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Scientific note

Experimental results on the formation of hard compacted snow in Rikubetsu in northern Japan: A first step toward the construction of a compacted-snow runway on the Antarctic ice sheet

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Abstract: This paper describes the experimental methods and results on the formation of hard compacted snow in Rikubetsu in northern Japan during the winter of 1999. This basic research was the first step towards the construction of a compacted-snow runway on the Antarctic ice sheet. In Rikubetsu, we constructed three test fields (20 m in length, 7 m in width, and 0.4–1.0 m in thickness) on compacted basal snow (approximately 0.05 m in thickness). First, 0.1–0.35-m-thick layers of snow were deposited on the basal snow of the fields using a rotary snowplow. Next, the surface snow was smoothed using an excavator. Finally, the snow layers were compacted four times using a bulldozer. This entire process was repeated three to four times in order to construct 0.4–1.0-m-thick test fields. The ram hardness, snow density, and snow structure of these fields were investigated. A comparison with the criteria established by a U.S. scientist for a large aircraft—such as the C-130 (Abele, 1990)—revealed that if snow in the form of three 0.2–0.25-m-thick layers is compacted four times by a bulldozer, it is sufficiently hard to serve as a runway at H68 (69°11′29″S, 41°03′34″E, 1204 m a.s.l.) for a wheeled C-130. The Japanese Antarctic Research Expedition plans to conduct a feasibility study on the construction of the hard compacted-snow runway at this location.

key words: compacted-snow runway, experimental results in Rikubetsu, Antarctic ice sheet

1. Introduction

Recently, Antarctica has become the focal point of global environmental issues because the global environment can be monitored and observations relevant to changes in the global environment can be made at this location. Therefore, the Japanese Antarctic Research Expedition (JARE) considers that it is important to construct a runway near their main research station—"Syowa Station" (69°00′S, 39°35′E)—for the efficient transportation of scientists and equipment from Japan. However, in Syowa Station, which is located on a small island (East Ongul Island) and 4 km from the East

Antarctic ice sheet, it is difficult to locate a sufficiently wide and flat landing area (*ca*. 3 km in length and 100 m in width for the Lockheed C-130 Hercules). Moreover, the campaign "Preservation of Natural Environment in Antarctica" (*e.g.*, Bonner, 1994) is an obstacle to build even a small runway on the ground in Antarctica. Thus, we must find a suitable location on sea ice, glacial ice, or snow.

Since 1947, compacted-snow runways near Little America IV on the Ross Ice Shelf have been used by the U.S. Antarctic Program (Moser, 1963). Currently, such runways are widely used on ice sheets in Antarctica and Greenland. Several works have been published on the construction of compacted-snow runways (*e.g.*, Moser, 1963; Wuori, 1963; Gow and Ramseier, 1964; Moser and Sherwood, 1967; Aver'anov *et al.*, 1985; Lee *et al.*, 1988; Russell-Head and Budd, 1989; Abele, 1990; Klokov and Shiraishi, 1997; Blaisdell *et al.*, 1998). Abele (1990), in particular, summarized all the successful techniques for constructing and maintaining compacted-snow runways and provided the strength criteria for compacted-snow runways to support several types of wheeled aircrafts (DHC-2, C-7, C47, C-130, KC-135, and C-141). Klokov and Shiraishi (1997) suggested a simple method for the construction of these runways. Thus, we conclude that the construction of compacted-snow runways on the ice sheet near Syowa Station is a feasible solution.

In this paper, we summarize the experimental results with regard to the construction of a hard compacted-snow layer (20 m in length, 7 m in width, and 0.4–1.0 m in thickness). These experiments are the first step toward the construction of compacted-snow runways on the Antarctic ice sheet for a large wheeled aircraft. The preliminary results of these experiments have already been published in Kameda *et al.* (2000).

