TR 18

Sipre Report 18

NOVEMBER, 1954

Review of Snow-Compaction Methods

with Recommendations for Road and Airfield Construction on Snow

SNOW, ICE AND PERMAFROST RESEARCH ESTABLISHMENT
Corps of Engineers, U. S. Army

FOREWORD

This report was prepared by the Field Operations and Analysis Branch, Snow Ice and Permafrost Research Establishment. Based on study of past snow-compaction exercises, its purpose is to bring together in one report a review of the results of those exercises, to serve as a helpful guide to those who have the responsibility of planning for future snow-compaction exercises. Of necessity, this review is confined to those exercises for which sufficient data were available for analysis. Suggestions are made for the minimum type and number of measurements that should be made in future snow-compaction exercises, in order to make possible analysis of test results and to derive the greatest value from the tests.

CONTENTS

REVIEW OF SNOW-COMPACTION METHODS with Recommendations for Road and Airfield Construction on Snow

by

R. W. GERDEL AND M. DIAMOND

PURPOSE

The purpose of this report is threefold:

(1) to review the literature on snow compaction;

(2) to assess present snow-compaction techniques;

(3) to recommend methods of constructing and maintaining snow roads in areas of deep snow such as the Greenland Ice Cap.

INTRODUCTION

Snow compaction has been used for road construction by the logging industry for many years in Canada, United States, and Russia. Airfields have been kept open both in Russia and Canada by compacting snow on runways rather than removing it. Both the Canadian and U. S. Defense Departments are interested in snow compaction as an answer to the mobility problem in Northern regions.

In 1945, the Soviet Government published a series of papers on snow compaction (Kragelski, 1945). These papers showed that snow hardening could be achieved by a process of agitation as well as by rolling. It was shown that, when snow is intensively mixed before it is compacted, the hardness or bearing capacity usually continues to increase for some time after compaction. This process is commonly referred to as age hardening.

The first section of this report presents the results of findings of previous snow-compaction tests in areas of deep snow. These results are discussed in section II, and the recommended procedures to be used in building and maintaining snow roads on the Greenland Ice Cap are given in section III.

RESULTS OF COMPACTION STUDIES

ANTARCTIC TRIALS (1946-47)

The Report of Operation High Jump (U. S. Navy, 1947) describes the three compaction trials made by the U. S. Navy in the Antarctic. Runways were constructed upon which ski- and wheel-equipped aircraft were able to land and take off without difficulty. The equipment used consisted of a drag for leveling the snow surface and a D-6 Caterpillar tractor and special drag constructed of pontoons for compacting and smoothing the surface.

It is stated in the report that compaction of the neve was accomplished in less time and more easily at low temperatures. However, a review of conditions associated with each of the three trials and the reported results as shown in the following summary do not indicate that temperature differences were great enough to influence results.

	Trial 1	*Trial 2*	*Trial 3*
Maximum temp. during construction	+10°F	+10°F	+10°F
Minimum temp. during construction	−23°F	−23°F	−23°F
Average temp. during construction	−7°F	−8°F	−11°F
No. of operations performed	10	5	3
No. of days from start to finish	5	3	2
Final density of surface	0.43		0.39
Density 12 feet below surface	0.55		0.46

Since the report points out that the roadways around the camp, which were in continuous use, had a greater hardness than the test strips, it appears that factors other than temperature were important in achieving good results. An R-4D (C-47) taxied on the prepared runways sank into several soft spots, but it did not leave a track on the main roadway.

It was found that new snow and drift snow were compacted under traffic more readily if a previously compacted surface existed beneath it.

LABRADOR TRIALS (1952-53)

The following equipment was used in compaction trials at Goose Bay, Labrador (Directorate of Engineer Development, 1953b):

- Seaman Pulvimixers
- TD-14 Crawler tractors
- TD-18 Crawler tractors
- Standard Department of Transport corrugated steel rollers, 5 feet in diameter and weighing 3200 lb each
- Standard drags (Department of Transport)

During construction of an air strip on snow about 43 inches deep at temperatures below 0°F, it was found that a TD-14 tractor-pulvimixer combination could not operate in unbroken snow deeper than 30 inches. When a breaking and precompaction pass was made with an independent tractor, the TD-14 combination was satisfactory.

It was found that a pitching action of the tractor-pulvimixer combination when processing deep, soft snow produced a wave effect on the strip surface which prohibited use by aircraft. The height of the waves was about 30 inches and the distance between crests about 18 feet, or about the length of the tractor-pulvimixer combination. It appeared that the waves were produced by the tractor pushing snow ahead until a stalling speed is approached. The snow was then delivered to the towed pulvimixer in greater concentration by the churning action of the tracks as they tend to lift and climb over the bow wave of snow. A very hard surface was produced on more than a mile of air strip with the pulvimixers and rollers in 42 hours of operation, but a week of reprocessing by sustained dragging and rolling was required to reduce the waves and produce a surface sufficiently level for a 32,000-pound RCAF "Canso" (SA-16) to land and take off. The waves produced by the initial processing were so hard that reprocessing was very difficult and much of the smoothing was achieved by fill-in resulting from a 4-inch snowfall.

Where some of the muskeg moss was brought to the surface by the pulvimixers, the increased absorption of radiation by the foreign material produced potholes and nonuniform surface.

In addition to the air strip, a network of roads was constructed in the Goose Bay area in snow ranging between 30 and 45 inches deep. The same pitching difficulty was encountered when TD-18 tractors were used with pulvimixers on 45-inch deep, unbroken snow. The TD-18 tractors tended to bog down in the deep snow during the road-construction trials, although they were used successfully in snow of about the same depth in constructing the air strip.

