Microscopic Observations of Snow Deformation

S. SHOOP AND S. TAYLOR

U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290 U.S.A.

ABSTRACT

Snow grains subjected to shearing or compressive forces, or both, were examined with a microscope to explore the conditions that cause melting of grains during snow deformation. Researchers have studied the deformation of snow, caused by wheels, tracks, sliders and skis, but little work has been done on snow deformation at a microscopic scale. This information is useful in defining the processes involved in snow deformation and is applicable to research on vehicle mobility and construction on snow, skiing and avalanches.

Snow samples were deformed using a variety of instruments and studied via thin sections and single grain observations. In general, the sheared zones contained broken grains, crushed material and aggregates of crushed material. Evidence of melting was observed immediately adjacent to sheared surfaces, and when the pressure and temperature conditions were conducive to pressure melting. Snow with large, rounded grains showed changes from deformation most clearly.

INTRODUCTION

Studies on the compressibility of snow (Bader, 1962; Abele, 1967; Colbeck et al., 1978) and on vehicle mobility in snow (Richmond and Blaisdell, 1981) describe the microscopic compression of snow. Compression has also been observed on a microscopic scale by Abele and Gow (1975, 1976). Shearing of snow and ice has also been studied in an attempt to explain the low friction of skis and sliders and how friction changes as a function of temperature and pressure (McClung, 1977; de Montmollin, 1982; Colbeck, 1988; Warren et al., 1989). Water films, generated by frictional heating, are thought to be responsible for the low friction of skis and sliders. Because of the energy expended in melting the snow and the subsequent changes in snow properties, we wanted to see what kinds of conditions and deformations caused melting. We studied the deformation of snow particles, caused by shearing or compression, or both, on a microscopic scale. The results of this research are applicable to studies of the construction of snow roads, vehicle mobility on snow and the interaction between snow and machines.

EXPERIMENTAL METHOD

Our experimental program explored different methods of deforming and observing the snow samples to determine whether melting had occurred during deformation. In addition, to see the results of the deformation more clearly, we tried to produce a snow having round grains of uniform size. Three snow types were thermally cycled at temperatures close to, but below, freezing to produce rounded snow grains through metamorphosis. The first snow type used was tested using a variety on instruments at three coldroom temperatures, –2.2, –3.3 and –4.4°C. Because the more interesting results were observed at the higher temperatures, tests on the next snow type, collected during the spring, were performed primarily between –1 and –2°C. This snow was the best for observing the results of deformation; therefore, most of the testing was done on this snow. Limited tests were performed on the final snow type because of the angularity of the snow grains. The following section describes the preparation of the snow samples, the observational techniques used and the way that the samples were deformed.

Sample Preparation

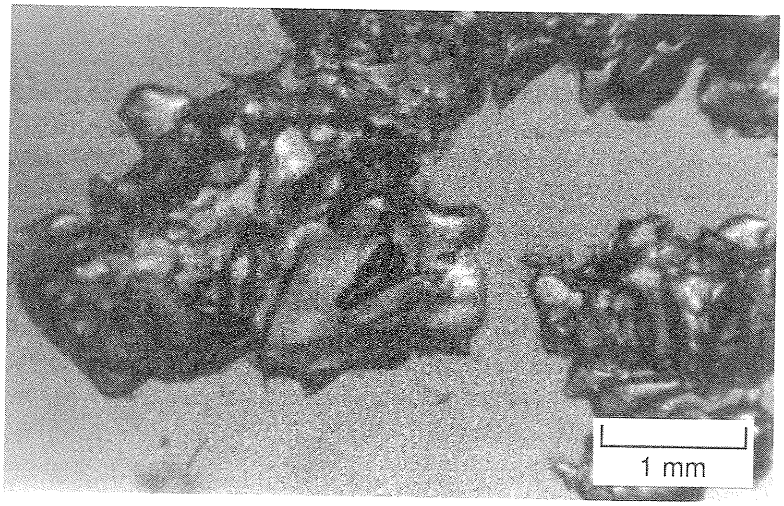
Using snow with rounded, uniform grains would make it easier for us to distinguish changes in snow grains caused by deformation of the sample from those features present in the undeformed snow. Three types of snow, a dry snow composed of small angular grains, a wet spring snow with rounded grains and grain aggregates, and a drained slush, were placed under conditions designed to cause metamorphosis and produce samples having rounded, uniform grains. All snow was sieved to obtain grain sizes between 0.48 and 2 mm and then placed in plastic or plexiglas sample containers. We found that by gently shaking and tapping the sample containers while adding snow we could regulate the sample densities to within 2%. The samples were then covered and left in a coldroom to metamorphose.

During metamorphism, under low temperature gradients, differences in vapor pressure cause water molecules to evaporate from convex areas of a snow grain and condense on concave areas, thereby producing rounded grains and minimizing the surface area (Bader, 1962; Colbeck, personal communication). In addition, the contact points between snow grains also grow and the snow becomes stronger; in this state it is said to be sintered or age hardened. As the rate at which evaporation/condensation takes place is related to the temperature; the closer the temperature is to freezing the more rapidly this process occurs. Therefore, we tried to create conditions where the snow was near the melting temperature and was subjected to a thermal gradient. The coldroom thermostat was set at either –2.2 or –3.9°C and fluctuated ±1.5°C. Except for tests where the deformation equipment was deliberately set at a temperature different from that of the snow (samples 5, 7, and 10a), all the test equipment and test samples remained in the same coldroom.