2. Experimental method

2.1. Construction of test fields

The experiments were conducted from January 15 to February 28, 1998, and January 16 to February 20, 1999, in the Kamitomamu area, Rikubetsu, Hokkaido, Japan (Fig. 1). The experimental methods employed in both the years are basically the same as that of Klokov and Shiraishi (1997): snow deposition by a rotary snowplow

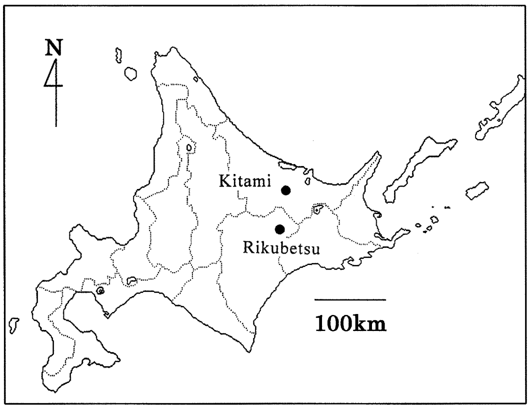

Fig. 1. Locations of Rikubetsu and Kitami in Hokkaido, northern Japan.

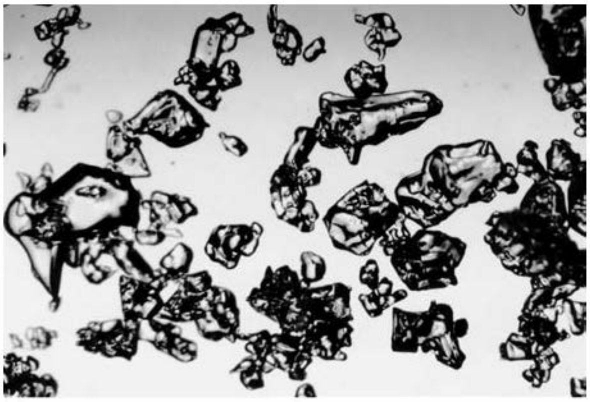

Fig. 2. Snow particles used in the experiments.

followed by compaction of the deposited snow using a bulldozer. Additionally, we used an excavator for surface smoothing just after the deposition of snow by the rotary snowplow. The snow was deposited on compacted basal snow (approximately 0.05 m in thickness and compacted using the bulldozer). Most of the snow used in these experiments was composed of small and solid faceted particles in a dry condition, as shown in Fig. 2. The grain size of these particles ranged from 0.5 to 2.0 mm, which corresponds to medium to coarse according to the international classification of seasonal snow by Colbeck *et al*. (1990).

In 1998, we conducted some preliminary experiments on the formation of hard compacted snow using a rotary snowplow (Fig. 3a; type HK-130, Kaihatsu Nohki Co. Ltd., Japan), excavator (Fig. 3b; type PC-40, Komatsu Ltd., Japan), and bulldozer (Fig. 3c; type DSC, Caterpillar Mitsubishi Co. Ltd., Japan; caterpillar pressure of 0.027 MPa under static conditions). We found that the time interval between snow deposition and snow compaction is important. When the bulldozer was used for snow compaction soon after deposition by the rotary snowplow, the snow layer was broken and sufficient hardness was not achieved. Thus, compaction must be performed at least 1 hour after the deposition. We think that the snow-sintering process, in which snow particles connect to each other, governs the hardening process. From these preliminary experiments, it was also found that the snow needed to be compacted four times in order to support large aircrafts such as a wheeled C-130 Hercules, as suggested by Abele (1990).

In 1999, we performed experiments by constructing three test fields—A, B, and C (20 m in length and 7 m in width)—with the same method used in 1998. First, 0.1–0.35-m-thick layers of snow were deposited on the fields using a rotary snowplow (0.1-m-thick layer for test field A; 0.2–0.25-m-thick layer, B; and 0.30–0.35-m-thick layer, C). The surface snow was then smoothed using an excavator bucket. One hour later, the snow was compacted four times using a bulldozer. This process was repeated three (B and C) to four (A) times at seven-day intervals. The interval period of seven days