It was found that dragging immediately after pulvimixing and before rolling was necessary to reduce the waves produced by pitching and achieve a smooth usable road surface.

Traffic studies on the test roads indicated that the high rammsonde number and hardness of the surface produced at temperatures below +10°F rapidly decreased at sustained high temperatures up to +40°F, but the increased density, which reached a maximum of 0.6 after the period of high temperature, contributed to an improvement in traffic-supporting capacity of the road. Those who conducted the compaction trials at Goose Bay believe that the high temperatures during the day increased the moisture content, which froze at night and increased the bonding of the mat of snow. It was reported also that a good smooth, compacted snow surface reduced the accumulation of drift snow during periods of sustained high winds. The opinion was expressed that an even greater reduction in drift effect could be achieved by proper attention to the embankment slopes or edges of the compacted strips. It was stated that three parallel trenches 10 feet apart on the windward side of the test road considerably reduced drifting on the road, but no information was given on the size of trenches and their location with respect to the road. However, windrows of snow left on the edge of the test strips increased the drift problem.

In common with most other compaction studies, it was found that increased hardness and traffic-supporting capacity was achieved by heavy use of the snow road. Tire pressure has a marked effect on the road and on vehicle trafficability, and the use of reduced tire pressures was stressed. For passenger cars and light trucks, the best tire pressure was about 15 p.s.i. For heavier trucks of about 3-ton capacity, tire pressures of about 30 p.s.i. appeared to be best, and 45 p.s.i. was found to be the optimum for large 5-ton vehicles.

Greenland Ice Cap (1951-52; 1952-53)

Snow-compaction trials were conducted on the Ice Cap during the summers of 1952 and 1953 and are discussed in detail in the reports on Project Snocomp (Directorate of Engineer Development, 1953a; 1953b; Northeast District, Engineer Research and Development Laboratories, and Snow Ice and Permafrost Research Establishment, 1953).

1952 trials. The 1952 trials were conducted only in the melt zone on snow of 12- to 22-inch depth over an ice subgrade. During the trial period, daytime temperatures were about 25°F and minimum temperatures at night were about 15°F.

The following equipment was used in these compaction trials:

- D8 Caterpillar 'Dozers with straight blade and 20-inch pads
- Seaman Pulvimixer, ski-mounted
- Snow rollers, corrugated type
- Snow drag.

The pulvimixers were set to process the snow to a depth of 12 inches. The only test roads that supported any traffic were those constructed with pulvimixers and rollers. Rollers alone did not produce sufficient compaction. The 24-hour ram hardness[1] of snow was found to increase with the number of passes of the pulvimixer up to about 5 passes, remaining relatively constant with additional passes. Although a density of 0.5 to 0.55 was produced by the pulvimixer-rolling process, the surface produced did not provide satisfactory support to normal rubber-tired vehicles. It is believed that temperatures after processing were not sufficiently low to favor good hardening conditions at this site, because the driving wheels of some of the test vehicles broke through the surface on the first pass although the greater weight on the front wheels was supported without failure of the surface. It was suggested that the use of artificial heat with the pulvimixing might increase temperature differences and improve hardening of the processed snow.

Continuous drifting made maintenance of compacted roads very difficult. Where compacting depressed the road surface, the drifting effect could be reduced by production of a depressed, dished profile with rounded sides. This was accomplished by towing three rollers over and on the sides of the processed road. Satisfactory evaluation of the influence of level or elevated surfaces on drift accumulation was not obtained during these trials.

1953 trials. The 1953 compaction tests in Greenland were conducted in both the melt zone and the dry snow zone on the high ice cap. The initial plan called for construction of test lanes at different elevations from the lower edge of the ice cap to the high, dry snow zone and then, if feasible, construction of about 150 miles of road over the cap.

The following equipment was used at the lower, or melt-zone site:

Pulvimixers, with burners, ski-mounted
Rollers, wheeled, pneumatic tires
Rollers, corrugated steel, 5-foot diameter
D2 tractor
D7 tractor with 35-inch pads.

Only six tests lanes were constructed and no tests were made to determine the success of construction methods. It was suggested by observers of these trials that ideal conditions for compaction are attained when processing is done near freezing temperatures and hardening takes place at below freezing.

Owing to many delays, the original plan was modified and an air strip constructed, in lieu of a road, on the Ice Cap above the melt zone. For this trial, the following equipment was available:

Pulvimixer, with burners, ski-mounted
Roller, wheeled, pneumatic tires
Rollers, corrugated steel, 5-foot diameter
Drag, Department of Transport equivalent
Grader
D7 tractors, one with 'dozer blade, 35-inch pads
D2 tractor

Air temperatures during the trials ranged from −10°F to +25°F with maximum change of 15 to 20 deg/24 hr. The snow temperature varied from about +18°F near the surface to +9°F at 3 feet.

The 5000- × 160-foot test area was first "cold-processed" by three passes of a pulvimixer, leveled with a timber drag, and rolled with the corrugated rollers. The rubber-tired roller was found to be unsatisfactory, producing ruts and accentuating the rolls produced by the tractor-pulvimixer combination.

Taxiing a C-47 over the cold-processed strip indicated that some sections were satisfactory and others not. The strip was constructed in sections and processed between 18 August and 27 September. Daily temperatures differed considerably during the processing period and different operational techniques were used on some sections, hence a satisfactory evaluation of the cold-processing method could not be made.

After testing the cold-processing strip with the C-47, sections of the air strip were heat-processed with pulvimixers equipped with Tri-D Engineering Corporation heaters. These heaters have an output of approximately 1,000,000 B.t.u./hr. The use of heat accentuated the tendency of pulvimixing to form rolls on the processed surface.