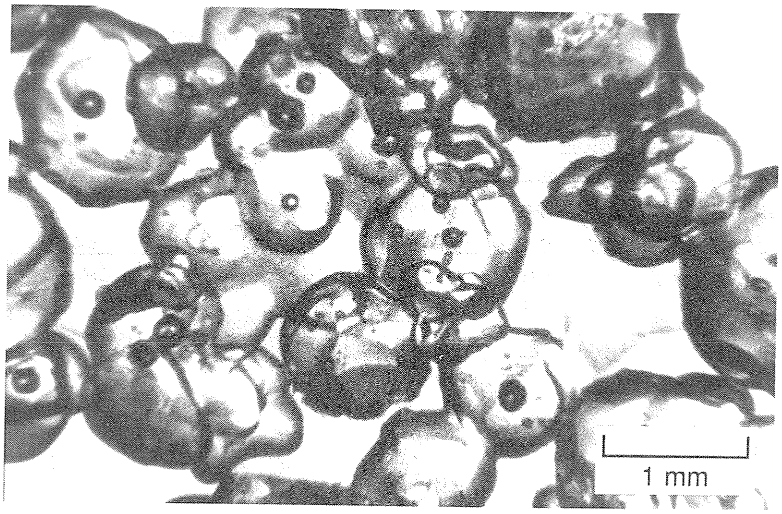
Snow 1, a dry snow composed of small angular grains, had been stored in a deep freeze (–29°C) for several years. It was age hardened and had to be broken apart before sieving. Snow 2, a wet spring snow, was collected locally and was composed of rounded grains and grain aggregates. The disadvantage of snow 2 was that it had been thermally cycled in nature and initially contained some aggregate grains and melt features.

Snow 3 was made by adding water to either snow 1 or 2 and placing the resulting slush in a container surrounded by an ice-water bath. In this way the sample was held at a constant 0°C and metamorphism would occur at an accelerated rate. Although this snow was previously sieved and stored, any sintering or aggregate grains formed during storage would break apart in the ice-water bath. After a day, the slush was dewatered by drawing the water through a porous membrane, leaving the grains. As the dewatered slush still had angular grains, it was placed in a sample container and allowed to metamorphose. In general, this snow was not greatly improved over snow 2 and, therefore, was not tested extensively. Examples of the undeformed snow grains for each snow type are shown in Figure 1; the springtime snow has the most uniform and rounded grains.

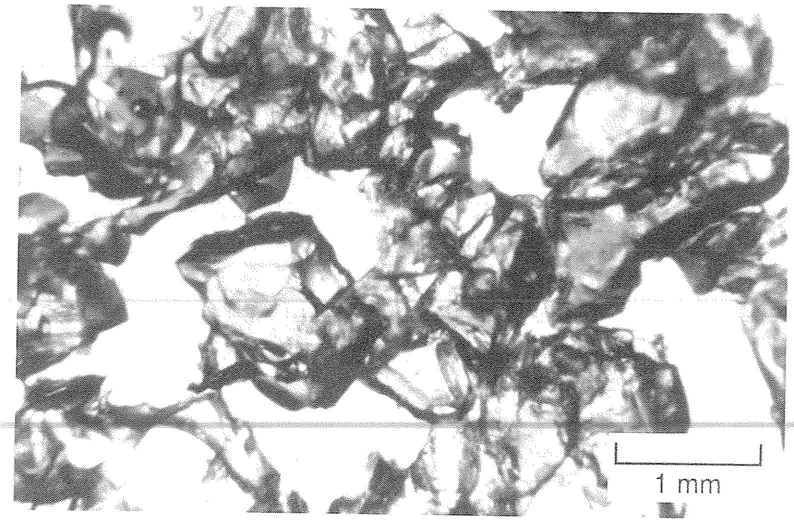
The snow samples were sized to avoid edge effects during the deformation tests. Although some of the samples had to be quite large (12.6-cm diameter), the majority of the tests were conducted on samples that were between 7 and 8 cm wide (either square or circular in cross section).



a. Snow 1—from old, dry snow stored in a deep freeze for several years.



b. Snow 2—collected during a spring snowfall.



c. Snow—made from slush.

Figure 1. Examples of the three snow types after metamorphosis.

Observational Techniques

Two methods were used to study the snow microscopically. Individual snow grains were examined with a Zeiss monocular microscope and thin sections of the snow were made following the procedures outlined by Watanabe (1974). Thin sections of the deformed snow sample were made by saturating the sample with a mixture of caprylic acid and ethyl cinnamate, which is liquid at temperatures above –8°C. The samples were then placed in a room set at –10°C, allowing the mixture to solidify. After the sample hardened, it was fastened to a glass plate, and sectioned using a microtome. Progressively thinner layers (the last 100 µm were removed a micrometer at a time) were removed until it was thin enough to view the grains under a microscope (50 µm). This was done to avoid disturbing the structure of the snow grains. A few drops of cinnamic aldehyde, added to the thin section, melted the solidified caprylic acid mixture and allowed the structure of the snow to be seen under both plane and polarized light. (Later in this paper, Figure 7 shows one of the sections before the final thinning.) Because it was difficult to maintain the snow structure during the sectioning process, most observations were not made by thin sections, but rather by single grain observations.

For the single grain observations, particles of snow from the deformed area were carefully removed, placed in a small amount of iso-octane and viewed under the microscope. Iso-octane is liquid at low temperatures, immiscible in water, and keeps the small grains from subliming. Snow grains from an undeformed part of the sample were also observed and served as a control. The single grain observations caused less disturbance of the snow grains, were quicker, and the individual grain changes were easier to see.

Deformation Equipment and Procedures

Several instruments were used to produce different kinds of deformation of the snow. A 5-cm-diameter steel cylinder was used to penetrate the snow, creating compression below the piston and shear along the sides of the piston. For the majority of tests, we used a hand-held cone penetrometer because it was easier to use and, as the largest cone was 2 cm in diameter, it required proportionally smaller samples. The penetrometer was used in several configurations (different sized cones, a rubber attachment and the rod with no cone) to produce different types of deformation. Lastly, to produce shear only, samples were held lightly against the side of an operating band saw. A description of each of the test types is given below. Table 1 lists the test conditions and the type of test carried out on each of the samples.

