specification for the Minimum Acceptable Sand uses the following sand sizes:
  - Maximum sand grain size: sieve size no. 4 (U.S. Standard)
  - Minimum sand grain size: sieve size no. 8 (U.S. Standard)

  The suggested specification for the Preferred Sand has three sieve sizes.

  Any changes made to the current TC specification should be accompanied by a monitoring program to evaluate the effects of these changes on foreign object damage (FOD).

- **The sand material.** Natural sands, manufactured sands, or a combination thereof, should be considered acceptable, provided they meet the other criteria listed in the Sand Guideline.

Because of a lack of detailed, quantitative information on how key sand properties, such as size gradation, contribute to FOD, further study in this area is recommended.

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16. Résumé

De nombreux essais en laboratoire et sur le terrain ont été réalisés afin d'étudier dans quelle mesure l'application de sable sur de la glace et de la neige tassée améliore l'adhérence des pneus. Le rapport présente les résultats clés de ces travaux se rapportant à l'établissement de normes concernant les sables épandus sur des pistes contaminées par de la neige et de la glace.

Voici les recommandations les plus importantes touchant les modifications à apporter aux normes actuelles de Transports Canada :

- **La granularité du sable.** Il est recommandé de préciser un «sable minimal acceptable» et un «sable désiré». En vertu de la norme proposée, un sable acceptable aurait les caractéristiques granulométriques suivantes :
  - dimension maximale du grain : passant au tamis n° 4 (norme américaine);
  - dimension minimale du grain : retenu au tamis n° 8 (norme américaine).

  Pour ce qui est du «sable désiré», le projet de norme précise trois numéros de tamis.

  Toute modification de la norme actuelle de TC devrait être assortie d'un programme de surveillance permettant d'évaluer les effets de la nouvelle norme sur les dommages par corps étranger (foreign object damage - FOD).
- **Le type de sable.** Les sables naturels, les sables manufacturés ou encore une combinaison de ces sables devraient être considérés comme acceptables, pourvu qu'ils respectent les autres critères énoncés dans la norme.

Devant l'absence de données quantitatives détaillées concernant l'effet des propriétés des sables, notamment leur granularité, sur les FOD, les chercheurs recommandent la poursuite des travaux.

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EXECUTIVE SUMMARY

Extensive laboratory and field tests were carried out to investigate the traction enhancement provided by sand applications on ice and packed snow. The key results related to the specification of winter maintenance sands for airside applications on ice and snow are summarized here.

The most significant recommendations for revisions to the current Transport Canada sand specifications are:

- **The sand size distribution specification**. A Minimum Acceptable Sand and a Preferred Sand should be specified. The proposed specification for the Minimum Acceptable Sand uses the following sand sizes:
  - Maximum sand grain size: sieve size no. 4 (U.S. Standard)
  - Minimum sand grain size: sieve size no. 8 (U.S. Standard)

  The suggested specification for the Preferred Sand has three sieve sizes.

  Any changes made to the current TC specification should be accompanied by a monitoring program to evaluate the effects of these changes on foreign object damage (FOD).

- **Sand material**. Natural sands, manufactured sands, or a combination thereof, should be considered acceptable, provided that they meet the criteria with respect to colour, impurities, and hardness.

Other recommendations are made regarding methods to quantify an “acceptably” dark sand colour, as well as unacceptable impurities. It is suggested that chlorides and other corrosive materials be specified as unacceptable impurities in winter maintenance sand.

Further investigations are recommended regarding:

- The acquisition of detailed, quantitative information to allow the evaluation of the effects of sand specification on FOD.

- Development of quantitative measures for an acceptable sand colour and an acceptable amount of impurities.

SOMMAIRE

De nombreux essais en laboratoire et sur le terrain ont été réalisés afin d'étudier dans quelle mesure l'application de sable sur de la glace et de la neige tassée améliore l'adhérence des pneus. Le rapport présente les résultats clés de ces travaux se rapportant à l'établissement de normes concernant les sables utilisés pour l'entretien des pistes contaminées par de la neige et de la glace.

Voici les recommandations les plus importantes touchant les modifications à apporter aux normes actuelles de Transports Canada :

- **La granularité du sable.** Il est recommandé de préciser un «sable minimal acceptable» et un «sable désiré». En vertu de la norme proposée, un sable acceptable aurait les caractéristiques granulométriques suivantes :
  – dimension maximale du grain : passant au tamis n^{o} 4 (norme américaine);
  – dimension minimale du grain : retenu au tamis n^{o} 8 (norme américaine).

  Pour ce qui est du «sable désiré», le projet de norme précise trois numéros de tamis.

  Toute modification de la norme actuelle de TC devrait être assortie d'un programme de surveillance permettant d'évaluer les effets de la nouvelle norme sur les dommages par corps étranger (foreign object damage - FOD).

- **Le type de sable.** Les sables naturels, les sables manufacturés ou encore une combinaison de ces sables devraient être considérés comme acceptables, pourvu qu'ils respectent les autres critères énoncés dans la norme, tels la couleur, les impuretés et la dureté.

Les autres recommandations formulées concernent des méthodes pour déterminer quantitativement une coloration foncée «acceptable» pour un sable, de même que les impuretés inacceptables. Il est proposé de classer les chlorides et autres matières corrosives parmi les impuretés inacceptables dans les sables utilisés pour l'entretien hivernal des pistes.

Il est recommandé de poursuivre la recherche dans les secteurs suivants :

- Acquisition de données quantitatives détaillées permettant d'évaluer les effets de la nouvelle norme sur les FOD.

- Mise au point de mesures quantitatives pour déterminer une coloration de sable acceptable et un pourcentage acceptable d'impuretés.

