Braking Traction on Sanded Ice

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Traction enhancement on iced pavements using abrasives was evaluated. The abrasives tested were five distinct gradations of sand built from a single host material. Four of the sands represented standard gradations as specified by the FAA, SAE, ASTM, and Transport Canada. Braking traction at a relatively fixed slip rate was measured with a full-size, self-contained instrumented vehicle. All tests were performed on an ice sheet inside a large refrigerated room. Results showed that coarse sands perform best on cold ice surfaces and that finer sands excel on warm ice. Sands with most of their grains about 1 to 2 mm in diameter performed well independent of ice temperature. The concentration of a sand on ice strongly influences the degree of traction enhancement, as does the temperature of the sand when applied to the ice. The results suggest that a mathematical expression could be generated that would relate sand type and concentration, along with several other influential parameters, to braking traction coefficient on ice.

Driving and braking traction on roads and runways in regions affected by subfreezing temperatures is often degraded by ice. Depending on the circumstances, an abrasive product may be the only way to enhance traction on iced operating surfaces. Natural sands are the most common abrasive product. Several standard gradations are identified by various agencies for specific applications. The use of abrasives at most airports is regulated by the FAA, which specifies the type of sand allowed for use on runways and the conditions and methods surrounding its use in its Airport Winter Safety and Operations Advisory Circular 150/5200-30.

This study was initiated as a result of concerns expressed by many airport operators about the lack of readily available sources of the FAA sand and its high cost relative to other sand types. At least one aircraft manufacturer has also expressed concern about the current FAA-specified sand. The manufacturer objects to the allowance of sand particles that are larger than 3.30 mm in diameter (No. 6 sieve), which the manufacturer claims can cause serious damage when ingested in turbine engines.

The goal of this study was to compare the ice braking friction coefficient of the FAA sand with that of other specified sands. The sands tested in this study were those specified by ASTM for mortar, SAE for runways, Transport Canada (TC) for runways (Table 1), and a very fine graded sand. The fine sand was included in this study because of our interest in determining the contribution of fine particles to traction enhancement. Sands containing a high fine content are generally less costly, and some aircraft personnel believe that fine particles are less likely to damage aircraft engines (*1*).

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BACKGROUND

The frictional properties of sanded ice as a function of grain size has been addressed in the literature. Hegmon and Meyer tested four granular materials on ice: boiler house cinders, coke cinders, sand, and crushed stone (*2*). In their tests they used a full-size tire mounted on a pivot arm that traveled around a circular ice track in a cold room. The test temperature was held at −6°C, and the abrasives were applied to the ice to yield surface concentrations between 160 and 650 g/m². Their study concluded that size fractions between 1.18 and 4.76 mm in diameter (falling between sieves No. 16 and No. 4) contribute most to the friction coefficient; they recommended that finer and coarser fractions be eliminated or minimized.

Hayhoe tested crushed and uncrushed materials of three distinct size gradations at a surface concentration of 980 g/m² (*3*). Hayhoe was primarily interested in the effect of varying sand and air temperatures on the friction coefficient. The uncrushed material consisted of a mixture of roofing gravel and concrete sand. The crushed material used was Pennsylvania Department of Transportation and mortar sand. Hayhoe also used a full-size tire on an indoor circular ice track. Test results for an ice temperature of −24°C indicated that the friction coefficient improved with coarsening of a sand; for ice temperatures near melting (−1°C), the friction coefficient improved with greater fine grain content. At intermediate temperatures (about −12°C), Hayhoe's results agreed with those of Hegmon and Meyer, that a sand consisting of grains between 1.18 and 4.76 mm in size (No. 16 and No. 4 sieves) gave the highest friction coefficient.

Connor tested four materials using both laboratory and field test methods: the British pendulum test, Tapley deceleration meter, and stopping distance measurement using a full-size automobile (*4*). The abrasives used in Connor's study included crushed stone, "pit-run" stone (source aggregate for the crushed stone), concrete aggregate with a high fine sand content, and coal cinders. All abrasives were applied in surface concentrations between 100 and 2000 g/m² on ice at temperatures of −23, −18, −9, and −1°C for the laboratory tests and at −20°C in the field. Connor found that coal ash—by far the finest of the four materials with 44 percent of the grains finer (by weight) than 0.297 mm in diameter (No. 50 sieve) and 20 percent finer than 0.074 mm (No. 200 sieve)—outperformed the other materials in most cases. Connor also concluded that angular material provided higher friction coefficients than rounded particles. The results were presented as a function of sand concentration on the ice.