CBR Apparatus

A standard California Bearing Ratio (CBR) apparatus, commonly used in soil mechanics (ASTM, 1989), was used to drive the 5-cm-diameter solid steel cylinder (with a cross-sectional area of 19.4 cm^2) into the sample at a constant speed (Fig. 2). This produces both compression beneath the cylinder and shear along the sides of the cylinder. The piston travel and corresponding load were measured with a proving ring and a dial gauge respectively. The load was recorded at displacement intervals of 25 mm. The piston was lowered until the maximum load on the proving ring was obtained. The entire test (2.54- to 5-cm displacement) was completed in approximately 1 minute.

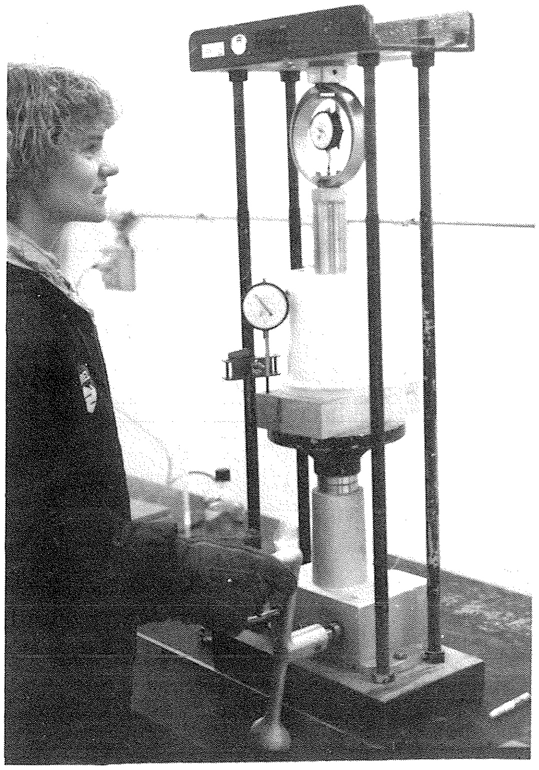


Figure 2. The California Bearing Ratio equipment used to deform snow samples. A steel cylinder is lowered into the sample using a hand crank while the corresponding snow displacement and load are measured.

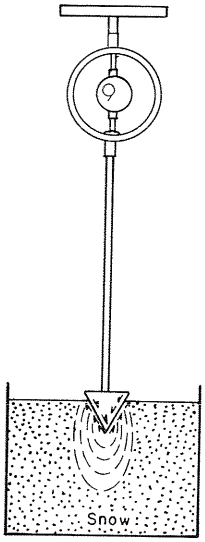


Figure 3. Sketch of hand-held cone penetrometer as used on a snow sample. The device shears the snow along the sides of the cone and compresses the snow beneath the cone.

Cone Penetrometer

Because of its ease of use and the various ways it could be configured, we did most of the deformation tests using a cone penetrometer. The cone penetrometer is also a standard piece of equipment, used for testing soils in the field (ASAE, 1985). The standard cone is 0° and either 1.28- or 2.02-mm in diameter. Penetration is measured along the rod and the corresponding load is measured with a proving ring. When the cone was pressed into the snow sample as shown in Figure 3, it caused both compression beneath the cone and shear along the cone surface. To better examine the effects of shearing alone, we sometimes conducted the tests using the rod without the cone, observing the grains along the side of the rod. The test was further modified to observe the effects of changing 1) the thermal conductivity and 2) the temperature of the penetration instrument. Sample 5 was deformed using a rubber attachment on the rod to see what effect a material with lower thermal conductivity had on the deformation (compared to the standard metal cone). Sample 7 was deformed using a warm cone to see the effects of thermal melting. The temperature and type of test are listed in Table 1.

Table 1. Snow sample specifications and type of test performed on each sample.

Sample ID	*Sample cross section (cm)*	*Sample vol. (cm^3)*	*Initial density (g/cm^3)*	*Length of metamorphosis (days)*	*Final density (g/m^3)*	*Temperature (°C)*			*Test type*
						Room	*Snow*	*Instrument*	
Old Snow (Snow 1)									
1	12.6 dia	1889	0.519	14	0.526	–2.2	—	—	CBR
2	12.6 dia	1889	0.524	18	0.542	–2.2	—	—	CBR
2a	12.6 dia	—	0.524	40	0.542	–3.3	–6.3	–4.2	Penetration (rod only)
3	8.2×8.2	375	0.514	21	0.527	–4.4	–4.3	–4.2	CBR
4	8.2×8.2	381	0.506	21	0.505	–4.4	–4.3	—	Cone penetration
5	8.2×8.2	380	0.483	21	0.476	–4.4	–4.3	+4.2	Rubber attachment on rod
6	8.2×8.2	379	0.476	23	0.474	–3.3	–6.3	–4.2	Penetration (rod only)
7	8.2×8.2	382	0.455	81	0.460	–2.1	–8.3	+9.4	Cone penetration (warm)
Spring Snow (Snow 2)									
10	8 dia	461	0.576	34	0.572	–1.4	—	—	Penetration (rod only)
10a	8 dia	—	0.576	70	0.572	–9.9	–9.5	–10.0	Band saw (short)
10a	8 dia	—	0.576	70	0.572	–9.9	–9.5	–9.3	Band saw (long)
11	8 dia	447	0.594	38	0.588	–1.8	—	–1.9	Penetration (rod only)
12	6.9 dia	285	0.594	42	0.623	–0.7	—	–1.3	Cone penetration
13	7.3 dia	318	0.586	42	0.636	–1.4	—	–1.4	Cone penetration
13a	7.3 dia	209	0.586	70	0.636	–1.5	–1.4	–1.5	CBR
14	7.3 dia	316	0.613	51	0.615	–1.5	–1.4	–1.6	Cone penetration
15	7.3 dia	319	0.587	51	0.575	–1.4	–1.9	–1.7	Cone penetration

Band Saw

To shear the snow sample with a minimum of compressional force (unlike the CBR and the cone penetrometer), a flat sample surface was lightly held against a band saw for a short test (1–5 seconds) or a long test (1 minute). The results of these tests were observed by single grain observations in the area of interest. For comparison, many grains were observed from the deformed areas as well as from an undisturbed area.