The reprocessing of the cold-processed, hardened snow with heat did not produce satisfactory results. Repulvimixing with heat broke up the surface into pieces three fourths of an inch or larger, which did not rebond as effectively as fine-grained snow. The failure to pulverize the previously hardened snow prevented satisfactory transfer and incorporation of the applied heat. Further, since heat processing was not followed by rolling in these tests, good contact between heated and unheated portions of the snow was not attained.

[1] 24-hour ram hardness refers to the hardness of the processed snow as measured with a rammsonde 24 hours after processing. It has been found that a minimum ram hardness of 300-400 is required for traffic-bearing roads.

It was reported verbally by SIPRE personnel that a satisfactory air strip had been completed by the end of the test period and a C-47 with wheels landed and took off. However, because of the numerous processes used in building this air strip, it is difficult to draw any conclusions from these tests.

Kapuskasing, Canada

During the 1952-53 winter, an extensive series of compaction trials were conducted at Kapuskasing to develop improved techniques and equipment for the construction of snow roads and compacted-snow air strips.

About 138 trials including approximately 100 different compaction processes were made during January, February, and March 1953. Usable snow roads several miles long and air strips, 150 $\times$ 5000 feet, capable of handling 60,000-pound planes were constructed.

All the equipment used at these trials cannot be described in detail, but the major items were:

- D6 tractors
- D7 tractors
- D14 tractors
- D18 tractors
- Pulvimixers, with and without snow-heating units
- Rollers, corrugated, segmented, and rubber-tired, 4-10 feet in diameter
- Drags, three types: wood and steel frames, adjustable, and nonadjustable.

The snow depth varied from 10 or 11 inches to not more than 30 inches during the course of the trials. In almost all cases the snow was compacted against the ground or muskeg beneath and, frequently, the local vegetation was deliberately or unavoidably incorporated in the processed snow.

The information derived from these tests, as presented in the Report on Snow Compaction Trials, prepared by the Directorate of Engineering Development (1953b), and from the analysis made by SIPRE (1953), is summarized below:

1. The 24-hour ram hardness was measured for 94 trials, of which 55 included the use of heat and 39 did not. Fifty-two percent of the heat-processed trials yielded ram hardness greater than 400, while only 15 percent of the trials without heat yielded ram hardness values greater than 400. It may be concluded that, in the Kapuskasing area, the use of heat is almost mandatory in processing snow to attain a ram hardness of 400, which is considered the minimum for a traffic-bearing road (1).
2. The ram hardness of compacted snow is directly related to the number of passes with the pulvimixer although the minimum number which will produce the hardest surface is not definitely indicated. From the Kapuskasing tests and those previously reported for Goose Bay and the Greenland Ice Cap, the best results appear to be attained with about 5 or 6 passes.
3. The densest and hardest snow was obtained with the heaviest rollers. At Kapuskasing, the segmented and rubber-tired rollers were superior to others, although the rubber-tired roller was not considered satisfactory on the Greenland Ice Cap.
4. Heat processing is superior to cold processing.
5. The hardest snow was produced with a 4,200,000 B.t.u./hr. heater mounted so that the hot gas discharge was to the rear of the pulvimixer canopy. This type was superior to front mounting of the same heater or to a rear-mounted 1,800,000 B.t.u. heater.
6. The rear-mounted 4,200,000 B.t.u. heater produced an average increase in snow temperature of 3°F per pass.
7. A 6-hour delay between pulvimixing with heat and rolling did not reduce the ultimate hardness of the test strip when air temperatures were below 15°F during processing.
8. Compacted snow increased in hardness for 24-hours or more after processing, regardless of whether air temperatures were rising or falling during the hardening period.
9. The hardness of compacted snow 24 hours after cold processing was not related to the mean air temperature during the 24-hour hardening period. However, hardening appeared to be a function of the difference between the temperature of the snow at the completion of the processing operation and the mean air temperature during the following 24 hours. This indicates that greater hardness can be expected if methods are used which produce a large temperature difference between the snow and the air during and after processing.
10. Hardening of processed snow during the first 24 hours proceeded regardless of whether air temperatures were increasing or decreasing. After the initial hardening period, which sometimes extended to 6 days, the hardness of the compacted

snow varied inversely with air temperature. That is, after the processed snow has become more or less stabilized, it will be harder or have greater bearing capacity when air temperatures are low than when they are high.

SUMMARY AND DISCUSSION

Optimum Temperature for Processing

The snow-compaction trials at Goose Bay demonstrated that satisfactory roads and air strips can be produced by cold process compaction in snow as deep as 40 inches. Good results were obtained by breaking or precompacting, pulvimixing and rolling during a period when the mean daily air temperature was about +15°F and the diurnal temperature variation was about 15°F.

At Kapuskasing the mean temperature during the test period, 20 February to 20 March, was about +15°F. High insolation on clear days combined with radiational cooling at night resulted in diurnal temperature variations of 30° to 40°F, which contributed to the production of exceptionally well compacted and hardened surfaces. However, by early March there was sufficient solar radiation on clear days to thaw the surface, and, because of the longer day, insufficient nighttime cooling to prevent gradual or even at times rapid deterioration of the compacted roads or air strip.

It appears that a mean daily temperature of +15°F or lower is required to ensure the development of a reasonably durable, load-supporting, compacted snow surface by any presently known processing method. No temperature data are available from the Greenland Ice Cap, but, by applying a normal lapse rate of 1°F/300 feet to the mean temperature at Thule, the elevation of the mean 15°F isotherm has been computed for the adjacent area in Greenland.

