FINAL REPORT

SNOW PROPERTIES AND SNOW BLOWER PERFORMANCE
A LITERATURE REVIEW

by

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ABSTRACT

This report details a comprehensive survey of various cold regions data bases and library bibliographies, seeking information on the performance of snow blowers and the relationship between snow shear, density and snow blower performance. The report is in two parts as follows:

1. Reference bibliography; and
2. Summary reviews.

The reference bibliography includes all items discovered in the search whose titles indicated that they possibly contained some information in one of these fields.
The summary reviews were made for all English language articles that could be obtained during the project either from collegues, the University of Alaska library system or interlibrary loan (ILL).

Contacts were made with snow specialists in several northern countries including Canada, Finland, Sweden, and Norway. Copies of those reports which appeared promising were requested from interlibrary loan and from the specialists contacted. It must be realized that the search of the literature is not exhaustive since most data bases only contain references for the last several years, this review should include the majority of references on this subject published during the past 25 years.

Reviews have been prepared for those references on the following pages, except for those marked (ILL), which are still being obtained through interlibrary loan, the second Mellor reference (Mellor, 1977), which is a summary of the first Mellor reference (Mellor, 1975) and those which were published in a foreign language.

The list on pages four and five is a sampling of foreign language references. See note at the bottom of that list.

SNOW BLOWER REFERENCES

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A SAMPLING OF FOREIGN LANGUAGE PUBLICATIONS ON SNOW BLOWER TESTING

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NOTE: These references are included to indicate a sampling of a large foreign language literature from several countries. It demonstrates that much work has been done in foreign countries. If this study is continued and expanded, translations of some or all of these works, plus others, should be considered.

SUMMARIES OF LITERATURE REVIEWED

Snow Blower References

Consumer Product Safety Commission 1985. CPSC Cautions Snow Thrower Users. U.S. Govt. Document No. Y 3.C 76/3:11-3S. Consumer Product Safety Commission, Washington, DC.

> This short pamphlet's purpose is to warn inexperienced operators of snow blowers about the dangers involved. The pamphlet details safe operations and dangerous actions during operation and while in the vicinity of the machine. It does not contain any information on snow properties.

Hanamoto, B. 1974. Snowblowers: Performance and Evaluation. U.S. Army Cold Regions Research and Engineering Laboratory Special Report 201, February 1974.

> Twelve snowblowers were tested. These were small, self-propelled machines in the seven to eight horsepower range, whose operator walks behind. The tests determined removal rate in pounds per minute for late snow, early snow, new snow, in drifts, and around obstacles, densities were recorded for each.

Huang, E.Y. 1973. Operational Systems for Snow Removal and Ice Control: A Background/Resource Paper. Houghton, MI: Michigan Technological University.

> This is a very general description of snow removal and ice control systems. It is essentially a proposal for "an organized, systematic study" of such systems in the Upper Great Lakes Region. The study would include:
>
> a) snow and ice properties;
> b) performance criteria;
> c) chloride salts and abrasives;

d) snow drifting; and

e) operational systems for maximum effectiveness.

There are more than 150 references (all pre-1973!).

We could not determine whether the proposed study was ever conducted. We found no reference to a report from such. Future investigations should include contacting Michigan Tech. for information and results.

Itagaki, K. 1990. Highway Snow Control Research in Japan. U.S. Army Cold Regions Research and Engineering Laboratory Special Report SR 90-33, September 1990.

This document contains a general discussion of snow control research in Japan. It includes basic studies, snow-removal equipment, road heating and six other topics.

The reference section includes eight on snow blowers, for two of which there are English language summaries, and four on snow shear measurements, for one of which there is an English language summary.

No information is given on snow blower capacity vs. shear and/or density, but there is a reference to a Japanese language report of such studies.

King, C. and J. Baker. 1983. Specification Guide for Snow Removal Vehicles for Rail Transit Systems. Final Report, November 1983. U.S. Dept. of Transportation, Urban Mass Transportation Administration. UMTA-MA-06-0025-83-8.

This report was prepared by Alexander Kusko Inc. for the U.S. Department of Transportation, partly in response to paralyzing snow storms in Boston in 1977-78 and Chicago in 1978-79. It is intended as a specification guide for snow belt rail transit operators; it is not a procurement document.

There are sections on General Specification of Materials and Workmanship, In-Service Support, and Operating Environment; the last includes weather (including snow density between 5 and 45 pcf) and site-specific features.