RESULTS AND DISCUSSION

CBR Deformation

The load and displacement curves for samples 1 and 2, deformed using the CBR, are shown in Figure 4. Sample 1 was loaded to 1254 N, near the limit of the proving ring, and sample 2 was loaded to 703 N, at which point the sample container broke. Sample 3 was tested at a lower temperature and because the snow was well sintered, the cylinder did not measurably penetrate the sample. Similarly, sample 13a, the undisturbed portion of sample 13, was also impenetrable using the CBR apparatus.

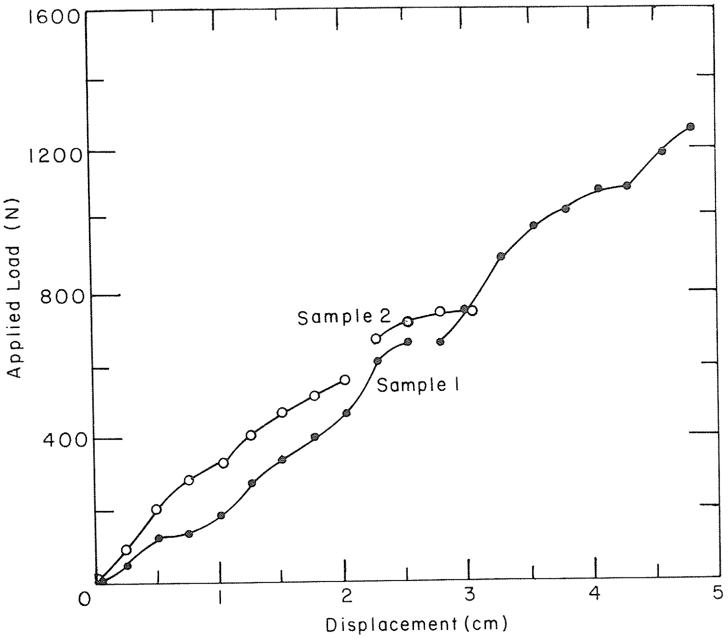


Figure 4. Displacement vs corresponding load generated using the CBR device on snow samples 1 and 2. While sample 2 was being deformed, the sample container broke prematurely.

Samples 1 and 2 were both tested when the snow and the equipment were close to –2.2°C. The deformation of sample 1 resulted in the formation of an ice bulb directly below the piston. The sample was cut in half and sectioned so that the geometry of the ice could be seen (Fig. 5). Because a lower load was applied to sample 2, the snow under the piston did not turn into ice, but was compacted under the piston. For both samples 1 and 2, the geometry of the ice bulb (sample 1) and compacted zone (sample 2) closely resemble the stress contours created by the load applied by the CBR device. Figure 6 shows the nature of the stress distribution caused by a load ap-

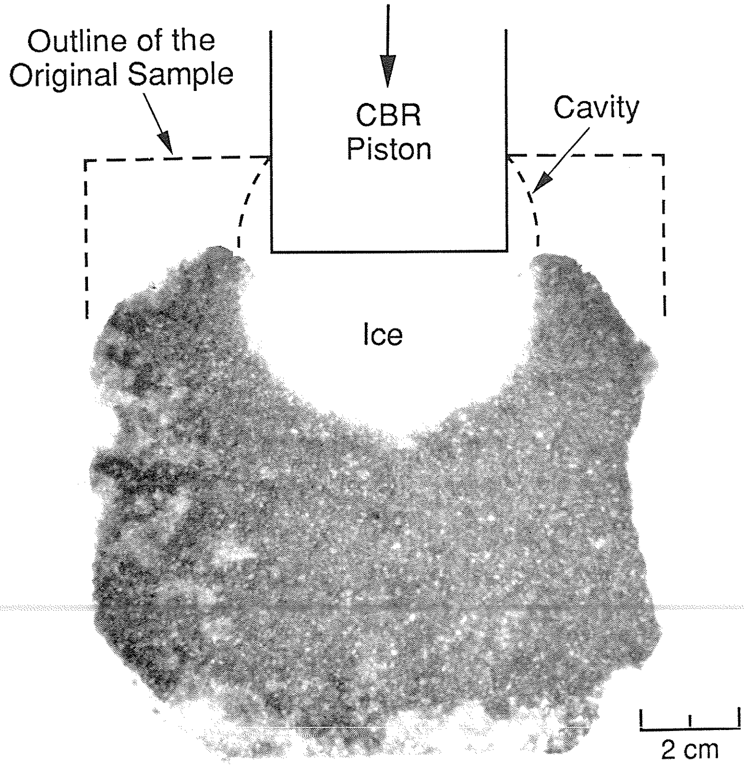


Figure 5. Section of sample 1 before final thinning, showing the ice bulb formed below the CBR piston. The upper part of the sample was destroyed during the sectioning process but is drawn in for reference.

plied by a plate as calculated using the Boussinesq equations for soil, and as measured in snow by Stehle (1970).