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GLOSSARY

ASTM	American Society for Testing Materials
CSA	Canadian Standards Association
CRREL	Cold Regions Research and Engineering Laboratory
ERD	Electronic Recording Decelerometer
FAA	Federal Aviation Administration
FOD	Foreign Object Damage
FTL	Fleet Technology Limited
Griptester	Friction-measuring device manufactured by Findlay-Irvine Ltd.
KJ Law RFT	Runway Friction Tester manufactured by KJ Law Engineers Ltd.
MOHS	A common materials hardness scale
MTO	Ministry of Transportation of Ontario
SAE	Society of Automotive Engineers
SFT	Saab Friction Tester
TC	Transport Canada

1. INTRODUCTION AND PURPOSE

1.1 Application

Sand or abrasives (which are termed winter maintenance sands here) are regularly applied by airport operators as part of their winter maintenance operations to increase friction on snow and ice.

Sand applications are used as a last resort because of potential foreign object damage (FOD) to aircraft.

1.2 Background

Transport Canada (TC) and the Federal Aviation Administration (FAA) have both had specifications for airside winter maintenance sands in place for a number of years ([1], and [2], respectively). The TC specification is quite restrictive for the reasons outlined below, and, as a result, most sands available locally at airports cannot be used. Consequently, sands meeting the TC specification are relatively expensive to obtain.

- Size gradation – only a narrow band of size ranges are recommended by the TC specification (Figure 1.1 and Table 1.1).

- Material – the TC specification requires that winter maintenance sands consist of crushed angular material. Screened aggregate is only acceptable with Regional approval.

Over the past two decades, many research programs have been conducted to study the friction produced by sand applications on ice and packed snow; they are summarized below:

- field tests conducted at Mirabel airport [3], at the Lebanon, N.H. airport [4], on highways in Ontario, [5, [6], [7], [8], and on highways in Alaska [9].

- laboratory tests conducted at the Pennsylvania Transportation Institute [10], [11], at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) [12], [13], and at Fleet Technology Ltd. [14], [15], [16].

A significant portion of this research was sponsored by Transport Canada as part of its ongoing effort to develop improved standards. Most recently, Transport Canada sponsored the preparation of a Sand Guideline [17] for applications on the airside.

It should be noted that the FAA has recently revised its sand specification [18]. Consequently, this report refers to two FAA specifications, as follows:

- the “old” specification, which is defined in [2], and;

- the “new” FAA specification, which is defined in [18]. The new FAA specification contains two specifications: (i) a criterion for the minimum acceptable sand; and, (ii) a sand size gradation recommended for optimum performance. See Figure 1.2 and Table 1.1.

1.3 Report Purpose

This document presents background information that was assembled to help develop the Sand Guideline.

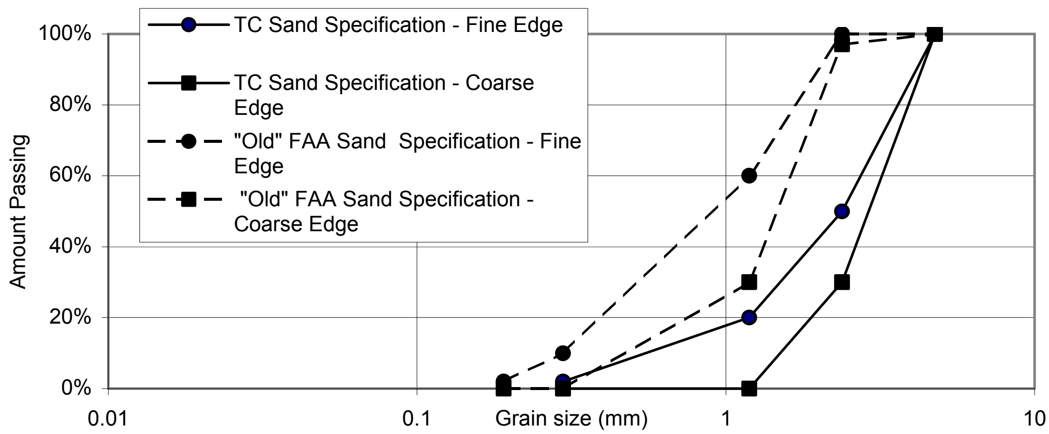

Figure 1.1: The TC and the “Old” FAA Size Specifications for Winter Maintenance Sand

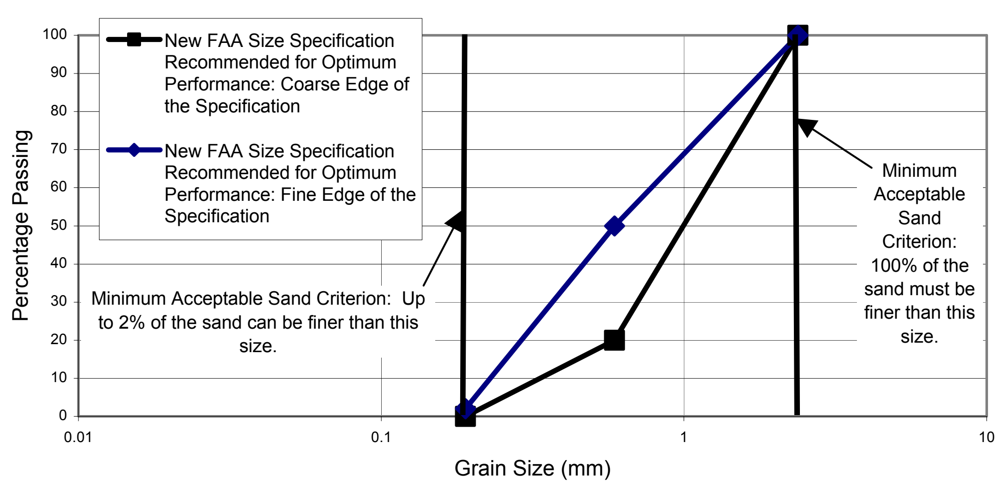

Figure 1.2: The “New” FAA Size Specification for Winter Maintenance Sand

Table 1.1: Comparison of the TC and the FAA Size Gradation Specifications

	Sieve Size (U.S. Standard)	Percentage Passing by Weight
TC Specification	No. 4	100
	No. 8	30-50
	No. 16	0-20
	No. 50	0-2
Old FAA Specification	No. 4	100
	No. 8	97-100
	No. 16	30-60
	No. 50	0-10
	No. 80	0-2
New FAA Specification: Minimum Acceptable	No. 8	100
	No. 80	0-2
New FAA Specification: Recommended for Optimum Performance	No. 8	100
	No. 30	20-50
	No. 80	0-2

2. REASONS FOR CONTROLLING SAND APPLICATIONS

The reasons for controlling sand applications fall into two main categories:

- Traction Enhancement and Safety – Sand applications are used to provide a short-term increase in friction in slippery conditions, such as on icy surfaces. Sands used on the airside should be selected to provide acceptable performance.