The Airports Authority Group of Canada also studied the effect of grain size on ice friction at ice temperatures of −9 and −3°C (*5*). Their tests were designed to determine the

TABLE 1 Allowable Gradations for Several Specified Sands

Sand Type	Sieve Number	Percent Finer by Weight
FAA	4	100
	8	97-100
	16	30-60
	50	0-10
TC	4	100
	8	30-50
	16	0-20
	50	0-2
SAE	6	100
	8	60-100
	25	0-20
	40	0-5
ASTM	4	100
	8	95-100
	16	40-75
	50	10-35
	100	2-15

relative surface concentrations of two sands that would give the same coefficient of friction. One sand had grain sizes no larger than 2.36 mm (No. 8 sieve), and the other allowed grains up to 4.76 mm in diameter (No. 4 sieve). Measurements were made on an actual iced runway with a Tapley deceleration meter and a Saab friction tester. They concluded that the finer material must be applied at a surface concentration of 85 to 95 g/m^2 to match the braking performance that was measured on ice treated with the coarser sand at a surface concentration of 50 g/m^2. For concentrations greater than 120 g/m^2 on cold ice or 240 g/m^2 on warm ice, however, the finer sand provided a higher coefficient of friction.

In a precursor to the study reported here, the authors performed an initial assessment of frictional qualities of four sand types on ice (*6*). They compared the FAA sand with three other popular sand types: from SAE (SAE AMS 1448), International Civil Aviation Organization (ICAO), and ASTM (ASTM C144). Using a small-scale sliding friction table, the sliding friction of a rubber-faced slider on sanded ice at -10°C was measured. Tests were done on bare ice, loosely sanded ice, and ice with sand frozen on at a single concentration of 1750 g/cm^2. The friction coefficients for the slider on bare ice were found to be higher than those measured on loosely sanded ice and, in some cases, on ice with sand frozen on. Test results were presented as a performance ratio (friction coefficients for sanded ice to bare ice), which allowed the sands to be ranked distinctly—in order of decreasing effectiveness—as ASTM, FAA, SAE, and ICAO. The performance ratio showed a strong, linearly increasing trend as the percentage of a given fine grain size in the sand was increased. Greater increases in traction with increases in fines were found for frozen-on sand than for loosely sanded ice.

EQUIPMENT AND FACILITIES

To ensure environmental control for our tests, the entire test program was conducted inside the Frost Effects Research Facility (FERF) at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. The FERF is a large building capable of holding a constant ambient air temperature ranging between -12 and 15°C. For a test surface, we constructed a temporary ice rink 30 m long and 3.6 m wide inside the building. Controlling the temperature of glycol that was passed through cooling coils in the ice enabled the temperature of the ice to be controlled. Thermocouple strings frozen into the ice sheet at three locations were used as feedback to the glycol source to attain the desired ice-surface temperature.

Traction was measured using a versatile instrumented vehicle that can operate in a variety of measurement modes. The CRREL instrumented vehicle (CIV) is based on a 1972 Jeep Cherokee and measures three mutually perpendicular forces at the contact patch for each of the four tires, the speed of each tire, and the speed of the vehicle itself. A computer-based data acquisition system collects data at a rate of 10 samples per second and stores the data in a spreadsheet format for later analysis. Further details on the CIV are given elsewhere (*7*).

To match the measurements taken by the usual FAA-endorsed devices (skidometer, Saab and K.J. Law friction testers, Tapley meter), the CIV was configured to operate at a constant rate of negative slip (braking) of between 10 and 20 percent. To accomplish this, all four tires were driven at a common rate of rotation, but they were installed with a 15 percent difference in circumference on the front and rear axles. Thus, the tires with the least vertical load (normal force) were forced to slip to take up the difference in rotation. For the CIV, the rear wheels have the least normal load. With smaller-diameter tires installed on the rear axles, all the slip took place there.