Month	*Elevation of mean 15°F isotherm (ft.)*
April	100
May	2100
June	6000
July	7800
August	6900
September	3600
October	100

It is apparent from the location of the 15°F isotherm that, from October to April, melting would not interfere with the construction and maintenance of a snow road at any elevation. A permanent road which is not subjected to melting at any time of the year could be constructed, however, only above 7500 feet. From May to September, other means than snow compaction will be required to provide access through the wet snow zone to the high-elevation permanent road. The rapid rise in elevation of the 15°F isotherm indicates the difficulties to be expected in maintenance of a snow road within the wet snow zone. It is probable however that, by judicious selection of sites, a satisfactory road could be maintained a thousand feet or more below the critical elevation (15°F mean isotherm) during the midsummer months.

Every effort should be made to use natural phenomena in the construction and maintenance of compacted snow surfaces. When the air above a snow surface is many degrees warmer than the snow, it contains much more moisture than the air in the voids of the snow. If the snow is mixed with the warm air, the temperature of the snow grains will be raised and the air voids filled with greater quantities of vapor. When compaction against the colder underlying snow or a drop in air temperatures reduces the temperature of the processed snow, freezing of the excess vapor produces bonds which contribute to the hardening of the snow. Warm snow mixed into cold air will lose some of its void vapor to the atmosphere, and less thermodynamic bonding of the crystals can be expected after rolling the processed snow. Low unchanging air and snow temperatures slow down the metamorphic processes which contribute to the crystal growth and bonding.

Solar and long-wave radiation, katabatic and anabatic movement of air, and normal diurnal temperature variations are some of the possible natural sources of energy which may contribute to the production of a trafficable compacted snow surface.

Use of Artificial Heat

The trials at Kapuskasing demonstrated that the application of artificial heat during processing was the most satisfactory method so far devised to produce a compacted snow surface which will support heavy wheeled-vehicle traffic. Of the lanes processed by pulvimixing and rolling, 82 percent of those to which heat was applied during pulvimixing were able to carry wheeled traffic and only 56 percent of the test lanes which did not receive heat were able to support wheeled-vehicle traffic. The most satisfactory results were obtained with a 4,200,000 B.t.u. heater mounted so that the hot gas was discharged to the rear of the pulvimixing canopy. The average increase in temperature of the snow by using this equipment for a number of passes was about 3°F per pass. The temperature rise is not continuous over the total number of passes but is really intermittent, since some cooling occurs between successive passes of the heater. If the time interval between successive passes of heater units is too great, much of the heat gained by the snow will be lost. This suggests that the most economical application of heat would probably require that successive heater units follow closely behind each other, so that little of the heat received is lost in the interval between passes. The temperature rise per pass is reduced as the temperature of the snow approaches 32°F, since some of the heat is used in melting snow rather than changing its temperature. The temperature increase per pass was greatest at lower speeds and the temperature change of 3°F per pass was obtained when the equipment was being moved at a speed of 168 feet per minute, the lowest speed at which the tractor-pulvimixer combination could be easily handled. It is probable that the reported difficulty of snow packing in the pulvimixer canopy can be partly alleviated by adjustment of the processing speed. It is probable also that the initial temperature of the snow will influence the processing rate.

Where the mean temperature of the upper 2 feet of snow is about +15°F, which may be expected on the Ice Cap during the summer, 5 passes of the heater-equipped pulvimixer are required to raise the temperature of the snow to 30°F and an additional pass or two might cause some melting which would facilitate subsequent bonding.

Roller and Drag Operation

The most satisfactory results appear to be obtained when the heaviest rollers are used to compact the processed snow. The segmented U. S. Navy roller, which weighs 22,400 pounds, and the 4-wheeled rubber-tired roller operated at a weight of 38,000 pounds produced the best compacted surfaces at Kapuskasing. The results of the trials do not permit evaluation of the rollers on a unit-loading basis.

In Greenland the rubber-tired roller produced ruts and was not considered satisfactory. It is possible that the use of artificial heat in the compaction process at Kapuskasing was conducive to more satisfactory operation of the rubber-tired roller. The difference in results reported from the Goose Bay trials and those at Kapuskasing indicate that there is probably an ideal combination of equipment and procedures and that the type of roller used may be an important item in the combination. Meteorological conditions, as well as the properties of the snow cover at the time of processing, may determine the proper combination of equipment and procedures.

The use of open-frame drags may be necessary during construction and is definitely essential for maintenance of compacted surfaces. Almost any form of drag appears to be suitable for leveling off drifts and uneven accumulation of new snow. Heavily weighted drags with sharp cutting edges are required to level off compacted snow. It may be necessary to repulverize some of the most uneven areas of compacted, hardened snow before leveling with drags, or a tractor with blade might be used to cut off the high spots.

Rollers and drags alone have been used for many years to compact and maintain good snow surfaces on airfields where removal was not practicable. The exceptionally good traffic-supporting capacity achieved on these airfields by roller-compacting each deposit of new snow indicates that the best compacted snow roads and air strips will be obtained when processing is undertaken in increments. If a snow road is to be constructed with the traffic surface level with or elevated above the surrounding snow, the increment construction method can be used by blading up, leveling, and compacting successive layers of snow, possibly with drags and rollers alone, after the first base course has been constructed with pulvimixers.

Breaking and Precompaction in Deep Snow

Tractor-pulvimixer combinations cannot be operated satisfactorily in unprocessed snow more than 30 inches deep. If the tractor is not stalled by the deep snow, the wave-like effect produced by the pitching of the equipment produces an unsafe surface. Some form of precompaction or breaking of the deep snow is desirable. This can be accomplished by operating light tractors or track-type snow vehicles over the operational area before pulvimixing and/or rolling. Since the precompacted surface may age-harden, there may be a critical time interval between the preprocessing operation and the actual pulvimixing or rolling.