- The Potential for Foreign Object Damage (FOD) to Aircraft Caused by Sand – This can range from impact damage, which tends to be caused by the larger sand sizes, to abrasion and increased wear, which is caused by ingestion of the smaller grain sizes.

Sections 3 and 4 present technical information related to the friction increase provided by sand applications, and FOD, respectively. Section 5 discusses some operational considerations related to sand selection and usage.

3. TECHNICAL INFORMATION: FRICTION FACTOR INCREASES PRODUCED BY SAND APPLICATIONS

This section summarizes the key findings of the work to date. More detailed information is presented in Appendix A.

3.1 General Magnitudes and Controlling Factors

Tests done under a wide range of conditions (e.g., laboratory versus field, different friction-measuring devices) have shown that sand applications on packed snow and bare ice produce friction factors up to about 0.3 for application rates up to about 400 kg/1000 m^2. The key factors controlling sand friction include:

- the sand application rate.
- the unsanded friction factor of the packed snow or bare ice – As expected, the friction factor achieved by applying sand on ice or packed snow increased with the initial unsanded friction factor of the ice or packed snow.
- the sand properties (e.g., mineralogy, size, angularity).
- the adherence of the sand to the ice or packed snow – this depends on temperature, and whether or not the sand is heated, among other factors.

3.2 Effect of Sand Application Rate

The sand application rate is the most important parameter affecting the friction produced. In all tests, the friction increased as more sand was applied to the surface (for application rates in the range of about 50 to 400 kg/1000 m^2) although the trends varied. In some cases, the friction increased steadily over the whole range of application rates tested (e.g., the Windsor sand, Figure 3.1). However, for other tests, the friction factor tended to "level off" at the higher rates, indicating that less friction increase was achieved by applying more sand to the surface (e.g., the Kapuskasing sand, Figure 3.1).

3.3 Effect of Size Gradation

Consistent trends are not evident regarding the type of sands that produce high and low friction. Some laboratory test programs indicated that finer sands provide higher friction at warmer temperatures while the coarser ones provide better performance at colder temperatures (e.g., [10]). As well, some laboratory test programs have suggested that the mid-range sand sizes contribute most to the friction factor produced (e.g., [10]).

However, field tests conducted at Mirabel airport [3] do not support this trend. Less of the coarser TC sand needed to be applied to achieve the same friction coefficient as the finer FAA sand at relatively warm temperatures, ranging from –2° to –9°C [3].

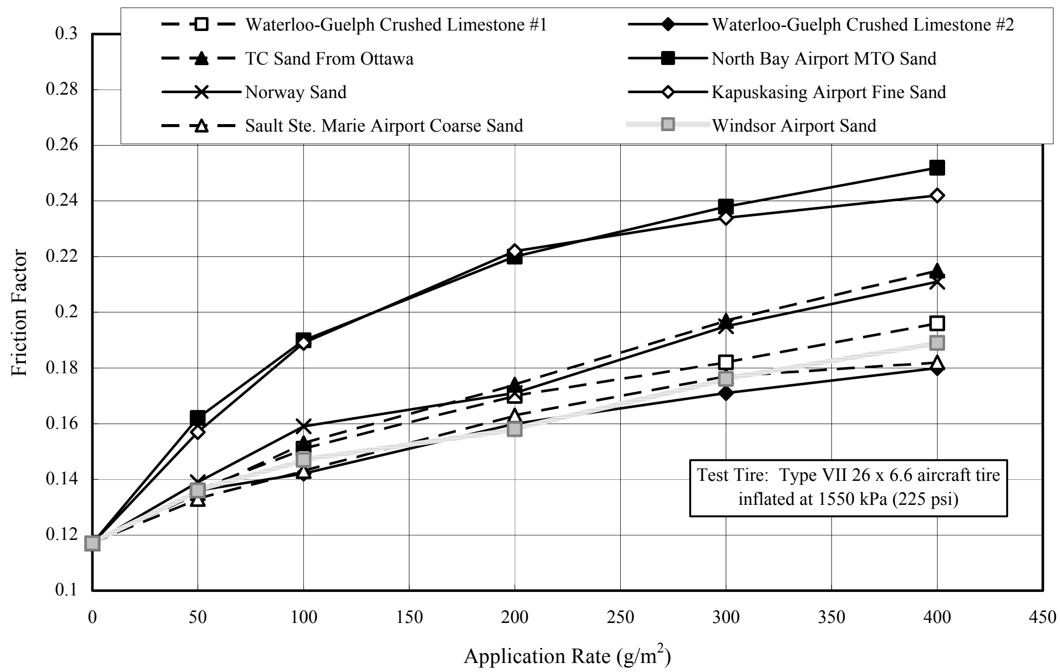

Figure 3.1: Sample Results from a Laboratory Test Program [16] with Local Sands Applied on Ice at –5°C

Extensive tests on highways [6], [7], [8] showed no statistically significant difference between coarse and fine sands on ice and packed snow over a wide temperature range. Note that the data obtained from these field tests contained a significant amount of scatter that made it difficult to draw conclusions. The following reasons were identified for the scatter:

- the sand was often spread non-uniformly by the spreader trucks used.

- the unsanded friction coefficients of the test sections varied significantly.