Data were collected with the vehicle operating at a constant ground speed of 5 km/hr over a 17-m segment of the ice surface. This yielded at least 10 sec of data collected at steady-state conditions (at least 100 data points for each tire).

During a braking traction test, the CIV measured the total tire-dragging force of the slipping tires, which included both the interfacial force at the tire-ice contact patch and the internal resistance to rolling naturally present in a tire (caused by flexing of the tire belts and carcass). To isolate the interfacial (friction) force, the internal resistance was determined in separate tests in which the CIV measured the tire-dragging force of the tires in a nonslip condition. This resistance force was subtracted from the total tire-dragging force to obtain the desired friction force.

New tires (P185/75R14 Goodyear Invicta) were installed on the rear axles where braking traction was measured; they were inflated to 240 kPa for all tests. Average dynamic vertical load on the rear axles was 5575 N/tire, and the average static contact patch measured 190 cm^2 in area.

TEST VARIABLES

The primary test variable in this study was sand gradation. A single source material from a local sand pit was used to produce all five of the test sands, which are given in Table 2. This material was a naturally occurring sand (glacial stream deposited) with semirounded particles.

TABLE 2 Grain Size Gradations for Study Sands and Source Material (percentage finer by weight)

Sieve							
Number	Opening (mm)	TC	FAA	SAE	ASTM	Fine	Source[a]
4	4.75	100	100	100	100	100	100
8	2.36	42.8	97.7	99.0	97.7	100	87.8
16	1.18	20.3	57.2	71.1	95.1	100	58.3
30	0.59	7.9	19.3	11.9	68.8	83.9	26.1
50	0.30	1.3	3.5	1.4	28.2	38.1	11.5
80	0.18	0.5	1.1	0.5	11.0	18.7	6.4
100	0.15	0.4	0.7	0.4	7.6	15.0	5.2

[a]Material taken from sand pit and selectively sieved to produce all study sands.

Tests were performed at two air and ice temperatures. To represent a "cold" condition, the ice was kept at −10°C and the air at −12°C. A "warm" ice condition was represented by ice at −3°C and air at −1°C.

Since abrasive performance is related to the quantity of material applied to the ice, two and sometimes three distinct concentrations of each sand type were tested for each set of conditions. Currently, the FAA recommends a sand application rate (concentration) of 49 to 98 g/m². We chose a concentration of 73 g/m² to fit the FAA specification and concentrations of 34 and 142 g/m² to represent half and double this.

All the test sands were heated to 70°C before application to ensure adherence of the sand particles to the ice surface. To determine the effect of sand temperature on abrasive "bonding" to the ice, a test series was performed in which the sand temperature was varied before application. A local sand pit product that had been run through a 9.5-mm slotted screen (3/8-in. sieve) was applied at 3, 20, and 70°C to simulate a sand kept in an unheated building, sand kept in a building with conventional heating, and sand that was super-heated just before distribution, respectively.

TEST PROCEDURE

Each test series began with traction and resistance tests run on a clean, smooth ice sheet immediately before application of a test sand. This provided a baseline reference of friction coefficient and was used to monitor the comparability of prepared ice surfaces. The ice sheet used for testing was much more slippery than would ever be allowed to exist on an operational runway, but the surface maximized our chances of detecting any differences in the frictional characteristics of various sand types.

After the bare-ice friction tests, sand heated to 70°C was applied to the ice surface with a conventional lawn broadcast spreader. Five minutes after sand application, four resistance tests followed by six traction tests were performed. Since measurements were being taken on both rear tires, 12 separate measures of traction were obtained. Each test was run in a fresh track on the sanded ice to avoid any areas disturbed by the slipping tires from a prior test.

After the completion of a test series, the test sand was removed from the ice sheet and the ice surface was restored to a clean, smooth surface for the next set of tests. A total of 560 tests were performed between March 18 and April 13, 1992.