The ice bulb, which extended roughly 3.75 cm below the piston, was caused by the effect of pressure on the melting temperature of ice (Hobbs, 1974). The decrease in the melting temperature of ice δT (°C), caused by pressure P (kPa), can be calculated from the Clausius–Clapeyron equation:

$$\delta T = P\ (0.0000738\ °\mathrm{C/kPa})\ .$$

To cause a 2.2°C decrease in melting temperature for these experiments would require a pressure of 29,810 kPa. In sample 1, the applied stress was 646 kPa so, using Figure 6, the stress at the base of the ice bulb would be approximately 23 kPa. If we assume the grain contact area is very small (100^{th} of the grain surface area), then the applied stress is adequate for melting the snow grains. This may be one of the processes involved in the ice bulb formation.

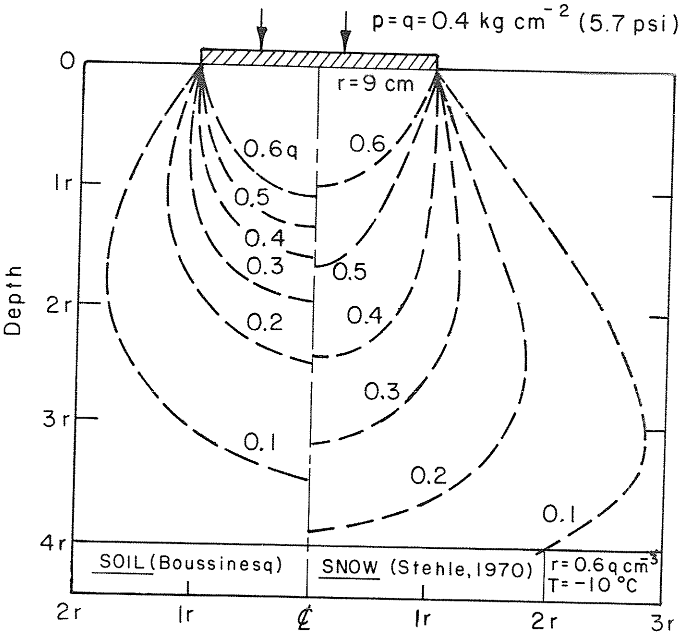


Figure 6. Measured stress distribution generated below a rigid plate on 0.6-g/cm^3 snow as compared with that calculated using the Boussinesq equations for soil (after Abele, 1990).

A cavity was formed around the piston in both samples 1 and 2, as seen in Figure 7 and sketched in Figure 5. We think that the snow grains within the spherically shaped pressure zone, as indicated by the stress distribution pattern (Fig. 6) and our experiments, are compressed and adhere together. As the cylinder is driven further into the snow, the entire bulb-shaped compressed zone moves with it, leaving the curious void around the cylinder.

On both samples 1 and 2, there was some melting around the lip of the cavity (near the sample surface) and the sample refroze to the metal piston. This melting was very localized and the snow just a few grain diameters away appeared unaffected by the deformation.

Cone Penetrometer

The cone penetrometer both sheared and compressed the snow grains. Those grains removed from the side wall next to the cone were found to be smaller and more angular than those grains removed from undisturbed sections (Fig. 8). The large number of small angular particles, often adhering to large grains, are thought to be the result of mechanical crushing of the grains. The compressional force exerted on the snow by the cone attachment on the penetrometer also tended to produce aggregates of melted and

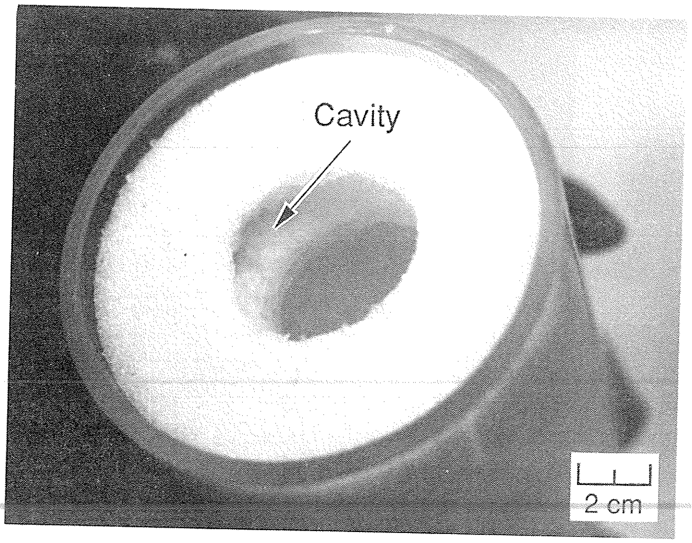
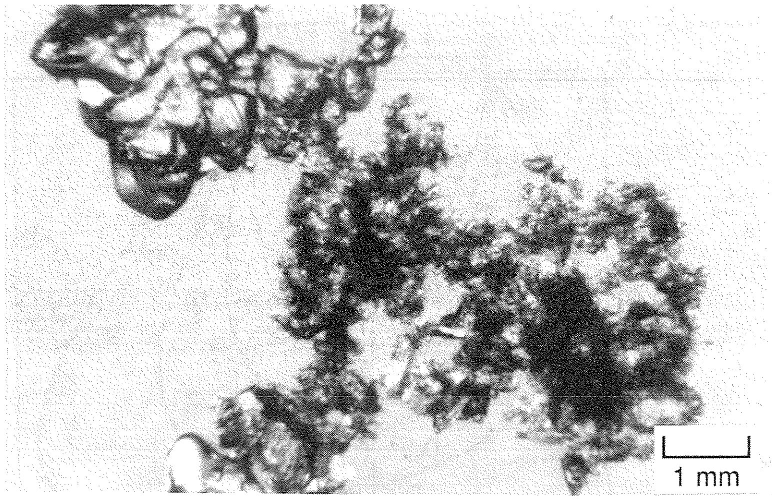
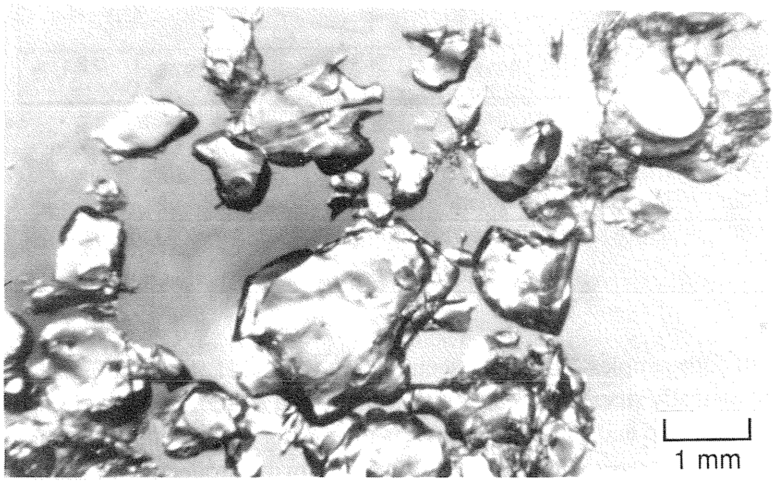