This "background" variability is probably responsible for the observed inconsistency between the field and laboratory test results.

In summary, universal trends are not evident although it can be stated that all of the sands tested produced friction factors that were generally similar.

3.4 Sand Type Versus Application Rate

Usually, the same friction level could be achieved with each of the sands tested by adjusting the application rate, depending upon the sands being compared and the target friction level. Sand selection at an airport thus becomes an operational issue to some extent, based on the relative quantities needed for different sands to provide the required friction level.

However, it should be noted that the relative quantities required for different sands to provide the same friction can be quite large, depending on the sands being compared, and the target friction level. For example, an extensive laboratory test program [15], [16] conducted to compare sands available locally at airports with a sand meeting the TC specification, found that the required relative application rates varied by up to a factor of about 5. In that same test program [15], [16], most of the local sands provided superior performance to the TC sand, as less local sand needed to be applied to achieve the same friction coefficient.

It should also be noted that in cases where the friction factor “levels off” with application rate (e.g., the Kapuskasing Airport Sand, Figure 3.1), it would not be possible to achieve a high friction (e.g., probably more than about 0.3, Figure 3.1) no matter how much sand was added to the surface.

Thus, it is concluded that sand selection is an operational issue to some extent (as a certain friction level can be achieved by applying more or less of a given sand); however, there are limits to the applicability of this statement as defined by the individual sand and the target friction level, and by realistic “practical” maximum application rates, which we understand to be in the range of 400 g/m^2.

3.5 Detailed Investigation of the Effect of Sand Properties

All of the tests showed that the friction coefficient increases with the application rate. This relationship was investigated further in a detailed laboratory test program [15],[16] in which the factors below were parametrically varied. A sand friction equation was developed, which is provided in Appendix A. The key results of the work are summarized below:

- <u>area coverage</u> – this parameter was found to be the most important one. As expected, the friction increased with the surface area covered by the sand. The area coverage increases with the application rate, and it varies with sand size gradation, being larger for finer sands.

- <u>grain size</u> – sands increase the friction by adding texture to the surface. The laboratory tests showed that the friction increased with the sand grain size, and that, after the area coverage, it was the next most significant factor.

- <u>sand grain angularity</u> – this was investigated in the laboratory by testing three sands which covered a range from mainly angular particles to mainly rounded particles. (The particle shapes were classified using ASTM D 2488-93 [19].) The tests indicated that the sand friction increased with the sand angularity, although its effect was minor compared to that of the area coverage and the grain size.

  However, systematic investigations on highways [6], [7], [8] showed no significant difference between natural sands and manufactured sands, within the "background" variability introduced by: (i) non-uniform spreading of the sand by spreader trucks; and, (ii) by variations in the unsanded friction levels of the test sections used.

3.6 Effect of Heating the Sand

Laboratory tests [11] and field tests [4] have shown that heating the sand can result in higher sand friction, by causing the sand to adhere better to the ice and snow on the surface.

The field tests showed that the benefit achieved by heating the sand depended on the grain size of the sand and the degree to which the sand is heated. Because coarse-grained sands retain heat longer than do fine-grained ones, heating was only found to have a significant benefit in the field for coarse-grained sands [4]. Furthermore, those field tests showed that the sand needed to be "superheated" (i.e., to 27°C [80°F]) to achieve a significant benefit.

3.7 Effect of Traffic

It is well known that traffic has an important effect because sand tends to be blown off the runway. Unfortunately, no data specific to airports are available to quantify the effect of traffic on friction.

However, tests on roads [6], [7], [8] have shown that exposure to truck traffic significantly reduces the friction levels achieved by applying sand on ice or packed snow. The friction factors measured immediately after applying the sand were typically higher than those measured after exposure to two spreader truck passes at 80 km/hr by amounts ranging from about 0.05 to 0.10.

3.8 Effect of Wetting the Sands with Chemical Agents

Field tests on roads [5], [6], [7], [8] using 32% calcium chloride solution as a pre-wetting agent applied at pre-wetting rates ranging from 1% to 4% showed that no significant increase in traction enhancement was achieved by pre-wetting the sand.

Tests at the Lebanon, N.H. airport [4] using three pre-wetting agents (i.e., UCAR, Octagon RD-1426, and Octagon RD-1432) showed that:

- each of the three chemicals provided similar performance.
- a significant friction increase was only achieved for warm ice temperatures (of greater than -2.8°C [27°F]).

3.9 Sand Hardness

3.9.1 Effect of Sand Hardness on Friction

The effect of aggregate hardness has been investigated for highway pavements without any snow or ice on them. It has not been investigated (to our knowledge) for pavements covered by ice or packed snow.

Testing on roads (without any ice or snow on them) showed that harder materials produced higher skid resistance than did softer materials [20]. Kinsey et al [21] report that many highway agencies specify that winter maintenance sands should be "clean, hard, and durable", but most do not include quantitative specifications for hardness.

However, these results are not directly applicable for snow and ice-covered pavements because snow and ice tend to be softer than bare pavement. Also, winter maintenance sands are used to provide temporary friction increases whereas highway materials are subjected to longer-term exposures where "polishing" becomes an important concern.

3.9.2 Sand Hardness Specification

The current TC specification [1] requires that sand materials not be softer than 3.5 or harder than 7 on the MOHS hardness scale. This specification is not very restrictive, as a large range of materials will qualify (Table 3.1).

3.9.3 Requirement for a Sand Hardness Specification

The rationale for including a hardness specification is not clear. It may be due to the following:

- the potential effect of sand hardness on friction – although this has not been investigated specifically by the research, it is our opinion that this would not impose a need for a hardness specification.
- the potential effect of sand hardness on FOD – it is possible that sand hardness may have an effect on the FOD caused by sand, although there is no quantitative data to establish this.

- impurities – a sand hardness specification serves as an indirect means of eliminating impurities from the sand. However, a more direct specification is believed to be preferable for this purpose, as discussed in section 3.11.