RESULTS AND ANALYSIS

Measurements of friction force and normal load on each tire were taken during steady state conditions of speed, slip, and direction, allowing average values to be calculated for each test. Friction coefficient, often referred to as μ, was calculated for each test as the ratio of friction force to normal force. Within the FAA, and at most airports, it is customary to refer to a friction number, which is a whole number obtained by multiplying μ by 100. Friction numbers for our tests are shown graphically in Figure 1.

Our initial analysis considered the FAA sand at its recommended concentration of 73 g/m² to be the standard for comparison. At this concentration, the FAA, fine, and ASTM sands provided about the same amount of traction enhancement on cold (−10°C) ice, as shown in Figure 1 (*top*). These sands provide a friction number of about 15, an 83 percent increase over the bare-ice friction of 8.2. The SAE and TC sands gave higher friction numbers, roughly equal at close to 20, a 140 percent improvement in traction on bare ice.

On the warm (−3°C) ice [Figure 1 (*top*)], the FAA sand had the lowest friction number (15.2). The TC, SAE, and ASTM sands showed better performance, respectively, averaging a friction number of 17.2. This was a 53 percent increase over the bare ice and 13 percent better than the FAA sand. The fine sand gave the highest friction number (18.4), giving a 64 percent improvement over bare ice and a 21 percent better friction number than the FAA sand.

For the two ice temperatures tested, the FAA sand is the least effective of most of the test sands at the 73 g/m² concentration. The fine sand gives the best performance on the warm ice, but the poorest on the cold ice. The best all-temperature sand would appear to be the SAE sand, although the TC sand shows nearly equal effectiveness.

The trends noted are not readily explained by the gradations of the sands. Plots of performance against percentage passing any given sieve size (example shown in Figure 2) looks similar for all the size fractions identified in Table 2. A slightly increasing (for −3°C ice) or slightly decreasing (for −10°C ice) friction number is seen with increasing percentages of fine material in these plots.

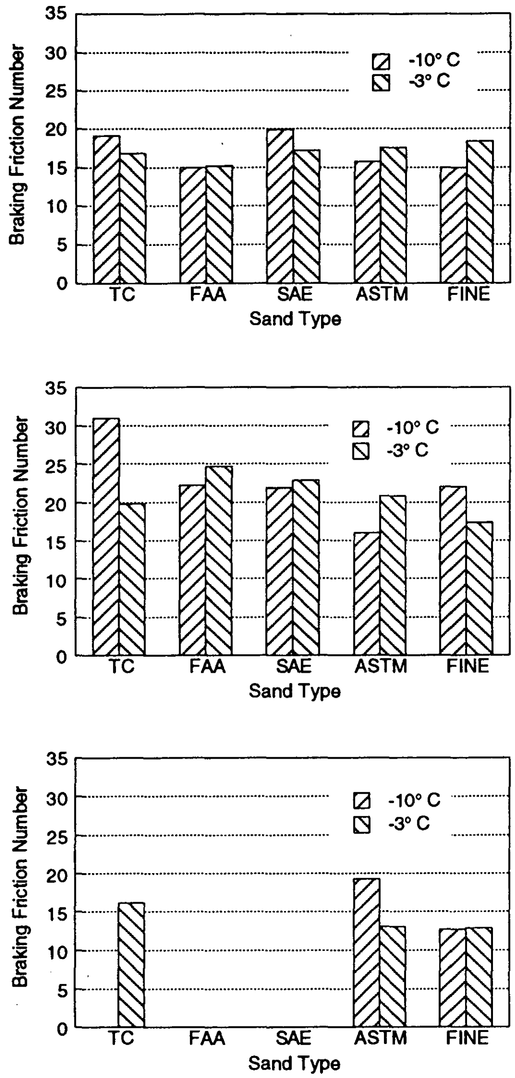

FIGURE 1 Braking friction performance at FAA-recommended sand concentration (73 g/m²) (*top*), twice the FAA-recommended sand concentration (142 g/m²) (*middle*), and half the FAA-recommended sand concentration (34 g/m²) (*bottom*).