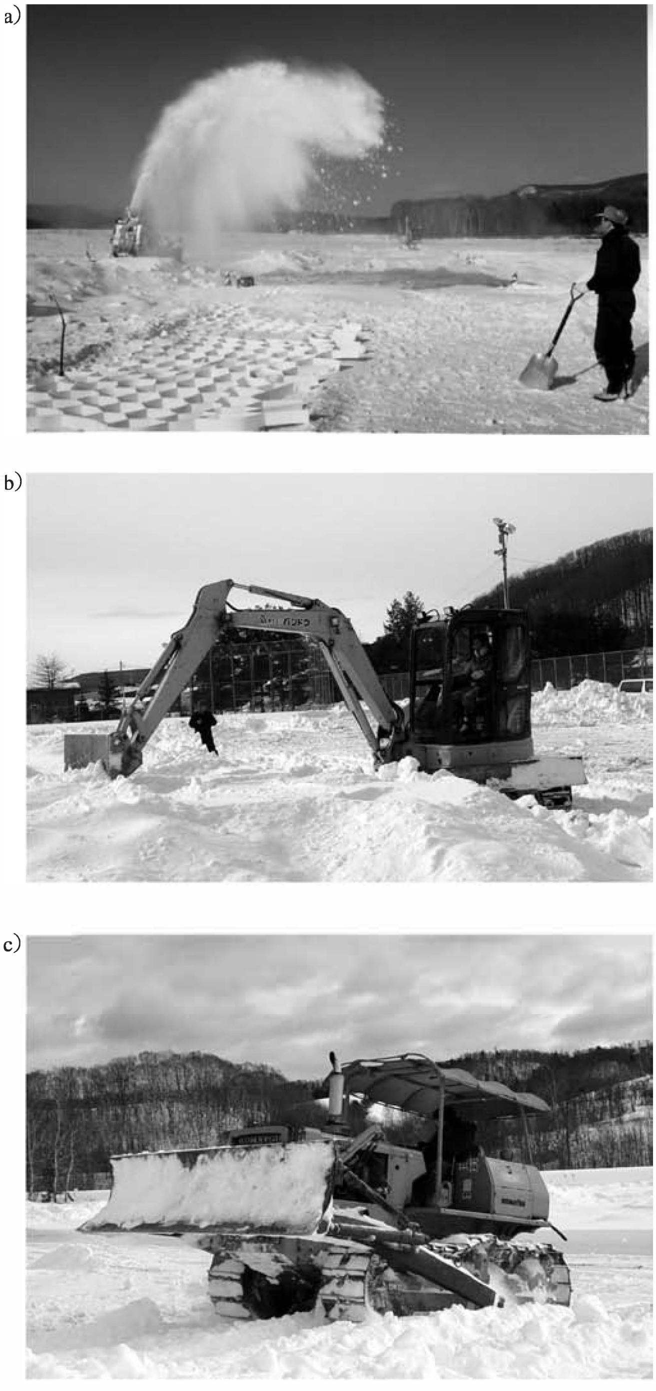

Fig. 3. (a) Rotary snowplow, (b) excavator, and (c) bulldozer used in the experiments conducted in 1998 and 1999.

has no significance; we could use the machines only on weekends. The snow surface was smoothed immediately after deposition using the excavator bucket. The smoothing was performed carefully to ensure that the bucket does not compress the surface snow. All the test fields were carefully compacted four times based on the experiments conducted in 1998. The time taken for compaction was approximately 1 hour. Tests fields B and C were formed on January 30 and test field A on February 6, and the snow was compacted four times at seven-day intervals on February 7, 14, and 20.

2.2. Hardness, density, and structure of deposited snow

The snow hardness was measured using the “rammsonde”, which is commonly used to quantify the hardness of compacted-snow runways (*e.g.*, Abele, 1990). The rammsonde is a cone penetrometer comprising a hollow, 2-cm-diameter steel shaft with a 60° conical tip. The tip penetrates the snow due to the free fall of the hammer (typically 3 kg) along the guide shaft of the rammsonde. The ram hardness (R) was calculated from the following expression given by Ueda *et al.* (1975):

$$R = Whn/x + Q + W,$$

where R = ram hardness (kg), W = weight of the hammer (kg), h = lift of the hammer (cm), n = number of hammer blows, x = penetration after n falls (cm), Q = weight of the rammsonde (kg). We measured the ram hardness of the test fields from top to bottom at 0.05 m intervals.