No changes to the current TC specification (with respect to the hardness specification) are recommended because:

- this requirement has not been investigated by the recent research, and;

- the present criterion is not very restrictive because a wide range of materials will qualify (see Table 3.1).

Table 3.l: The Hardness of Some Materials on the MOHS Scale

Material	Typical Value On The MOHS Hardness Scale
Talc	1
Gypsum	2
Calcite	3
Dolomite	3.5 to 4
Flourite	5
Apatite	5
Orthocaise	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

3.10 Effect of Colour

The current TC specification [1] requires that winter maintenance sands have a dark colour. A dark sand is preferable to a light-coloured one because:

- it allows the sand to be seen by pilots and other users.

- dark materials absorb sunlight well, which causes them to adhere better to ice and snow on the runway.

Although no data are available to compare dark versus light sand with respect to the friction levels achieved, the above reasons clearly make a dark sand advantageous, and the colour requirement should be maintained.

The principal problem with the current TC specification (regarding sand colour) is that it does not include a quantitative measure to define an “acceptably dark” colour, which makes it difficult to enforce. Two general options for “enforceability” are considered possible:

- the acceptability of a sand, with respect to colour, could be left up to the discretion of Transport Canada.

- an “acceptably dark” sand could be defined based on an accepted colour scale for rocks and geo-materials, such as the Munsell Colour Scale [22]. Preliminary investigations were conducted by reviewing the Munsell Colour Scale Charts [23].

  It is suggested that winter maintenance sands need to be darker than about medium to dark grey (i.e., N 4.75 or less) on the Munsell Neutral Value Scale. However, more testing is required before this could be implemented into a specification.

At present, the “discretionary” approach (i.e., first item above) is the only feasible one.

3.11 Effect of Impurities

The current TC specification requires that winter maintenance sands be free from “clay, cementation, organic material, or other extraneous or non-friction material”, and to “have a physical and chemical structure which is unaffected by water”.

No other specifications are included regarding impurities. Although the effect of impurities was not investigated by the research, it is suggested that some additional requirements may be useful, as follows:

- chlorides and other corrosive materials – there are no specific requirements in the TC specification [1] regarding these materials, and it is suggested that these impurities should be specifically excluded. It is suggested that de-icing chemicals, or other corrosive materials, should not be present in the sand, or added to it, unless the de-icing chemical(s) are approved for airside applications.

  It is recognized that trace amounts of chlorides or other corrosive materials may be present in winter maintenance sands, which represent difficulties for developing a specification.

  Further work is required to develop a specification. Testing and investigation would be required to develop an acceptable quantitative specification. As an alternative, this issue may be left up to the discretion of Transport Canada.

- enforceability or measurability – the current TC specification does not include quantitative measures that could be used for enforcement or for definitive evaluations. Two general approaches are considered possible for developing an enforceable standard:

(i) specify quantitative measures – although a number of alternatives are available, the most appropriate method is unclear. The current Canadian Standards Association (CSA) code for fine aggregate in concrete [24] was reviewed. It specifies a number of test methods and criteria that are believed to have some applicability, although testing and further investigation would be required to establish suitable criteria for winter maintenance sands. For completeness, the relevant portions of the CSA code are reproduced in Appendix B.

(ii) the acceptability of a sand, with respect to impurities, could be left to the discretion of Transport Canada.

At present, the "discretionary" approach (i.e., item (ii) above) is the only feasible one.

4. TECHNICAL INFORMATION: THE FOD CAUSED BY SAND

4.1 Size Gradation

Although firm guidelines are not available to relate FOD to sand size or other sand properties, it is generally accepted that FOD is affected by:

- the maximum sand grain size – large sand particles will cause impact damage; and,
- the minimum sand grain size – small sand particles will be ingested into turbines causing cause abrasion, among other damages.

4.2 Sand Hardness

FOD may be related to the sand hardness, although no definitive information is available at present. As described in section 3, the current TC specification [1] includes a hardness specification. It states that winter maintenance sands must have a hardness between 3.5 and 7.0 on the MOHS scale.

Because this has not been investigated in the current research, no comments or recommendations are made here.

5. TECHNICAL INFORMATION: OPERATIONAL CONSIDERATIONS

5.1 Sand to Remain Free-Flowing and Lump-Free

Although this was not investigated by the current research, it is well known that moisture in the sand may freeze, producing lumps, making it difficult to apply the sand using spreader trucks. These lumps are also a FOD hazard for aircraft. The current TC specification outlines a number of actions that can be taken to minimize this problem:

- Minimize the moisture content of the sand received. The material, as delivered, should be as dry as possible. The current TC specifications [1], state that the moisture content of the delivered sand should be no more than 3%.

- Storage – The sand should be kept dry. Storage considerations are given in [1].

- Add de-icing chemicals to the sand. This approach can be used provided that: (i) the de-icing chemical is approved for airside applications; (ii) the chemical is operationally effective over the range of temperatures expected; and, (iii) the costs are acceptable.

5.2 Sand to be Spread Uniformly

Non-uniform spreading will produce variations in friction among various sections of the runway, which are potentially unsafe. Efforts should be made to spread the sand as uniformly as possible.

6. RECOMMENDATIONS FOR CHANGES TO THE CURRENT TC SAND SPECIFICATION

6.1 Size Gradation

FOD is the primary consideration for selecting the size gradation, as the results showed that all of the sands tested produced friction levels that were generally similar, depending on the application rate. Unfortunately, quantitative information is not available to define how FOD is affected by sand size, and this is the principal factor limiting the changes that can be made to the current TC specification.

In the absence of this information, the recommendations made here follow the same general approach used by the FAA to update its specification. Thus, recommendations are made here for:

- a minimum acceptable sand; and,

- a preferred sand.

The minimum acceptable sand is specified by only a maximum and a minimum sand size. The following values are recommended based on the specifications of Transport Canada [1], and the Federal Aviation Administration [2], [18].