There are specific sections on:

- 7.0 Rail-Mounted "Jet" Blower
- 8.0 Rail-Mounted Rotary Blower
- 9.0 Rail/Highway Blower

The snow removal capacity statements are nearly the same for each of these three sections. In section 9.0, the statement is:

> "The rail/highway vehicle shall be capable of removing snow of any consistency from paved surfaces and rail right-of-way. Width of the cleared swath shall be specified by the Purchaser. Average depth of snow shall be as high as two feet, with three foot drifts. The rate of snow removal shall be at least 1500 tons/hr."

Appendix A of the report is titled, "Test Procedure to Verify Snow Removal Rate." It provides a simple procedure that combines snow width, snow depth, snow density and vehicle speed to calculate removal rate in tons per hour. No mention is given of the relationship between snow shear and removal capacity.

Sasaki, T. and G. Horikawa. 1979. Development of a High-Speed Rotary Snowplow (HTR 700). U.S. Army Cold Regions Research and Engineering Laboratory Translation TL 709, March 1979.

This high speed rotary snowplow was designed to remove 3000 tons per hour at a vehicle speed of 20 kilometers per hour. It is powered by a 700 horsepower diesel engine.

This was an operational test to determine mechanical problems and the like. Snow densities were recorded, but there is no mention of snow hardness or shear strength.

Shibuya, M. and H. Kuriyama. 1979. "On Performance of A Two Stage Rotary Snowblower." Snow Removal and Ice Control Research. Special Report 185,

Transportation Research Board National Academy of Sciences. Proceedings of the Second International Symposium, May 15-19, 1978, Hanover, NH, pp. 185-191.

The test measured the performance of a 260 rated horsepower rubber tired snowblower which requires a crew of two operators.

Snow hardness was measured, but snow removal rate as a function of hardness was not reported. Hardness was measured with Kinoshita's Hardness Gauge, in kg/cm^2, as F/S, where F = the average resistance which the snow exerts on a plate of area S as the plate depresses the snow due to a falling weight.

The paper reports snow removal rate as a function of blower circumferential speed, with some reports of different snow densities. Snow removal rate is reported as "snow removing performance rate," in tons/HP hr.

A table gives maximum snow removing capacity (tons/hour) for different configurations of the machine and different snow densities.

Torres, W.R. 1988. Evaluation of Rail Borne Snow Removal Vehicle (S-500), Final Report 1980-87. Chicago Transit Authority. UMTA-IL-06-0048, May 1988.

This report contains basic information on the Chicago Transit Authority's S-500, purchased from Mitsubishi International Corporation and manufactured by Niigata Engineering Company, Ltd. It describes design, manufacture and operational problems.

The machine was designed for a maximum snow removal rate of 1500 tons per hour, at a snow shear strength between 0 psf and 750 psf.

The machine failed its snow removal tests, due to power shift transmission problems and hydrostatic drive propulsion problems. A conclusion was "...the design concept employed on this vehicle is unsuitable for heavy snow fighting."

There is no mention of snow shear strength during the operation test. Snow density was 30 pcf, and snow depth was 2.5 feet.

Length of the test run was supposed to be 60 feet, but the machine failed after 20 feet and again after another 10 feet.

Snow Density and Shear

Adam, K. 1978. "Building and Operating Winter Roads in Canada and Alaska." Minister of Supply and Services-Canada Catalogue No. R71-19/4-197. ISBN 0-662-01514-2 214 pp.

This reference is a very long and detailed account of snow road construction in northern Canada and Alaska in the 1960s and 70s. It contains a short four page section on snow mechanics in one of its many appendices. The emphasis on snow strength in this book is for use as a snow "pavement." The density and hardness of concern to the road builder is orders of magnitude greater than what must be dealt with by snow blowers and snow plows. The article contains interesting accounts of road building under many varied conditions but no data on snow blower performance.

Alger, R.G. 1989. "Shear and Compressive Strength Measurements of Snow Using the Bevameter." Proceedings, 1st International Conference on Snow Engineering, Santa Barbara, CA, July 10-15, 1988, U.S. Army Cold Regions Research and Engineering Laboratory Special Report SR 89-06, February 1989, pp. 325-334.

The Bevameter is "probably the most complicated but accurate of the techniques" (for measuring snow strength). It consists of a combination of two strength measurement systems: (1) a plate sinkage test, and (2) an annular shear test.