Figure 7. The deformation of samples 1 and 2 generated a cavity along the side of the CBR piston that was thought to have formed as the bulb of compressed snow was pushed further down into the snow sample.



a. Grains from the shear zone.



b. Snow grains from an undisturbed part.

Figure 8. Sample 13.

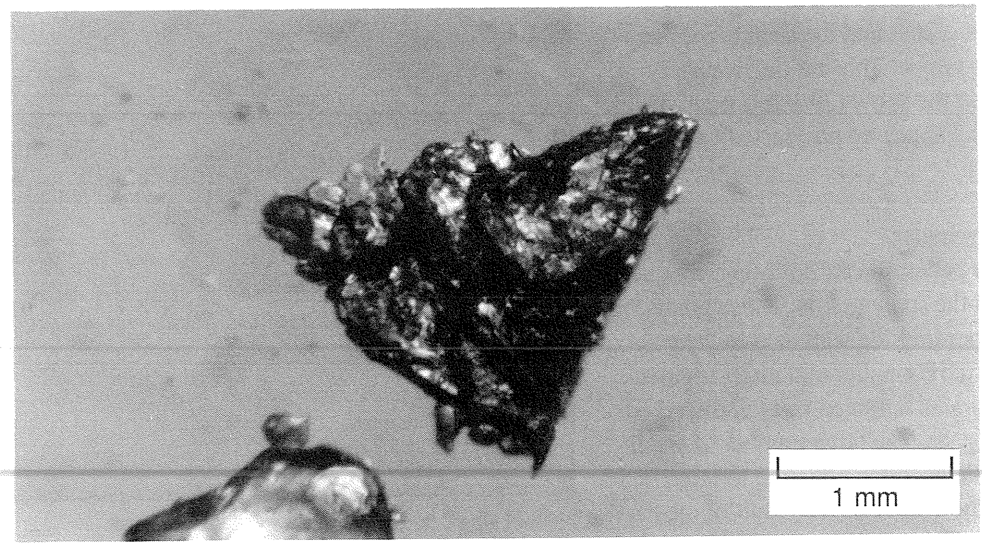


Figure 9. A grain from a shear/compressional zone (sample 13). The flat side was next to the penetrometer. The grain is made up of small fragments that have been frozen together.

crushed material (Fig. 9). In general, grains taken from this shear/compressional zone tended to be melt aggregates with incorporated crushed material, not the delicate melt structures mentioned below. We saw no additional evidence of melting when the cone was rotated in the snow rather than simply pushed into the sample.

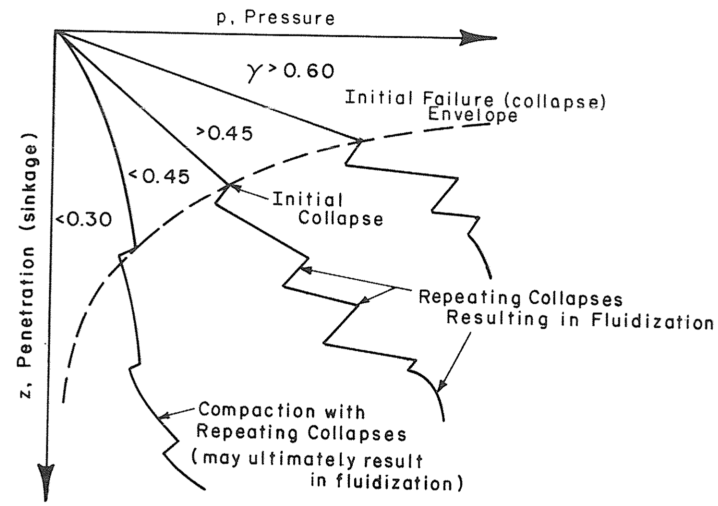


Figure 10. Progressive collapse response of snow to an applied load (after Abele, 1967).

Although the cone is equipped with a proving ring so that the applied load could be monitored (similar to the CBR tests), most of the samples failed in a progressive collapse mode, as is often the case in snow (Abele, 1967). In progressive collapse failure, the stress in the sample increases without failure until, suddenly, the snow collapses. The stress again increases until another collapse, and so on, as shown in Figure 10. This progressive collapse behavior interfered with observing the sheared surface along the penetrometer since much of the shear zone is destroyed during the collapse. To alleviate some of the compressional forces, and the destruction of the sheared particles, the cone was removed from the penetrometer rod and only the rod was pushed into the sample. This way, although progressive collapse occurred, the snow being sheared along the side of the rod was still intact. The grains found adhering to the metal penetrometer rod had flat surfaces with "lips" (Fig. 11), indicating that there was melting immediately adjacent to the rod, probably caused by friction or slight differences in the temperature between the rod and the snow, or both.