- Maximum sand grain size – sieve size no. 4 (U.S. Standard)
- Minimum sand grain size – sieve size no. 80 (U.S. Standard)

This change would allow most of the local sands tested in a recent laboratory test program conducted to compare local sands with TC sand [16] to qualify (Figure 6.1).

The suggested specification for the preferred sand is described in Table 6.1, and it contains a third sieve size.

Table 6.1: Suggested Specification for the Preferred Sand

Sieve Size (U.S. Standard)	Percentage Passing by Weight
No. 4	100
No. 16	10-85
No. 80	0

This change would also allow most local sands to qualify (Figure 6.2), although, of course, it is somewhat more restrictive than a specification based on only the maximum and minimum sand size. However, this specification could help prevent airports purchasing sands that contain too many fine or coarse particles (which is possible with the minimum acceptable sand criterion).

It is recommended that any changes made to the current TC specification be accompanied with a monitoring program to evaluate whether or not FOD is affected significantly by these changes.

6.2 Mineralogy

The specification should be opened up to include natural sands. This change is recommended because the research has shown that this does not significantly affect the friction produced.

It is suggested that winter maintenance sands be allowed to comprise natural sand, manufactured sand, or a combination thereof.

6.3 Impurities

Chlorides and other corrosive materials should be added to the list of unacceptable impurities.

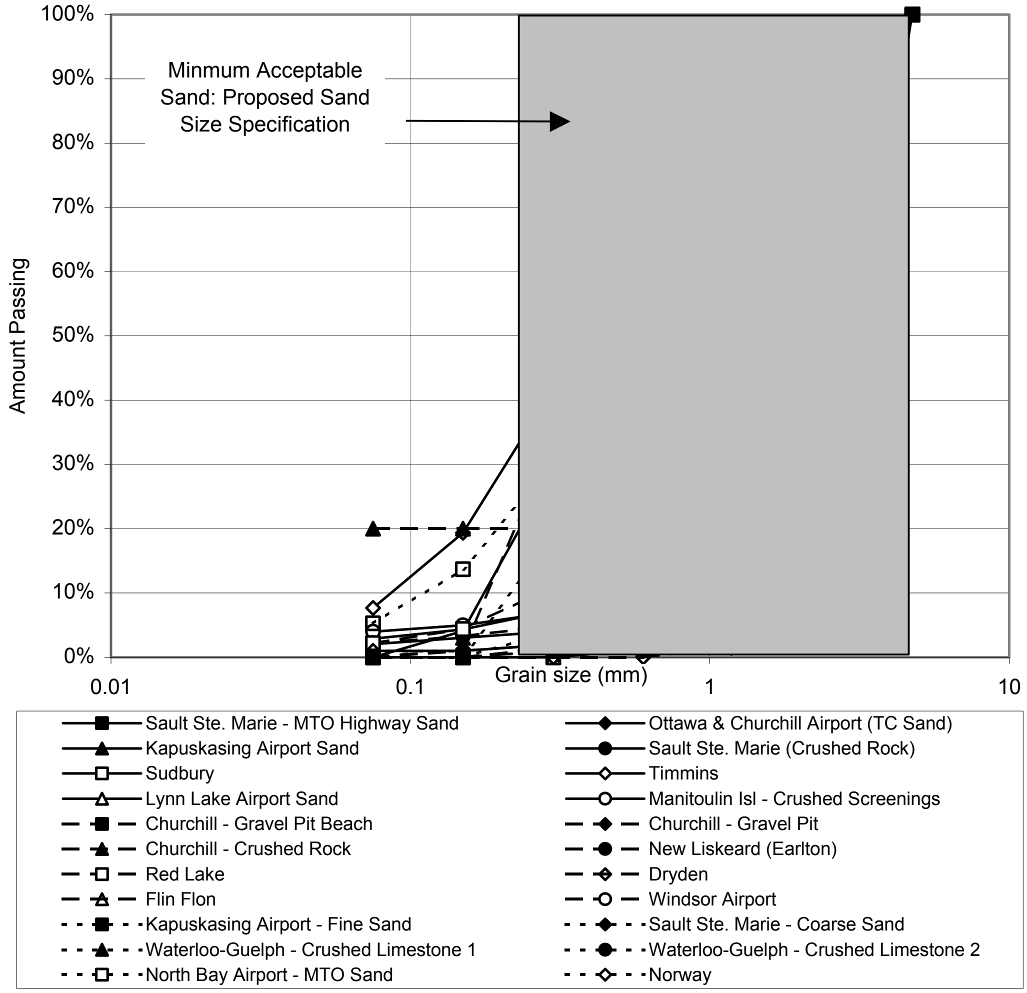

Figure 6.1: Comparison: Suggested Specification for the Minimum Acceptable Sand Versus the Local Sands Tested