The Bevameter was improved by the Institute of Snow Research, Michigan

Technological University. In that version, the device is mounted on a vehicle, which (1) acts as a counterbalance and (2) allows the device to be moved easily.

For the plate sinkage test, a 20.3 cm diameter plate is lowered into the snow at an initial speed of approximately 5 cm/sec. A computer program records and plots load and pressure vs. sinkage.

For the annular shear test, either a grousered or rubber covered ring shaped annulus is rotated on the snow pack with various normal loads. (Michigan Tech. uses rubber covered). The ring has an inside diameter of 6.67 cm and an outside diameter of 9.21 cm, giving a ring area of 126.6 cm^2. The test is run on undisturbed snow through a rotation of 360 degrees. Torque implied to the rubber ring is recorded, and a plot of shear vs. normal stress is developed.

The tests were sponsored by CRREL because of an interest in vehicle mobility in different snow conditions. As a result of the tests, shear stress vs. normal stress relationships were developed for various snow densities. The outcome was a linear regression of shear angle as a function of density.

<u>This study may be quite valuable to Alaska DOT&PF in its snow blower capacity specification and verification</u>.

Brun, E. and L. Rey. 1987. "Field Study on Snow Mechanical Properties with Special Regard to Liquid Water Content." <u>Avalanche Formation, Movement and Effects</u> (Proceedings of the Davos Symposium), September 14-19, 1986. B. Salm and H. Gubler, eds. International Association of Hydrological Sciences IAHS Publication 1987 No. 162, pp. 183-193.

This field experiment was conducted in the French Alps in 1984/85. Parameters measured included the following:

- Grain shape and grain size
- Density

- Liquid water content
- Temperature
- Shear strength along the slope plane using a shear frame, a small shear vane, and a large shear vane
- Shear strength perpendicular to the slope plane using a small shear vane
- Ram hardness
- Resistance to penetration using three conic penetrometers

Comparison of the three types of shear measurements along the slope plane gave good correlation. Comparison of shear strength along the slope plane and perpendicular to the slope gave excellent correlation. Ram hardness and penetration strength with the big conic penetrometer were also compared.

The relationship between shear strength, as measured with the shear frame, and wet density was developed, for both dry snow and wet snow. The relationship is shown in Figure 3.

A major finding, applicable to this snow blower study, is the following:

> "The dependence of shear strength versus density can be described approximately by two curves derived by linear regression on log values, the first one for dry snow and the second one for wet snow. We note that a given shear strength is corresponding with a density much larger for wet than for dry snow. So, the transition from dry to wet snow, without a significant change of density, must involve a decrease of shear strength."

A multi-linear regression analysis was also performed of shear strength vs. density, liquid content and grain size. For dry fine grained and dry fresh snow, good evaluation was found using density as the only parameter. This agrees with earlier work by Perla (1982).

For wet coarse snow, the multi-regression analysis did not yield as good a correlation, but, again, density was the major predictor of shear strength.

With density as the only predictor, the correlation coefficient (R) was 0.52. Adding liquid content gave an overall R of 0.54; adding grain size increased the overall R to 0.55.

The authors also performed a principal component analysis of the mechanical, density and liquid water content data.

This reference may also be a valuable contribution to the Alaska DOT&PF snow blower program.

Colbeck, S. 1992. "A Review of the Processes that Control Snow Friction." U.S. Army Cold Regions Research and Engineering Laboratory. Monograph 92-2, April 1992.

This 40 page report discusses the friction between snow surfaces and various materials in contact with the snow. It is a compilation of work done over a period of time by both the author and others. The paper is an excellent review of the many mechanisms that interact to make up the overall friction coefficient of a snow surface. Effects of speed, load, temperature, snow type, and the characteristics of the material in contact with the snow are all considered. Different types of waxes and polymer surfaces and the aspects of each concerning their frictional characteristics when in contact with snow are discussed. The paper, however, does not discuss snow mechanics or strength of a snowpack and thus has little information for this study.

The paper may be useful if information concerning the frictional loads encountered during snowremoval or a concern for coatings to minimize friction for a plow moving through the snow is desired.

The report lists 112 references on snow, friction and wear.

Casassa, G., H. Narita and N. Maeno. 1991. "Shear Cell Experiments of Snow and Ice Friction." Journal of Applied Physics. March 15, 1991, Vol. 69, No. 6, pp. 3745-3756.