If the hardened snow produced by the precompaction process is not thoroughly disaggregated by the pulvimixer, a satisfactory surface may not be produced by subsequent compaction. The length of the critical period between precompaction and final processing is undoubtedly determined by the air and snow temperatures during and following the precompaction or breaking operation.

At Kapuskasing, precompaction with rollers prior to pulvimixing and rerolling did not produce a surface with an ultimate hardness greater than that achieved without precompaction.

Precompaction or breaking should not be considered as one of the direct constructive processes and, quite possibly, should not be used if not needed to improve operation of the heavier tractors and pulvimixers or rollers.

Hardening after Processing

Hardening of snow takes place for 24 hours or more after processing, whether air temperatures are rising or falling. This hardening is largely the product of the re-establishment of thermodynamic and mechanical equilibrium within the processed mass. The greatest hardness is obtained when the processed snow undergoes a large decrease in temperature after compaction and when the temperature of the snow at the time of processing is high. It is stated in TM 5-560, *Arctic Construction* (Departments of the Army and Air Force, 1952) that, when the temperature of snow is 30°F at the time of compaction, a density of 0.60 can be developed; at a temperature of 13°F, this is reduced to 0.41, and at 0°F it drops to 0.35. Since methods and equipment used in processing to attain these densities are not discussed, the figures may be considered as indicative of the range of densities achievable rather than as probable expected values, since some processing methods will produce higher densities than others.

Curves presented in TM 5-560, *Arctic Construction,* derived from Kragelski (1945), show that, after processed snow attains a maximum hardness through re-establishment of thermodynamic and mechanical equilibrium, further changes in hardness and bearing capacity are determined by the temperature of the snow. It is shown also that high-density compacted snow has a greater bearing capacity than low-density compacted snow at any given temperature.

The role that temperature and temperature change play in compaction of snow indicates that every effort should be made to process snow during the warmest period of the day, or to take advantage of a foreseeable change in the synoptic situation which will permit processing during a warm spell followed by a large or rapid drop in air temperature. Even when artificial heat is used with pulvimixer processing, the greatest advantage can be expected when operations are performed at a time which will insure the greatest change in temperature of the snow.

The Drifting Problem

Previous compaction trials in Greenland indicate that drifting snow may create a serious maintenance problem. Successful operation of a compacted snow road on the high ice cap may require much emphasis on the development of maintenance techniques and equipment as well as construction procedures.

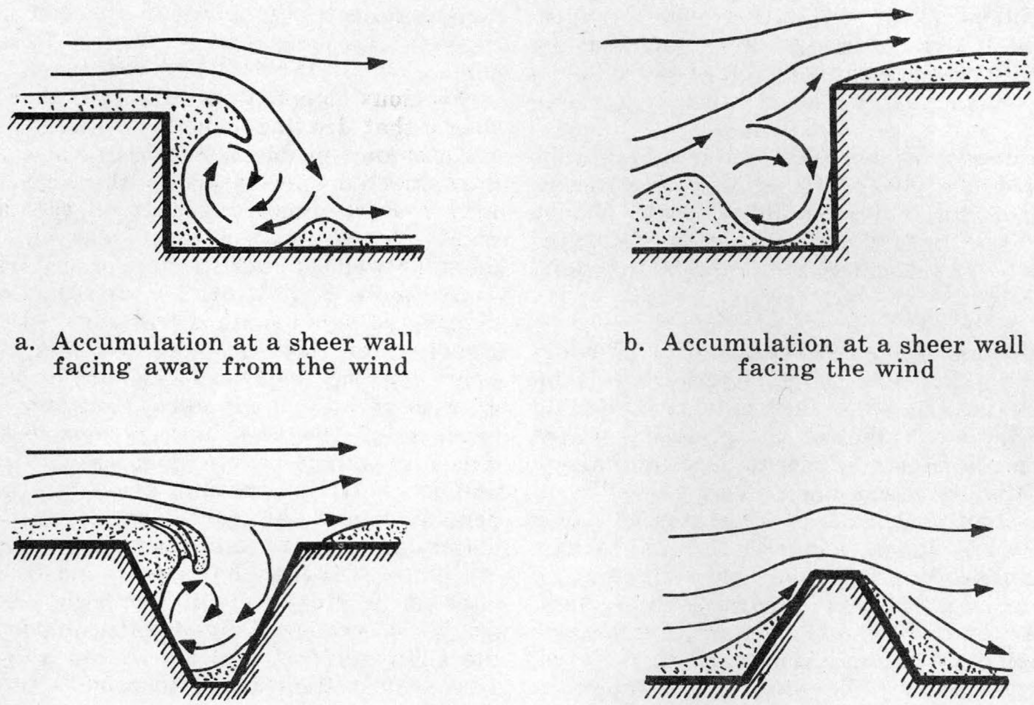
At Goose Bay, Labrador, drifting over the compacted snow surface was reduced by construction of three parallel trenches, 10 feet apart, on the windward side of the road. In an area of permanent snow, continuous maintenance of the trenches or construction of new ones might require a large service crew and much equipment and also place a heavy demand upon the road for supply of the maintenance crews and tractors.

Rikhter (1945) shows how snow accumulates in a steep-walled depression, such as would be produced by direct compaction of the snow surface, and how a low ridge with symmetrical slope tends to remain snow-free (Fig. 1).