Comparing the rankings of the sands at the two ice temperatures, the ASTM and fine sands had improved friction numbers at the higher temperature, the TC and SAE sands had diminished performance, and the FAA sand remained unchanged. This may be related to the relative percentage of fines contained in each sand type. To check for this trend, each sand's warm-to-cold ice tractive performance was plotted against the percentage of material less than 0.595 mm in diameter (No. 30 sieve) (Figure 3). A performance ratio greater than 1 indicates a sand that works better at higher temperatures, and a ratio less than 1 indicates a sand that works better at lower temperatures.

Freehand curves highlight the trends indicated by the data in Figure 3. The data for the 73-g/m² concentration indicate that when an abrasive contains at least 20 percent material passing the No. 30 sieve, the performance of the sands is independent of temperature. As the percentage of fines becomes less than about 20 percent, a very strong decrease in friction number occurs for warm ice compared with cold ice. For sands with high fines content (greater than 20 percent), only a slight increase in performance is seen for warm ice as compared with cold ice. Because the sand types used in this study leave a large gap between those containing large and small amounts of fines, a regression analysis could not legitimately be performed on the data in Figure 3.

With higher concentrations of sand applied to the ice, higher friction numbers were expected. This was found for all but one case; the fine sand showed a drop in performance when the sands were applied at a concentration of 142 g/m² on the warm ice sheet. [Relative performances of the sands at this concentration are shown in Figure 1 (*middle*).] On cold ice, the FAA, SAE, and fine sands had equal performance, giving a friction number of about 22. This was nearly 170 percent better traction than the bare ice. By comparison, the ASTM sand provided 27 percent less friction (16), and the TC sand 41 percent better performance (31), than the FAA, SAE, and fine sands.

At the high sand concentration on warm ice, the FAA sand showed the highest friction number (24.7). This represented a 120 percent increase in traction over the untreated ice. The

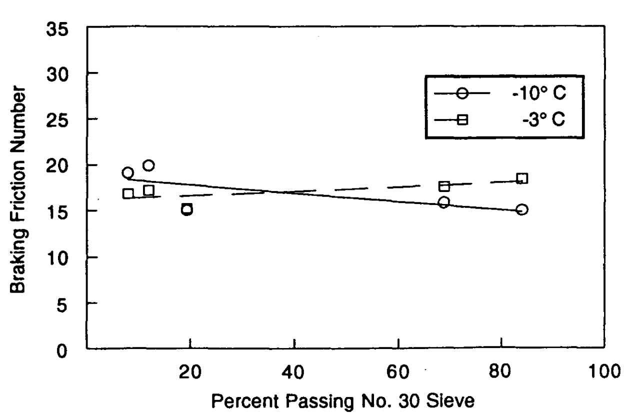

FIGURE 2 Variation in braking friction performance with fraction of sand smaller than a No. 30 sieve (0.595 mm) for the FAA-recommended sand concentration (73 g/m² at 70°C).

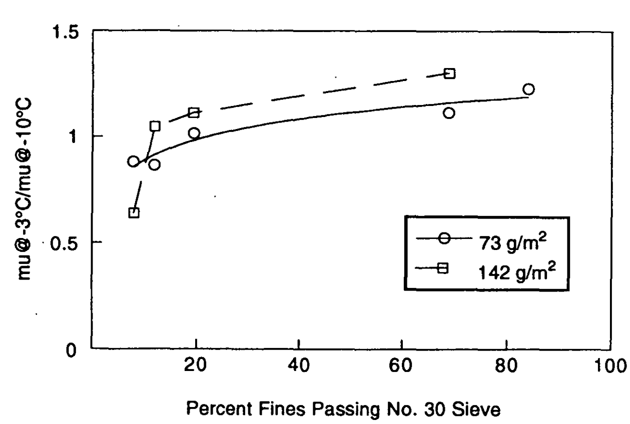

FIGURE 3 Relative improvement in tractive performance with ice temperature increase as a function of fraction of sand smaller than a No. 30 sieve (0.595 mm) for two sand concentrations.

other sand types provided 7 percent (SAE), 20 percent (TC), 25 percent (ASTM), and 30 percent (fine) less traction than the FAA sand. The friction number obtained for the fine sand in this case is suspect, since it did not follow the trend of improved performance with increased concentration that was seen for all the other sands.