Bulk snow samples (cross section of approximately 0.2 m × 0.2 m) obtained from the three test fields on February 20 were transported using an insulation box to a cold room in the Kitami Institute of Technology (KIT). KIT is located approximately 40 km northeast of Rikubetsu, and the transportation from Rikubetsu to KIT takes about an hour. As the air temperature was below 0°C during the transportation of snow samples from Rikubetsu to KIT, the variations observed in its structure were minimum. In the cold room, the samples were cut into rectangles (average volume of 200 cm^3) using a band saw. The snow densities of the samples were measured on February 21 with a measure (minimum reading of 1 mm) and an electronic balance (minimum resolution of 0.1 g; type EL-500, Shimadzu Co. Ltd., Japan). The maximum error in the measurements is $\pm 1\ kg\ m^{-3}$.

The aniline thin section method developed by Kinoshita and Wakahama (1959) was employed for preparing the thin sections in the cold room.

3. Meteorological conditions in Rikubetsu during experiments and comparison with East Antarctic sites

During the experiments conducted in 1999, the air temperature near the test fields was recorded at a height of 1.5 m, as shown in Fig. 4a. The snow temperatures at six heights from the top of the basal snow layer in test field C are also shown in Fig. 4b. This test field was formed layer by layer on January 16, 23, and 30, and the collection of snow temperature data at the six heights was started on January 16, 25, and 30, respectively (the starting date for snow temperature measurements at heights of 0.4 m and 0.55 m was delayed by two days, *i.e.*, January 25 instead of January 23).

Table 1 lists the average air temperature in Rikubetsu during the experiments, the average snow temperature in test field C, and the average air temperature at two East Antarctic sites from December to January. Since JARE plans to conduct a feasibility study on the construction of hard compacted-snow runways at S17 (69°01′32″S, 40°04′58″E, 608 m a.s.l.) and H68 (69°11′29″S, 41°03′34″E, 1204 m a.s.l.) (Shiraishi and Klokov, 1997; Takahashi *et al*., 2003), we compared the air temperature conditions at Rikubetsu with those at the two East Antarctic sites.

S17 is located 1 km south of S16—the location from which JARE snow vehicles begin their expedition to the inland Antarctic ice sheet. Therefore, S17 is convenient

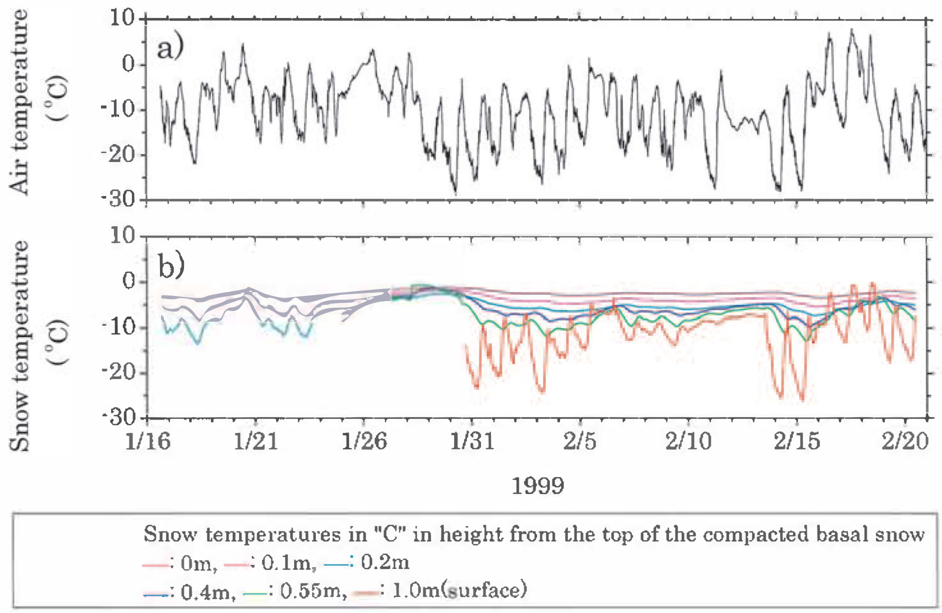

Fig. 4. Air temperature at a height of 1.5 m (a) and snow temperature (b) during the experiments in Rikubetsu. The heights from the compacted basal snow layer are shown.