Probably, a snow road should be either level with or elevated above the surrounding area to reduce the effect of drifting. Rikhter (1945) refers to research work which indicates that "zero spots," i.e., sections of road lying right at the level of the surrounding area, tend to clear themselves of snow. There is insufficient information available to indicate the most satisfactory height, bank slope, or width of elevated roadways. The most satisfactory cross section appears to be one with gently sloping shoulders, but it may be expected that the design will be influenced by the orientation of the road with respect to the prevailing wind and the velocity and persistency of the wind. TM 5-560, *Arctic Construction,* gives diagrams showing the effect of cross section of dirt fill roads on snow drifting. The gently sloping road shoulder is recommended in this manual also.

In the construction of compacted snow roads, careful attention to the slope on the windward side would probably be sufficient, as natural fill-in on the lee side will quickly produce a slope compatible with the elevation of the road surface and the velocity of the wind.

It might be possible to make deliberate use of drifting snow to build up the compacted roadway above the surrounding snow surface.



a. Accumulation at a sheer wall facing away from the wind

b. Accumulation at a sheer wall facing the wind

c. Accumulation in a cut with sloping sides

d. Accumulation on both sides of a fill with symmetrical slope

FIGURE 1. ACCUMULATION OF DRIFT SNOW (FROM RIKHTER, 1945)

A natural fence constructed of snow might be built along the windward side of the proposed route, or if practicable a trial section of one or two miles of the lath-type of snow fence might be set up along the route. With proper spacing, the snow mound or wood snow fence would induce the deposition of a large amount of snow on or adjacent to the planned roadway. It is probable that the cross section of a compacted road could be designed to facilitate the accumulation of drift snow in the early stages of construction, and thus permit the highly desirable unit-by-unit compaction of snow. Subsequently, after reaching the proper elevation, the shoulders might be reworked to produce a slope which would tend to prevent accumulation of snow on the road crown.

The opinion has been expressed that an elevated snow road can be quickly blocked by a stalled vehicle, since there is no solid path around it. The same criticism applies to a dirt road built through swamp or tundra. The snow road has the advantage of having the repair material at hand, with a supply constantly furnished by drifting if not by precipitation.

It appears that constructive use can be made of snow drifting just as use can be made of diurnal temperature changes and solar radiation in the processing of a compacted snow road or air strip, although the extremely wide air strip will present a greater drift problem.

Use of Additives in Snow Compaction

The use of additives to produce increased hardness or greater stability of a snow road warrants consideration. The success achieved by ski-resort operators in maintaining a good ski slope, even when temperatures are above freezing, by the incorporation of additives in the snow has been reported in many winter sports magazines. One of the most readily available, economical, and efficient additives is common salt (sodium chloride). Its use with crushed ice in the old-fashioned home ice-cream freezer to produce a temperature much lower than that of the ice itself is a typical example of the effect of an additive.

The freezing point of water containing approximately 30 percent sodium chloride is about 0°F. If there is less salt, pure ice crystals are first formed if the temperature drops below 30°F. When the remaining solution reaches a concentration of 30 percent salt, it freezes in the form of a eutectic mixture if temperatures drop to 0°F or below. A eutectic mixture is one in which the components completely solidify or crystallize at a constant temperature in the exact proportions in which they were present in the solution and where there is no change in composition as the mixture passes from the liquid to the solid, or solid to the liquid phase. The melting point diagram for a mixture of lead and tin showing the eutectic point for the alloy "solder," which may be found in most textbooks on physics, is a classic illustration of the eutectic-mixture phenomena.

If salt is added to an excess of cold snow some liquid solution will be produced, heat being withdrawn from the excess solid phase to cause melting and the production of a liquid film on the snow grains. This film will have an equilibrium concentration determined by the temperature of the snow. If the snow becomes colder, some of the liquid will freeze and bind the adjacent snow grains together. If the snow temperature rises, some of the solid phase will melt and excess solution beyond the film or capillary capacity may percolate downward and refreeze at lower (and colder) levels in the snow. The slight slush which may be produced on the surface of the snow when the equilibrium mixture is exposed to higher temperatures may be offset by a greater thickness and strength of the subgrade produced by infiltration and refreezing of the solution. Since the temperature of the snow grains in contact with the salt solution is depressed, more heat is required to melt the solid phase. Ski-resort operators use a figure of 50°F as the "effective" melting point of snow treated with a commercial snow cement. This "effective" melting point consists of the 32°F normal melting point for water plus the heat required to raise the ice or snow in contact with the salt solution to the 32°F melting point.

In the ice-cream freezer, the brine solution is withdrawn at the bottom and more salt added to the top of the ice as the cold ice and salt mixture withdraw heat from the warm cream mix. The melting of the ice produces a concentrated brine at the bottom of the freezer on which, because of their lesser specific gravity, the ice grains float instead of being in intimate contact with the solution. In snow, the downward percolation of the salt solution under alternate freezing and thawing provides a constant contact between the brine and the snow grains, at least until the solution percolates to the ground. Thus the additive has the advantage of being almost permanently effective in snow.

There are a number of chemicals which might be used as additives to produce increased trafficability of a snow surface. Among them are ammonium chloride with an aqueous-solution eutectic point of about +5°F, sodium chloride with a eutectic point near 0°F, and calcium chloride which produces an aqueous eutectic mixture with a freezing point near −60°F. It is not known whether the greatest advantage (if any) would be attained by the use of additives capable of producing a large or only a relatively small depression of the freezing point, or whether some organic liquids or water-soluble organic salts might be more desirable, since most electrolytes and chlorides in particular are relatively corrosive to metals.

The use of calcium carbide to apply heat to the snow was tried at Kapuskasing. Ignition of the gas produced by mixing the carbide into the snow produced flames which reached a height of 10 feet. Not only was most of the heat delivered to the atmosphere instead of the snow surface, but, since the gas is noncombustible until mixed with oxygen, an insulating layer of nonflammable gas separated the snow surface from the flame.