The research reported in this paper used an annular shear cell assembly to measure frictional shear stress between two annuls for various values of normal stress. The method records F_t, the friction force at the torque arm. Then,

$$M = F_t R,$$

where R = length of the torque arm.

Then, with M, we find:

$$f = 3M / [2\pi(r_2^3 - r_1^3)],$$

where r_1 and r_2 = inner and outer radii of contact area, respectively, and f = frictional force per unit contact area (or frictional shear force).

The ultimate purpose of these experiments was to find:

$$\mu_T = f/N,$$

where N = normal stress.

Thus, μ_T 1 is the total, or "apparent," friction coefficient.

NOTE: this experiment was a laboratory test.

The experiment investigated the effects of various snow temperatures, and it recorded some snow densities.

Hardness was measured with the Kinosita hardness meter.

Granberg, H.B. and C.M. Kingsbury. 1984. "Tests of New Snow Density Samplers." Proceedings, 41st Eastern Snow Conference. pp. 224-228.

Two new snow density samplers were tested near Schefferville, Quebec. These new samplers are attempts to alleviate the shape bias connected with earlier samplers.

One sampler was a "Swedish Sampler," developed by Hugo Weichel of the Swedish Defense Research Institute, Stockholm. It consists of a rectangular scoop with a hinged lip which cuts off the snow sample at the front end of the scoop. A sliding lid cuts the top off the snow sample to give a nearly rectangular slab.

The other sampler was the "G-C Sampler," developed by Hardy Granberg and Gregory Crocker of the Department of Geography, McGill University. It has five main components--a tubular cutter, a set of slicers which section the core, a pod to suspend the sampler for bagging samples, a precision spring balance for weighing bagged samples, and a wooden dowel. The cutter tube is inserted vertically into the snow cover, a pit is dug alongside the sampler, slicers are inserted and samples are removed and bagged, beginning with the lowest slicer.

Preliminary results indicate that both the samplers and the sampling technique may have significant influence on the results in sampling of both snow densities and snowpack contaminants.

Mellor, M. 1975. "A Review of Basic Snow Mechanics." Proceedings, International Symposium on Snow Mechanics, Grindelwald. International Association of Hydrological Sciences Publication 114, pp. 251-291.

This long paper is a comprehensive and valuable review of current knowledge of snow mechanics through 1975. Information on snow shear stress and shear strength may be valuable to the present study.

One figure compiles in one graph experimental results of major principal stress as a function of bulk density for compression in uniaxial strain at various rates and temperatures. NOTE: these results are stresses but not necessarily strengths.

With respect to shear strength, the following discussion seems valuable:

> "The term `shear strength,' which is subject to various interpretations, tends to generate confusion at the best of times, but in the case of highly compressible snow it can be very confusing indeed. One measure of shear strength can be obtained from uniaxial stress tests, in which maximum shear stress is $_1$/2 and the octahedral shear stress is $_1$/3, $_1$ being the axial stress. However, the general practice has been to define and determine shear strength according to the Mohr-Coulomb failure criterion for biaxial stress fields:
>
> $$(\sigma_1 - \sigma_2) - (\sigma_1 - \sigma_2)\sin\phi = 2c\cos\phi$$
>
> or
>
> $$s = c + p\tan\phi$$
>
> where $\sigma_1$2 and $\sigma_2$3 are principal stresses, c is cohesion, ϕ4 is the angle of friction, s is shear strength and p is normal stress."

Mellor warns that some of the shear strength presentations in the literature give a misleading impression, and he does not summarize them. But he does offer a graph of shear strength vs. density, shown here as Figure 18, which "gives a general idea of the magnitude of shear stress for small values of (density) as measured by shear boxes, shear cylinders, shear vanes, torsion tests and avalanche fracture line analyses."

There is also a discussion of strength as a function of ram resistance, citing attempts to develop linear correlations, such as work by Keeler and Weeks (1967; 1969). However, Mellor concludes that, "for the time being, the only sensible course is to compile completely empirical correlations in direct graphical form."

The paper includes 94 references, of which at least five appear to apply directly to the present project.

Samoilov, R.S. 1986. "Annular Blade for Snow Shear Tests." Soviet Meteorology and Hydrology. No. 4, pp. 89-93.