A rubber stopper was attached to the rod to determine if a material with a lower thermal conductivity would change the results. The snow grains deformed by the stopper were not noticeably different from those deformed with the metal penetrometer. This may be because of the the short duration of the test and the rapid collapse failure of the snow. To assure thermal melting, sample 7 was deformed with a warm cone. The result was a 1-mm thick, welded, conical snow structure formed around the cone.

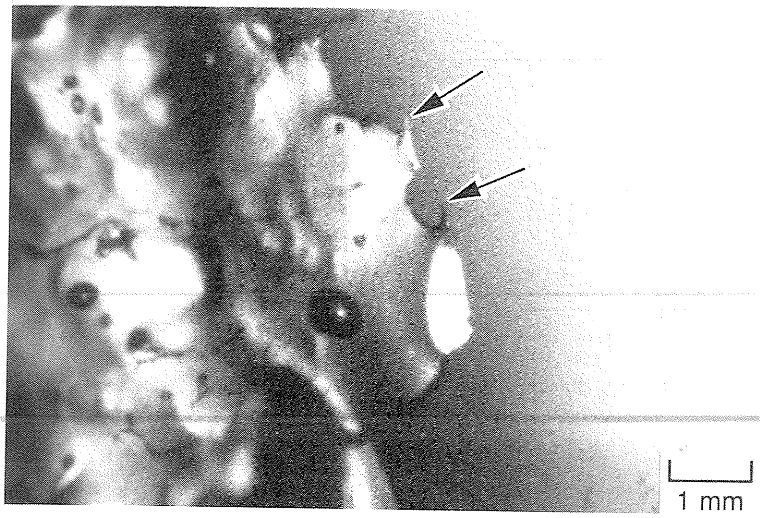


Figure 11. Grains adhering to the penetrometer rod showed delicate melt features such as these "lips" (sample 10).

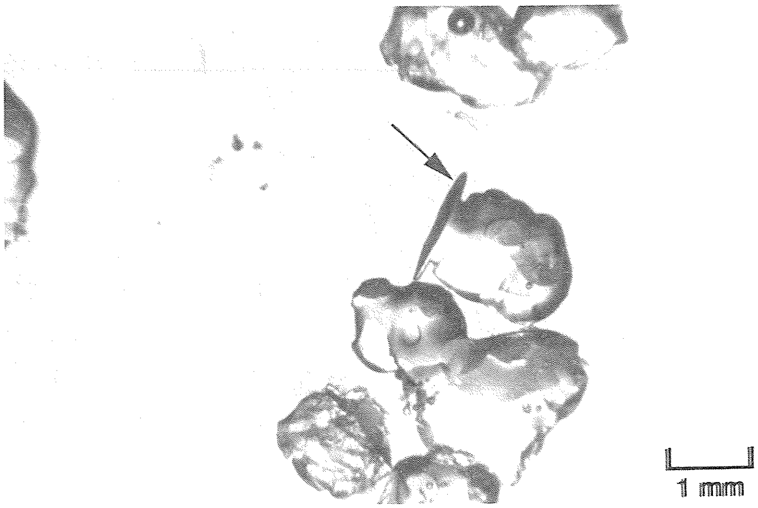


Figure 12. The disc shaped "hat" found in an undeformed part of sample 12 may have been formed during the storage of the snow, which was collected wet.

Although crushing was seen in all the deformed samples, unambiguous evidence of melting was difficult to find except immediately adjacent to the device. In addition, delicate melt-like structures termed "hats" (Fig. 12) were found in the undeformed portion of the samples and confounded our search for melt features produced by deformation. These "hats" may have formed during the storage of the snow, which was wet when collected.

Band Saw

To create shearing while minimizing compressional forces and to avoid the collapse type of failure, sample 10a was held lightly against a running band saw blade. Two tests were made, one for approximately 5 seconds and one for 1 minute. Both tests generated very flat, shinny surfaces with asymmetrical "hats" or "lips" bridging grains together (Fig. 13). These features indicate that melting took place. The band saw was located in a room set at –10°C and the temperature of the saw blade was measured immediately after each test (Table 1). Since the

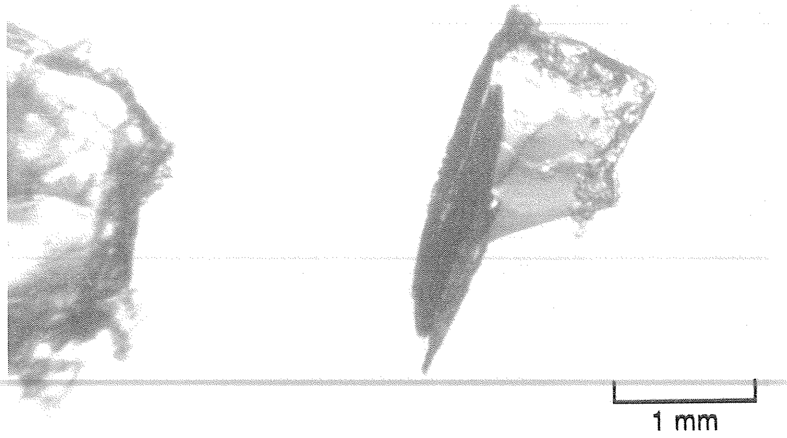


Figure 13. Flat surfaces and asymmetrical overhanging lips were seen when snow grains were subjected to shear forces from a band saw (sample 10a).

temperature was below –9°C, melting would be caused by heat of friction rather than the temperature of the device or pressure melting. The microscopic observations of the grains from the long and the short test looked essentially the same. To the eye, however, the surface exposed during the long test appeared smoother and shinier, indicating more melting.