Although the TC sand showed clearly superior traction on the cold ice, it displayed only mediocre performance on the warm ice. However, the SAE sand provided high friction numbers relative to the other sands and its relative ranking was not significantly affected by ice temperature.

The percentage improvement in traction with increasing ice temperature at the 142-g/m² concentration was also plotted (Figure 3). The fine sand was not included in this plot since, as noted, its behavior was anomalous. At this concentration, it is also clear that sand performance changes with ice temperature as a function of the amount of fines the sand contains. At the high sand concentration, this trend seems to be somewhat stronger than was observed at the recommended concentration. It also appears that the transition (performance ratio of 1) occurs at about 20 percent material passing the No. 30 sieve.

For the higher sand concentration, the results shown in Figure 1 (*middle*) do not correspond with the behavior displayed at the recommended concentration [Figure 1 (*top*)]. In fact, it can roughly be said that the rankings for the recommended concentration are the inverse of those found at twice this concentration (this is more true for the warm ice than the cold ice). This implies that traction is a strong function of concentration of abrasives on ice. By themselves, the physical characteristics of sand grains and the size distribution of the grains cannot be used to determine traction enhancement potential; application concentration must be included to make a determination.

Several tests were also performed at a sand concentration (34 g/m²) below that recommended by the FAA. The ASTM and fine sands were tested on the cold ice. Results showed a surprisingly high friction number for ASTM sand (19.3) and a value of 12.7 for the fine sand [Figure 1 (*bottom*)]. On the warmer ice, the two sands showed essentially equal performance with friction numbers of 13. The TC sand was also tested on the warm ice, on which it yielded a friction number of 16.2.

The results of the low sand concentration tests show that, even with minimal abrasive application, at least a 50 percent improvement over bare-ice traction is possible.

Braking friction number was plotted against concentration for each sand type at both temperatures (Figure 4). Linear regression analyses were performed for each sand type by itself, and in nearly all cases a strong correlation resulted. The bare-ice friction number was included in the regression, corresponding with a sand concentration of zero.

Table 3 lists the regression coefficients and R^2, a measure of variability. The ASTM sand at low temperature showed a poor linear correlation because of the high performance recorded at the low concentration. The fine sand at the warm temperature also had a low regression correlation owing to the lower performance recorded at the highest concentration. A second-order regression on each of these data sets would yield a much better fit. However, confirmation of the trends shown by these two sands would be prudent before attempting to move to higher-order regression analyses.

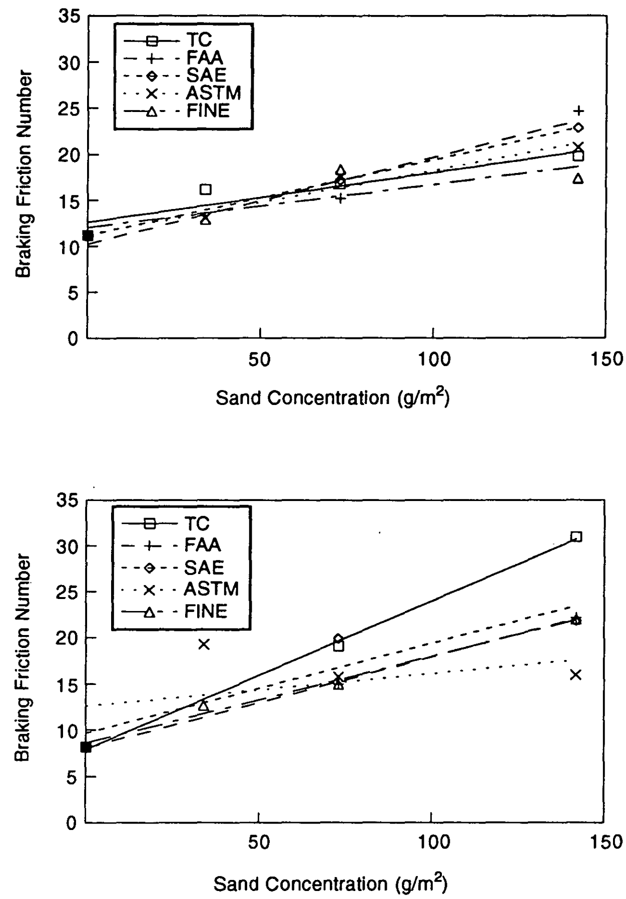

FIGURE 4 Braking friction number variation with application rate for test sands at −3°C (*top*) and −10°C (*bottom*).