Field measurements of snow shear in Russia are usually performed with a shear carriage and a dynamometer (not described and the references are in Russian!). But there are drawbacks to this method, such as labor intensity and the need for many data points. Therefore the author modernized the shear meter of the Kalinin Polytechnic Institute, utilizing different types of blade tips.

The essence of the method "is in the insertion of a blade into the sampled horizon of the snow cover, turning it by the handle of the shear meter until the snow is completely cut along the surfaces of rotation with notation of the maximal rotary moment M_{max}. After the cut, a second rotation measures the rotary moment to overcome friction (M_f)."

The annular blade may be considered as a tube, at one end of which is attached a cross-shaped blade, at the other a measuring device for determining torque. When the tube is inserted into the snow, the cut occurs along its lateral surface due to the force of impression. Then, upon rotation of the instrument, the cut is made along one or two end surfaces of the blade.

Tests were conducted using (1) a shear carriage and the SK-8 blade shear meter with (2) cross shaped and (3) annular blades. Shear resistance results were remarkably consistent, such as 9.15/9.63/8.0 kPa for the three methods in the first snow layer and 14.8/12.3/13.9 kPa in the fourth snow layer.

Interest in the results of such testing is motivated by the need for "making avalanche estimates, designing anti avalanche structures, determining the resistance of the snow to cutting during snow removal and estimating the passability of snow-covered virgin areas."

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Yanagisawa, Y. et al. 1983. "Performance Tests on A Rotary Snowblower (Class 200PS, Equipped with An Automatic Control Device)." Hokkaido Development Bureau Proceedings, 1983, Vol. 27, pp. 1577-1584. In Japanese.

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SUMMARIES OF FOREIGN LITERATURE AND CONTACTS WITH FOREIGN SPECIALISTS

Eerola, Martti 1992. Personal letter concerning the Finnish practices in snow removal.

> Mr. Eerola, who is an engineer for the Finnish National Road Administration in Helsinki, states that most snow removal using snowblowers is done in the north of Finland. He will send more information as soon as summer vacations are over and his contacts in northern Finland return to work.

Hedvall, L. 1990. In-Situ Tests of Snow: Shear Strength and Stratification. Luleå, Sweden: Luleå University of Technology, Examensarbete 1990:038 E.

> This very interesting experiment was performed by a student at Luleå University of Technology in Sweden. The experiment itself was carried out in northern Sweden to correlate shear strength, as measured with a vane apparatus, with Ram hardness. The primary motivation was possible applications to avalanche security work.
>
> The report describes the Swiss Rammsonde for measuring hardness (R = resistance to penetration in kg) and both the vane bore apparatus and the shear frame to measure shear strength in kPa.
>
> Among the results, a few points relate density to Ram hardness.
>
> In its literature review, the report cites Abele (1963 or 1975?) and Karlèn (1983). From the Abele reference, we find an equation relating unconfined compressive strength to Ram hardness. Karlèn gives relationships between Ram hardness and snow density, but those are in Swedish!
>
> Future work in this regard could (1) do a larger number of similar tests, (2) use a shear frame, and/or (3) delve more deeply into Swedish and other Scandinavian references. Note that one of the investigators on this project (Bennett) is spending the fall 1992 semester at Luleå.

Järvinen, E. and Makkonen, L. 1987. "Lumen Ominaisuuksien Mittaaminen" (in Finnish). Valtion Teknillinen Tutkimuskeskus, Technical Research Centre of Finland Research Note 759.

> This report is 54 pages long and describes methods used to measure the physical properties of snow and the instruments used at the Technical Research Centre of Finland (VTT) for snow studies.
>
> The report refers to the shear frame method of measuring snow shear strength. The report contains a complete chapter on mechanical properties of snow, and may be worth having translated. One of the authors (McFadden) speaks some Finnish and knows persons competent in both Finnish and English that may be willing to translate the chapter for a nominal fee.

Norum, Harald 1992. Personal letter regarding the Norwegian practices in snow removal and snowblower design.

> Mr. Norum of the Norwegian Geotechnical Institute states that rotary plows have been used in continental climates, and "two step plowers" have been used for maritime climates. He doesn't define "two step plowers."
>
> He states that Rahmsonde Penetration Resistance is usually used for shear strength measurements, although they have also used shear frames and some triax equipment. Shear frames are also mentioned in the Finnish literature (see Järvinen and Makkonen).
>
> Mr. Norem states that he is not aware of any studies in Norway that relate snow shear strength to snowblower performance.