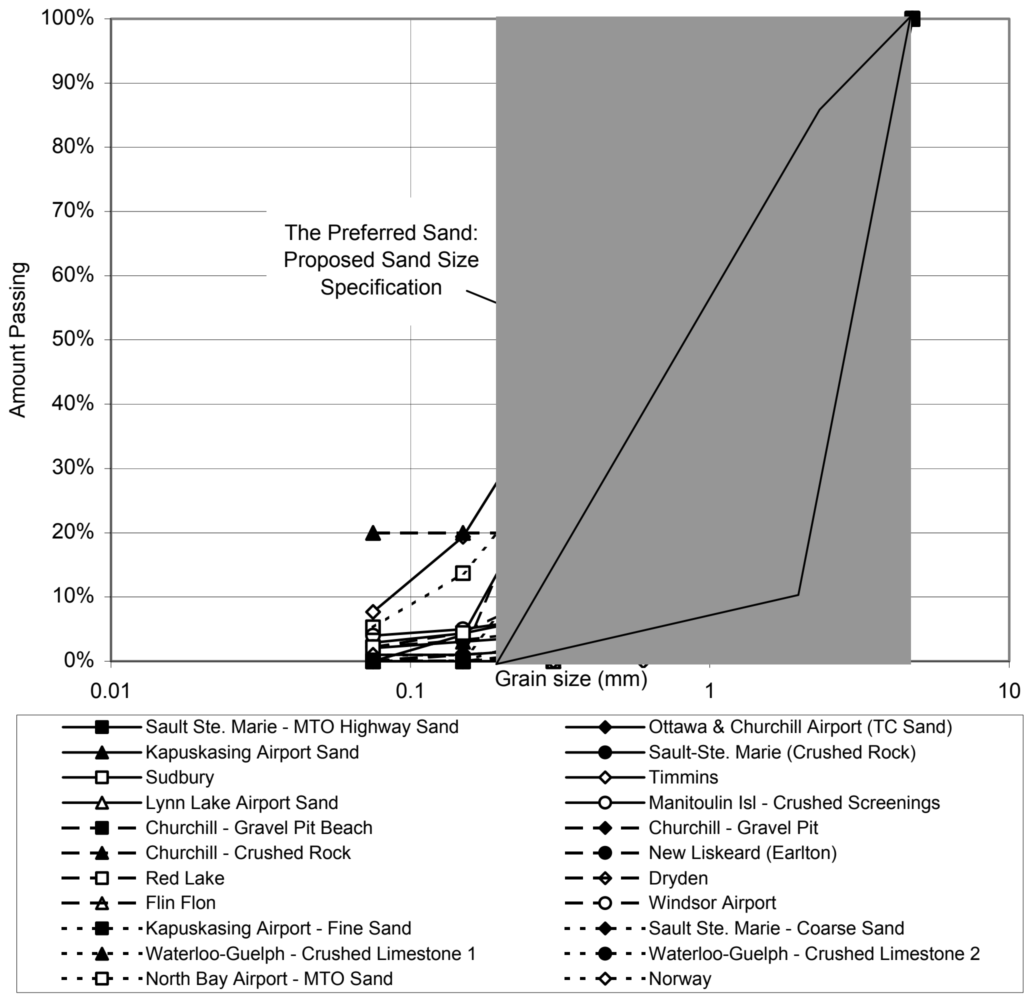

Figure 6.2: Comparison: Suggested Gradation for the Preferred Sand Versus the Local Sands Tested [16]

7. CONCLUSIONS

Extensive research was conducted to investigate sand friction on ice and packed snow. These findings were used to produce a Sand Guideline, and to make recommendations for changes to the current TC Sand Specification. The following changes are recommended:

- **Size Gradation** – a Minimum Acceptable sand and a Preferred Sand should be specified. The suggested specification for the Minimum Acceptable Sand is as follows:

Table 7.1: Suggested Specification for the Minimum Acceptable Sand

Sieve Size (U.S. Standard)	Percentage Passing by Weight
No. 4	100
No. 80	0

The suggested specification for the Preferred Sand is as follows:

Table 7.2: Suggested Specification for the Preferred Sand

Sieve Size (U.S. Standard)	Percentage Passing by Weight
No. 4	100
No. 16	10-85
No. 80	0

It is recommended that any changes made to the current TC specification be accompanied with a monitoring program to evaluate whether or not FOD is affected significantly by these changes.

- **Sand Mineralogy** – natural sands should be allowed provided that they meet the requirements for impurities.

- **Impurities** – chlorides and other corrosive materials should be added to the list of unacceptable impurities.

Additional research and development is required in the following areas:

- **FOD** – more information is needed to understand how FOD is affected by sand size, sand mineralogy, and other sand properties.

- **Enforceability or Measurability** – quantitative criteria need to be developed regarding sand colour and impurities.

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APPENDIX A

SUMMARY RESULTS FROM RECENT FIELD AND LARGE-SCALE LABORATORY TEST PROGRAMS

SUMMARY RESULTS FROM RECENT FIELD AND LARGE-SCALE LABORATORY TEST PROGRAMS

A.1 Program Scopes

The major field test and large-scale laboratory test programs that have been conducted recently are summarized in Table A.1.

Table A.1: Major Field And Large-Scale Laboratory Test Programs

Proj. #	Test Type	Facility Or Loc'n	Test Parameters			Ref & Year
			Sands	Substrate	Air Temp.	
1	Labor-atory	Refrigerated Track At CRREL (funded by FAA)	1. Mat'l. : All from same source - natural sand with semi-rounded particles 2. Sizes - 5 sand size dist'ns. tested	Ice	-3°C & -10°C	[12]; [13] (1992 ; 1993)
2	Labor-atory	Refrigerated Track At FTL (funded by Transport Canada)	• 24 sands available locally at airports within Canada • TC, Flin Flon & Red Lake Sand - sieved to 4 size ranges	Ice & Frozen Snow	-5°C & -15°C	[15];[16] (1996) & (1998)
3	Field	Mirabel Airport (carried out by Transport Canada)	1. TC Sand 2. FAA Sand	Ice	-2°C & -8°C	[3] (1986)
4	Field	Lebanon, NH airport (funded by FAA)	1. SAE Sand 2. ASTM Sand	Ice	0°C to -9°C	[4] (1996)
5	Field	Roads near Ottawa, and New Liskeard, Ont. (funded by MTO)	• Crushed limestone - sieved to three size dist'ns. • Natural sands - sieved to three size gradations Note - all sands had about 5 % salt added to them.	Ice & Packed Snow	-7°C to -29°C	[5]; [6]; [8] (1995-1997)

A.2 The Friction Factor Increases Achieved by Sand Applications

The maximum friction factor increases achieved by sand applications in the above programs are summarized in Table A.2. For brevity, only an overview of the results is presented here. For more detailed results, the individual references should be consulted.