SUMMARY AND CONCLUSIONS

Snow samples were deformed using a variety of instruments and methods at different temperatures to assess what type of deformation and conditions cause melting of the snow grains. After each deformation test, the samples were examined under a microscope, either in thin section or using individual grains taken from the sample. Of the observational techniques tried, looking at individual grains removed from the sheared surface proved the easiest and also the most informative. Of the three snow types tested, the snow that was collected during a spring snowfall (snow 2) had the most uniform, rounded grains.

In all of our tests, we found evidence for mechanical crushing of grains. A compressional force, like that exerted on the snow by a cone attachment on the penetrometer, tended to produce aggregates of crushed and melted material (Fig. 8 and 9). Immediately adjacent to the deformation instrument there is evidence of melting of the grains, and sometimes the snow would melt and refreeze on the equipment. Shearing in the absence of compressive forces was found to make very flat surfaces with melt "lips" (Fig. 11 and 13). Such localized melting would not have a great influence on the performance of machinery on snow unless the snow refroze to the equipment, as it sometimes did on our equipment, causing it to accumulate and clog.

Substantial melting occurred when large compressional forces were applied (in samples 1 and 2) or when the equipment was above freezing (sample 7). The cavity and ice bulb formed during the CBR tests at temperatures near –2°C may illustrate what happens when warm snow is compacted by vehicles or machinery. This process can be tested in the field by observing the deformation pattern as a vehicle passes and by taking samples of the deformed snow for microscopic observation. On the other hand, when older snow was tested at lower temperature (using the CBR device), no substantial deformation resulted. What was observed in the lab, although of a preliminary nature, indicates that substantial differences in vehicle and machine performance may occur, depending on whether the snow is warm (above –2°C) or cold.

Our greatest difficulty was obtaining a snow consisting of well-rounded and uniform, single grains. Snow 1 remained angular and nonuniform, even after having been left to metamorphose for months, at temperatures hovering just below 0°C. The angular and irregular nature of the snow grains made it difficult to see the effects of the deformation on the grains of snow 1. The spring snow (snow 2), because of its large, round grains, most clearly showed changes that occurred along the shear zone. However, the presence of "hats," which look like melt structures, in undeformed sections of the sample confounded our search for melt features produced by deformation. The origin of the very delicate "hat" structures seen in the undeformed parts of the spring snow sample is not understood but may have resulted from storing the wet snow. In general, however, grains taken from the shear zone tend to be melt aggregates with incorporated crushed material and not these more delicate structures. Future work should include devising a reproducible test snow.

ACKNOWLEDGMENTS

We thank Mr. Paul Richmond and Dr. Sam Colbeck for their helpful suggestions and three unknown reviewers for their comments.

REFERENCES

Abele, G., 1967, Deformation of Snow under Rigid Plates at a Constant Rate of Penetration. Masters Thesis for Michigan Technological University. Also USA Cold Regions Research and Engineering Laboratory, Research Report 273 (1970).

Abele, G., 1990, Snow Roads and Airfields. USA Cold Regions Research and Engineering Laboratory Monograph 90-3.

Abele, G. and A.J. Gow, 1976, Compressibility Characteristics of Compacted Snow. USA Cold Regions Research and Engineering Laboratory, CRREL Report 76-21.

Abele, G. and A.J. Gow, 1975, Compressibility Characteristics of Undisturbed Snow. USA Cold Regions Research and Engineering Laboratory, Research Report 336.

ASAE, 1985, Soil Cone Penetrometer. ASAE Standard: ASAE 313.2, American Society of Agricultural Engineers, St. Joseph, Michigan.

ASTM, 1989, Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils, ASTM Designation 1883-87, Annual Book of ASTM Standards, Section 4, volume 04.08, p. 241–248, American Society for Testing and Materials, Philadelphia, Pennsylvania..

Bader, H., 1962, The Physics and Mechanics of Snow as a Material. In Cold Regions Science and Engineering (F.J. Sanger, Ed.). USA Cold Regions Research and Engineering Laboratory, Cold Regions Science and Engineering Monograph IIB.

Colbeck, S.C., A. Shaw and G. Lemieux, 1978, The Compression of Snow. USA Cold Regions Research and Engineering Laboratory, CRREL Report 78-10.

Colbeck, S.C., 1988, The Kinetic Friction of Snow. *Journal of Glaciology*, **4**(116): 78–86.

de Montmollin, 1982, Shear Tests on Snow Explained by Fast Metamorphism. *Journal of Glaciology*, **28**(98): 187–198.

Hobbs, P.V., 1974, *Ice Physics*. Clarendon Press, Oxford, 837 p.

McClung, M., 1977, Direct Simple Shear Tests on Snow and Their Relation to Slab Avalanche Formation. *Journal of Glaciology*, **19**(81): 101–109.

Richmond, P.W. and G.L. Blaisdell, 1981, A Macroscopic View of Snow Deformation under a Vehicle. USA Cold Regions Research and Engineering Laboratory, Special Report 81-17.

Stehle, 1970, Snow Compaction—Investigation of Metamorphosis of Snow. NCEL Technical Report 706.

Warren, G.C, S.C. Colbeck and F.E.Kennedy, 1989, Thermal Response of Downhill Skis. USA Cold Regions Research and Engineering Laboratory, CRREL Report 89-23.

Watanabe, 1974, A Method of Making Thin Sections of Deposited Snow by Mixed Solution. *Journal of the Japanese Society of Snow and Ice*, **36**(3).