Reinforcing additives such as sawdust may improve the physical and mechanical properties of a processed snow surface. In addition they may provide insulation, reducing melting and destruction of the snow surface. Trials at Kapuskasing indicated that the insulation effect of sawdust preserved the compacted snow for a period of 6 weeks when temperatures were above freezing. The value of a reinforcing additive where the temperature remains below freezing most of the year has not been demonstrated. In the Arctic, the procurement and transportation of a bulky material, like sawdust, might present difficulties greater than any benefits derived from its use. However, the possibility of using sawdust or a similar insulating material to preserve a compacted snow road in the upper part of the wet snow zone warrants consideration. At lower elevations, such insulation material may be expected to wash away from the surface or accumulate in patches during extended periods of high temperature.

RECOMMENDATIONS

The following recommendations are specifically applicable to the construction of a snow road on the Greenland Ice Cap, at elevations above 7000 feet, during the summer months of July and August. With slight modification they may be applicable to lower elevations in Greenland during the winter and to other areas with a similar climatic regime during the snow season. Major maintenance would be imposed by the *snow accumulation* on the ice cap. The annual total accumulation varies from 10 to 30 inches of water equivalent, corresponding to 30 to 90 inches of snow, part of which falls at relatively high temperatures during the summer. If the road surface is to be kept level with or above the surrounding snow surface, the layer-by-layer compaction becomes of necessity an almost continuing maintenance job over the whole length of the road. It would be advantageous to build the road up sufficiently high during the summer daylight to render all but minor maintenance unnecessary during the very cold and dark winter. Construction and maintenance of roadside camps would also have to be planned with due regard to the never-ending accumulation.

It is believed that, if properly applied, the results of previous trials can be used to formulate a plan of operation which will produce a satisfactory snow road. What appears to be the most logical combination of processes applicable to the area under consideration has been incorporated in these recommendations. The proposed snow road is visualized as being two traffic lanes wide with frequent turn-out and parking stands off the main roadway for handling maintenance equipment and parking disabled vehicles.

The use of the methods listed below, concurrently or in sequence, to attain a level or elevated road surface may be appropriate. The fact that in the past the most desirable traffic-supporting roads have been built up in layers indicates that a construction procedure which produces the desired elevation layer by layer will produce the most satisfactory snow road. It is suggested that roads both level with and elevated above the surrounding area be constructed and maintained. This will provide information on which type of road is most desirable for the Ice Cap.

Level of Road Surface with Respect to Surrounding Snow

Snow road level with the surrounding area. This may be accomplished by leveling, processing, and compacting to produce a trafficable surface depressed below the undisturbed snow. As drift snow accumulates on the depressed roadway, it should be leveled and compacted as often as necessary. The snow road will gradually build up to the level of the surrounding area.

Snow road elevated above surrounding area. This may be accomplished by:

1. Bulldozing or rotary plowing snow onto an elevated roadway with immediate leveling and processing before hardening takes place. If the snow undergoes hardening after bulldozing, the lumpy material will be difficult to disaggregate with the pulvimixer. Applied heat will not be well distributed in the pulvimixed snow and the rolled surface will not have uniform mechanical properties.
2. Construction of a drift-control structure along the proposed route, to induce the deposition of drift snow on or adjacent to the future roadbed. The control structure could be a mound of snow prepared with a blade-equipped tractor or a portable snow fence. The height of the structure, its distance from the roadway and its orientation should be determined by trial and error with experimental sections. The wind-deposited snow should be bulldozed into a suitably shaped roadbed and processed as soon as possible by the mechanical procedures described below.

Since the wind direction may not always be favorable to the deposition of snow at the desired location, directional structures may be required to channel the wind-blown snow toward the primary drift-control structure.

Processing Procedures

As emphasized in this report, all processing should be accomplished during periods of high temperature. Processing during periods of low temperature, 0°F or lower, may not be economical.

Primary processing.

1. Break or precompact if necessary.
2. Level with drag or blade if necessary.
3. Hot process with pulvimixer with heater mounted to discharge gas to rear of canopy. Process with repeated passes until there is some indication of moisture in snow (i.e., good snowball can be made). At approximately 3° temperature rise per pass, snow at +15°F will require five to seven passes to produce the best conditions for compaction and hardening. If it appears that processing will produce a rolling surface, the snow should be precompacted or broken with a tractor or a tracked snow vehicle before further pulvimixing as suggested in paragraph 1.
4. Roll with a heavy (30,000 lb) roller such as the Navy segmented or the rubber-tired roller.
5. If there are large humps, waves, or pockets after rolling, they should be immediately leveled off with blade, drag, or ski-mounted grader and the leveled area re-pulvimixed and re-rolled before hardening takes place. An uneven surface is difficult to repair after it has hardened.
6. Permit the compacted surface to age-harden one or two days before subjecting it to heavy wheeled traffic.
7. If an elevated road is prepared, construct 3:1 fill slope on the windward side. Any cut slope for borrow adjacent to the fill should be given an 8:1 slope rising to windward.
8. Bulldoze two or three windrows on windward side to catch drifting snow. Repeat as needed, blading snow into a protective mound or natural snow fence.
9. Keep snow on the lee side level with or below surface of roadway.
10. Avoid cuts, but, if necessary to prevent steep grades, give the bank on each side a 5:1 slope. If persistent high winds and heavy drifting is expected the bank slope should be at least 8:1 wherever the roadway is depressed.

Secondary processing and maintenance.