On the basis of the regression analyses, increasing the concentration of any of the study sands on the ice caused an increase in traction coefficient. The expected increase in friction number ranges from 6 to 16 for each 100-g/m² increase in sand concentration, ignoring the two cases with poor correlation.

Comparing the slopes of the regression lines for the warm and cold ice for a given sand type supports the trend depicted in Figure 3. The TC sand, with very few fines, has a much stronger performance increase with concentration on the cold ice. The FAA and SAE sands show a nearly identical slope for the cold and warm ice. The ASTM sand has a stronger concentration dependence on the warm ice, as would the fine sand if the anomalous data point for 142 g/m² were not considered.

The test series designed to look at the effect of sand temperature was performed with the source material used for the study sands. This sand had a more evenly distributed range of grain sizes (Table 2) than the study sands. Tests were performed only on the warm ice (−3°C), with a concentration of 73 g/m². The sand was applied at a low temperature (3°C), a typical room temperature (20°C), and a super-heated temperature (70°C); braking friction numbers of 12.8, 14.7, and 19.7, respectively, were measured. Regression analysis on these data showed an excellent fit (Figure 5) to a linear equation, with increasing performance achieved for higher sand

TABLE 3 Regression Coefficients for Braking Traction as a Function of Sand Concentration for Each Study Sand

Regression coefficients: $(Y = mX + b)^a$	TC	FAA	SAE	ASTM	FINE
			Ice temperature: -10° C		
b	7.9	8.1	9.7	12.6	8.6
m	0.161	0.099	0.098	0.035	0.094
R^2	0.999	0.999	0.933	0.456	0.994
			Ice temperature: -3° C		
b	12.6	10.2	11.2	11.3	12.0
m	0.055	0.095	0.083	0.070	0.047
R^2	0.861	0.938	0.999	0.966	0.683

[a]Where Y is the friction number, X is the sand concentration in g/m^2, b is the y-intercept of the equation, m is the slope of the best-fit line, and R^2 is the coefficient of determination.

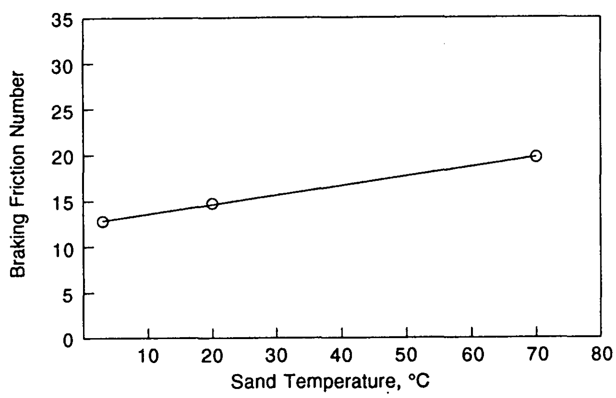

FIGURE 5 Braking friction number variation with sand temperature for source material applied at concentration of 73 g/m² at −3°C ($y = 12.6 + 0.102x$).

temperature. From this equation, every 10°C increase in sand temperature over ice temperature increases the friction number by 1.

DISCUSSION OF RESULTS

When comparing the results with those of past research, strong agreement was found. On cold ice with a high concentration of sand, the TC sand was found to provide significantly better performance than any of the other sands. This corresponds exactly with Hegmon and Meyer's conclusions that a coarse sand (primarily containing grain sizes between the No. 4 and 16 sieves) worked best in cold ice (−6°C temperature) tests (*2*). Hayhoe confirmed this result but concluded that, on warm ice (−1°C), traction was improved by increasing the percentage of fines contained in a sand (*3*). We also found this to be true, as shown in Figures 2 and 3.

Our results confirmed the importance of sand concentration on traction enhancement with abrasives, as pointed out by the Airports Authority Group (*5*). Both of the sands that they studied were coarse by comparison with some of those included in our study, but the group found that equal performance with two different sands could be obtained by applying each sand at a different concentration. Given a particular ice temperature, Figure 4 could be used to determine an application rate for each sand that would result in equal performance for all the sands used in this study.