Table A.2: Summary Results: The Friction Factor Increases Achieved by Sand Applications

Proj. No. (see Table A.1)	Device Used To Measure Friction	Summary Of Measured Friction Factors Or Friction Numbers (*)			
		Substrate	Unsanded Value	Max. Appl'n. Rate	Sanded Value
1	Instrumented Vehicle	Ice	8* to 11*	143 g/m^2	31*
2	Instrumented Aircraft Tire on Moving Trolley	Ice Frozen Snow	.12 to .14 .13	400 g/m^2 400 g/m^2	.3 .25
3	SFT	Ice	.11 to .13	280 g/m^2	.32
4	K.J. Law RFT	Ice	0.17 (avg)	290 g/m^2	.3
5	1995 : ERD	Ice Packed Snow	0.13 0.28	1340 kg/ 2lane km (~180 g/m^2) 960 kg/ 2lane km (~130 g/m^2)	.25 .4
	1995: GripTester	Ice Packed Snow	17* 32*	1340 kg/ 2lane km (~180 g/m^2) 960 kg/ 2lane km (~130 g/m^2)	29* 41*
	1996 : ERD	Ice Packed Snow	0.13 0.20	940 kg/ 2lane km (~130 g/m^2) 800 kg/ 2lane km (~110 g/m^2)	.19 .35

A.3 Important Sand Properties: Detailed Investigation

All of the above test programs have shown that the application rate is a very important parameter, (and usually the most important one), affecting the friction factor increases achieved by sand applications on ice and packed snow. These test programs also showed that in most cases, the same friction level could be achieved with each of the sands tested by adjusting the quantity of each sand that was applied.

This section summarizes the results obtained from a detailed laboratory investigation [16] that was conducted to investigate the relationship between friction coefficient and application rate in greater depth. The tests were conducted by varying the following factors parametrically:

(a) the surface area covered by sand applications;
(b) the grain size of the sand; and
(c) the sand's angularity

A sand friction equation was developed from these tests. 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 A.1 and A.2.

- Bare Ice Surface: $\mu_{\text{After Sanding}} = \mu_{\text{Ice}} + \Delta\mu$
[A.1]
- Frozen Snow Surface: $\mu_{\text{After Sanding}} = \mu_{\text{Froz Snow}} + \Delta\mu$ [A.2]

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

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

(b) 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 :

$$1/\Delta\mu = f(\Delta\mu_{\text{Angularity}}) \bullet [\, 1/f(\Delta\mu_{A\_cov}) + 1/f(\Delta\mu_{\text{Grain Size}})\,] \qquad [A.3]$$

(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 A.4 and A.5, respectively.

- Temperature : -5°C: $\Delta\mu = (A_I / 100)^{0.1} / [(1.2/A_c) + (0.8/G_s^2)]$ [A.4]
- Temperature : -15°C: $\Delta\mu = (A_I / 100)^{0.1} / [(2.4/A_c) + (1.6/G_s^2)]$ [A.5]

where: A_I = the angularity index (defined using equation A.6 below)
A_c = the area coverage, expressed as a decimal value
G_s = the weighted-average grain size, in mm

A_I = % Rounded · Weighting $\text{Factor}_{\text{Rounded}}$ + [A.6]
% Sub-Rounded · Weighting $\text{Factor}_{\text{Sub-Rounded}}$ +
% Sub-Angular · Weighting $\text{Factor}_{\text{Sub-Angular}}$ +
% Angular · Weighting $\text{Factor}_{\text{Angular}}$

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 [18], respectively.

Weighting $Factor_{Rounded}$,Weighting $Factor_{Sub\text{-}Rounded}$,Weighting $Factor_{Sub\text{-}Angular}$ and Weighting $Factor_{Angular}$ = 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 input parameter ranges for which equations A.4 and A.5 are considered applicable 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 Figure 3.2, which shows a plot of all the size gradations tested. See also reference [16].
- Sand Sizes:
  - Local sand tests: weighted-average grain size: 0.29 to 2.76 mm [16]
  - Parametric sand tests: < 1.18 mm to 4.0 mm
- Substrate: Bare ice and frozen snow
- Temperature: -5°C and -15°C

The previous equations suggest that:

(a) the friction will increase with the area coverage, and that it is the most important factor.

(b) the friction will increase with the sand's grain size, and that it is the next most important factor.

(c) the friction will increase with the sand's angularity although it has considerably less effect than the area coverage or grain size.

It is of interest to compare these results to those observed in the other recent test programs. The characteristics of the sands producing high friction in the test programs are summarized in Table A.3.

The other test results show reasonable agreement with the predicted trends.

Table A.3: The Sand Properties Producing High Friction: Summary of Trends Observed

Proj. No. (See Table A.1)	Trends :	Characteristics Of The Sands Producing High Friction		
		Area Covered	Sand Size	Angularity
1	-3°C : No Strong Trends -10°C: TC & SAE Sands Best But Much Scatter	The area coverage is greater for fine sands than for coarse ones. Conversely, the coarser ones have larger grains. Because strong trends were not observed, it is evident that both factors affected the results.		Naturally-Occurring Sand With Semi-Rounded Particles
2	Fine To Mid-Range Sized Sands Produced Higher Friction Than Did The Coarser Material	Greater area coverage	Smaller Grains	Angular sands provided slightly higher friction
3	TC Sand (TC) Vs FAA Sand : TC Sand (Coarse) Produced Higher Friction Than FAA (Mid-Range)	Smaller area coverage	Larger Grains	Both Angular (as per spec'ns)
4	SAE Sand Vs ASTM Sand : SAE Sand (mid-Range) Produced Higher Friction Than ASTM (Fine)	Smaller Area	Larger Grains	? Not Specified In Report
5	No Measurable Trends (At 95 % Confidence Level) w/r to : • Crushed Rock Vs Natural Mat'l • Size Gradation - Coarse to Fine • Temperature • Ice Vs Packed Snow	No Clear Trend - Therefore All Factors Contributed To The Results		

APPENDIX B

SPECIFICATIONS FOR FINE AGGREGATE FOR CONCRETE FROM CSA A23.1-94 & A23.2-94 [24]

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