1. Drag and roll new snow or drifted snow as it accumulates to about 4 inches during light storms.
2. Deep drifts produced by wind storms should be removed completely or leveled and reprocessed. Blower-type snow plows should be used if possible, to prevent development of snow-catching embankments. Rolling alone probably will produce a trafficable surface unless the deposit of new snow is more than 12 to 18 inches deep.
3. Emergency service and maintenance should be performed during warm periods if the disturbed snow is to be reprocessed into a road surface. Snow may be plowed off the roadway, snow-trap windrows constructed, and embankment construction and maintenance operations conducted at any temperature.

Equipment and Manpower Requirements

All the equipment essential to the construction and maintenance of a usable road should be provided. Spare parts and stand-by equipment should be provided in quantities that will ensure continuous operation and eliminate the all too frequent interruptions that have prevented satisfactory accomplishment in past years.

The equipment should include track-type vehicles of many sizes and with low ground-pressure pads. Blades and front lift shovels should be available for the tractors and all vehicles should be equipped with power winches. It is expected that equipment will be winterized.

Pulvimixers with heaters, rollers, and drags should be available in quantities sufficient to ensure continuous operation on a 24-hour basis during the most favorable weather conditions. Mobile repair facilities should be available at all times.

The size and qualifications of the staff should be comparable to a major road-building program in other areas, further augmented in accordance with the demands of the climate. Capable construction engineers and qualified equipment operators and repair personnel must be provided, in quantities that will ensure "round-the-clock" operations when conditions are favorable.

One or more scientists should be on the staff continuously, to collect data and conduct collateral studies as discussed in Tests and Records.

Tests and Records

In order to evaluate snow-compaction methods reliably and provide criteria for future design and construction, the following measurements should be obtained:

1. Temperature and density of the undisturbed snow, immediately prior to processing, at 6-inch depths to 3 feet and at 1000-foot intervals on or adjacent to the right-of-way.
2. Temperature and density of the processed snow at the surface and at 6-inch depths through the compacted snow to 1 foot below the processed layer. Measurements should be made at 500- to 1000-foot intervals, immediately after processing is completed or before

any hardening takes place if possible.

3. Ram-hardness profile to a depth of at least 3 feet immediately after processing is completed, and at 12-hour intervals for 48 hours after processing. Ram-hardness measurements should be made at the same site where density and temperature data on the freshly processed snow are collected.

4. Daily maximum and minimum air temperatures, cloudiness in tenths of cloud cover, and wind velocity. Small pocket-size velometers should be used to measure wind speed if information is not available from a standard meteorological station.

An accurate record of the processing operations should be maintained and variations noted and emphasized in the record. The following information may be considered as minimum:

1. Height of unprocessed embankment formed from snow which has been bulldozed into an area prior to processing.

2. Height of final processed road above surroundings, or depth below surroundings if depressed.

3. Number of leveling operations and type of drag used.

4. Number of pulvimixer passes, and speed of operation.

(a) Speed of pulvimixer rotor.

(b) Forward speed of tractor.

5. Snow temperature rise in degrees F per pass.

6. Number of passes with rollers and type of roller used.

7. Embankment slope of both elevated and depressed sections of roadway, and influence on drift snow accumulation.

8. Influence of road orientation with respect to prevailing wind on accumulation of drift snow.

9. Effect of type and intensity of traffic on traffic bonding of drift snow.

Supplemental Procedures and Tests (to be undertaken if time and facilities permit).

Drift control. Construction and maintenance procedures should be designed to permit evaluation of different types of drift-control methods, such as:

1. Wood-slat and other fences.
2. Windrowed snow.
3. Directional drift control.
4. Road clearance by use of wind sweeping action, including banking of road surface with respect to direction and velocity of prevailing wind.

Use of additives. The possibility of increasing the strength of the snow road by the use of chemical additives should be investigated. Test sections should be treated with varying quantities of both ammonium chloride and sodium chloride which have been processed with a drying agent to improve their spreading characteristics.

Forecasting trafficability and load limits. Forecasts of temperature, snowfall, and wind may be used to determine load and tire-pressure restrictions. For example, high loads will be permitted during low temperatures and vice versa.

References

Departments of the Army and Air Force (1952) *Arctic construction,* TM 5-560.

Directorate of Engineer Development (1953a) *Field trip to Snocomp-Greenland, 1953,* Report 6, (Canadian) Army Headquarters, Ottawa, Canada. (SECRET)

——————— (1953b) *Report on snow compaction trials, Winter 1952-53,* (Canadian) Army Headquarters, Ottawa, Canada, (SECRET)

Kragelski, I. V. (1945) *O metodike opredeleniia tverdosti i plotnosti snegovykh pokrytii* (*Method of determining hardness and density of a snow surface*), in *Fiziko-mekanicheskie svoistva snega i ikh ispol'zovanie i aerodromnom i dorozhnom stroitel'stve* (*Physico-mechanical properties of snow and its use in the building of airfields and roads*). Moscow: Akademiia Nauk SSSR, Chapter VI, p. 61-66. Translated, 1949, Bureau of Yards and Docks, U. S. Navy.

Northeast District; Engineer Research and Development Laboratories; and Snow Ice and Permafrost Research Establishment (1953) *Report on Project "Snocomp"* Corps of Engineers, U. S. Army. (SECRET)

Rikhter, G. D. (1945) *Snezhnyi pokrov, ego formirovanie i svoistva* (*Snow cover its formation and properties*), Moscow: Akademiia Nauk SSSR. Translation 6, 1950, Snow Ice and Permafrost Research Establishment.

Snow Ice and Permafrost Research Establishment (1953) *Summary of snow-compaction tests, 1952-53, Kapuskasing, Canada.* Special Report 7. (SECRET)

U. S. Navy (1947) *Operation High Jump.* (CONFIDENTIAL)