In our previous study, friction on a cold ice sheet was found to strongly increase with increasing fines (*6*). This seems generally to disagree with the study reported here. However, the nature of the friction measurement in the two studies was significantly different. In our prior study, a small slider was used to generate a friction force, which resulted in a 100 percent slip rate (i.e., corresponding to a locked-wheel skid). In the current study, a low rate of slip that duplicates the slip present at the tires of large braking aircraft was used.

The difference in the two slip rates is significant in that, with a 100 percent slip condition, the tire is not rolling. This means that abrasives on the ice surface can only enter the tire-ice contact patch by being forced under the locked tire. The potential for dislodging, tumbling, and tossing the abrasive particles out of the path of the tire is great. In fact, it is greatest for the larger sand particles since they have a higher relief above the ice surface and would be more difficult to force under the leading edge of the tire. It follows then that sands with a high percentage of fines would stand a better chance of allowing more abrasive product to be drawn under the tire where they can contribute to traction enhancement.

A tire operating at a moderate to low rate of slip is rotating at a rate that is only somewhat less than a nonslipping tire. By rotating, the tire is able to roll onto and over sand particles on the ice surface, no matter what their size.

Our results also showed that heating a sand before it is applied to an iced surface can increase the friction number significantly. This behavior is clearly the result of the sand grains bonding more fully to the ice when applied at a high temperature. A greater percentage of the sand grains were partially imbedded in the ice as the application temperature increased. Heated particles of sand melt into the ice and refreeze to create a surface texture similar to sandpaper. The greater the difference between sand and ice temperature upon application, the stronger the mineral-ice bond and the higher the level of friction enhancement generated. Larger grains of sand held their heat longer and thus did a better job of bonding with the ice than did fine sand particles. More sand grains remained in the tire tracks for the hot sand than for the cold sand.

CONCLUSIONS AND RECOMMENDATIONS

Generally, coarse sands such as the TC sand provide the highest level of friction enhancement on cold (−10°C) ice surfaces. On ice at temperatures just below melting, sands with a large percentage of fines yield the highest friction coefficients. Sands composed mostly of grains from 1 to 2 mm in diameter (approximately No. 8 to No. 16 sieves), such as the SAE sand, showed good performance at both test temperatures.

The abrasive concentration on an ice surface is a more controlling factor than sand gradation in friction enhancement on ice surfaces. However, cost, environmental consequences, and logistics problems with storage, handling, and cleanup most likely will dictate practical limits on concentration.

The effect of sand application temperature can also easily overshadow sand type. A sand with a large percentage of 1- to 2-mm-diameter grains (approximately No. 8 to No. 16 sieves) heated to 70°C will hold its heat long enough during application to ensure a good bond to the ice. However, like sand concentration, logistical matters will govern what level of sand temperature is reasonable.

If the FAA were to endorse a single sand type, of the five sands included in this study, we would recommend that the SAE sand be specified for airport use. However, this would do little to alleviate the concerns of airport operators, because the SAE sand is no more likely to be available at sand pits than the current FAA-specified sand. Thus, a much more flexible specification must be generated to be of any practical value and to represent a step forward from current practice.

This study suggests that any sand is capable of matching the performance of another sand by the calculated selection of its application rate and the temperature at which it is applied to the ice. The effect of variable sand friction performance with ice temperature was also found to be linked to the amount of fines in the sand. Combining these factors, it appears entirely feasible to generate a mathematical expression that would describe the general relationship between sand type (degree of fines), ice temperature, sand application rate, sand application temperature, and braking friction performance. Using this approach, an airport operator would be free to explore various options for producing a desired level of friction enhancement on iced runways.

ACKNOWLEDGMENTS

This work was sponsored by the FAA; the authors thank it for the opportunity to do this work and for its keen interest in this project. The authors also sincerely appreciate the hard work of their colleagues Byron Young and Rosanne Stoops in completing this study. The assistance of CRREL FERF personnel was also greatly appreciated.

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