Table 1. Average air ($\bar{T}_a$) and snow ($\bar{T}_s$) temperatures in Rikubetsu during the experiments conducted in 1999, and the average air temperatures at S17 and H68 from December to January 1973–1982. Average snow temperatures at three heights from the basal snow layer in test field C are shown.

Site name (period)	$\bar{T}_a$ (℃)	$\bar{T}_{s(1.0\,m)}$ (℃)	$\bar{T}_{s(0.55\,m)}$ (℃)	$\bar{T}_{s(0.1\,m)}$ (℃)
Rikubetsu, Japan (Testing period in 1999)	−10.4	−11.5	−6.9	−4.1
S17, East Antarctica (December to January 1973–1982)	−5.7	—	—	—
H68, East Antarctica (December to January 1973–1982)	−10.3	—	—	—

for the construction of a compacted-snow runway. On the other hand, H68 is located at a small convex point on the ice sheet, and its average annual snow accumulation is relatively low (annual snow accumulation of 130 mm from January 1993 to January 2001 according to the data of Motoyama *et al.* (1995), Shiraiwa *et al.* (1996), Azuma *et al.* (1997), Fujita *et al.* (1998), Motoyama *et al.* (1999), and Furukawa *et al.* (2002)). This low accumulation rate is suitable for the maintenance of compacted-snow runways. The average air temperatures at S17 and H68, as shown in Table 1, was calculated using the monthly mean air temperature from December to January 1973–1982 at Syowa Station (69°00′S, 39°35′E, 21 m a.s.l.) and Mizuho Station (70°42′S, 44°20′E, 2260 m a.s.l.) (National Institute of Polar Research, 1985) assuming a constant lapse rate between the two stations in each month. The monthly mean air temperature during this period was selected because most of the operations by aircrafts in Antarctica will be carried out during this summer season.

As evident from Table 1, the average air temperature in Rikubetsu during the experiments in 1999 is lower than that at S17, but similar to that at H68. However, since we do not have any data on the snow temperatures at S17 and H68, it is difficult to draw a comparison between these temperatures. S17 is located in the percolation zone, where 10–20-mm-thick ice layers were sometimes observed in the surface snow strata due to the refreezing of surface melt water (Watanabe, 1972); thus, the maximum snow temperature near the surface increases to 0°C in summer. The strong solar radiation in summer contributes to an increase in the snow temperature near the snow surface. On the other hand, H68 is located just above the percolation zone, where ice layers are rarely observed (Watanabe, 1972; Takahashi *et al.*, 2003); thus, the maximum snow temperature is less than 0°C. Since we did not find any thick ice layers in the three test fields in Rikubetsu, the snow temperature condition in this study is considered to be similar to that at H68, but probably lower than that at S17.

4. Results and discussions

4.1. Ram hardness, snow density, and snow structure in test fields A, B, and C

Figure 5 shows the time series of the ram hardness profiles for the three test fields —A, B, and C—just after the snow is compacted four times each day using the bulldozer. Each profile represents the average of two measurements. The heights from the top of the compacted basal snow layer are shown in this figure. The snow layers labeled (a) to (d) were deposited on January 16, 23, and 30 and February 7, respectively. Layer (d) was formed only on test field A to increase its thickness to approximately 0.4 m. The time and date of the ram hardness measurements are shown within parentheses.

It was found that in general, the ram hardness increased with time due to the compaction by the bulldozer, densification of the overlying snow, and the aging effect caused by the thickening of ice bonds between snow grains. The ram hardness, however, decreased in some cases (*e.g.*, upper part of layer (b) in test field C from February 7–14). This was probably caused due to the inadequate formation of hard compacted snow in areas that were not compressed sufficiently. The ram hardness showed the maximum at a distance of 0.05–0.1 m below the snow surface. This is

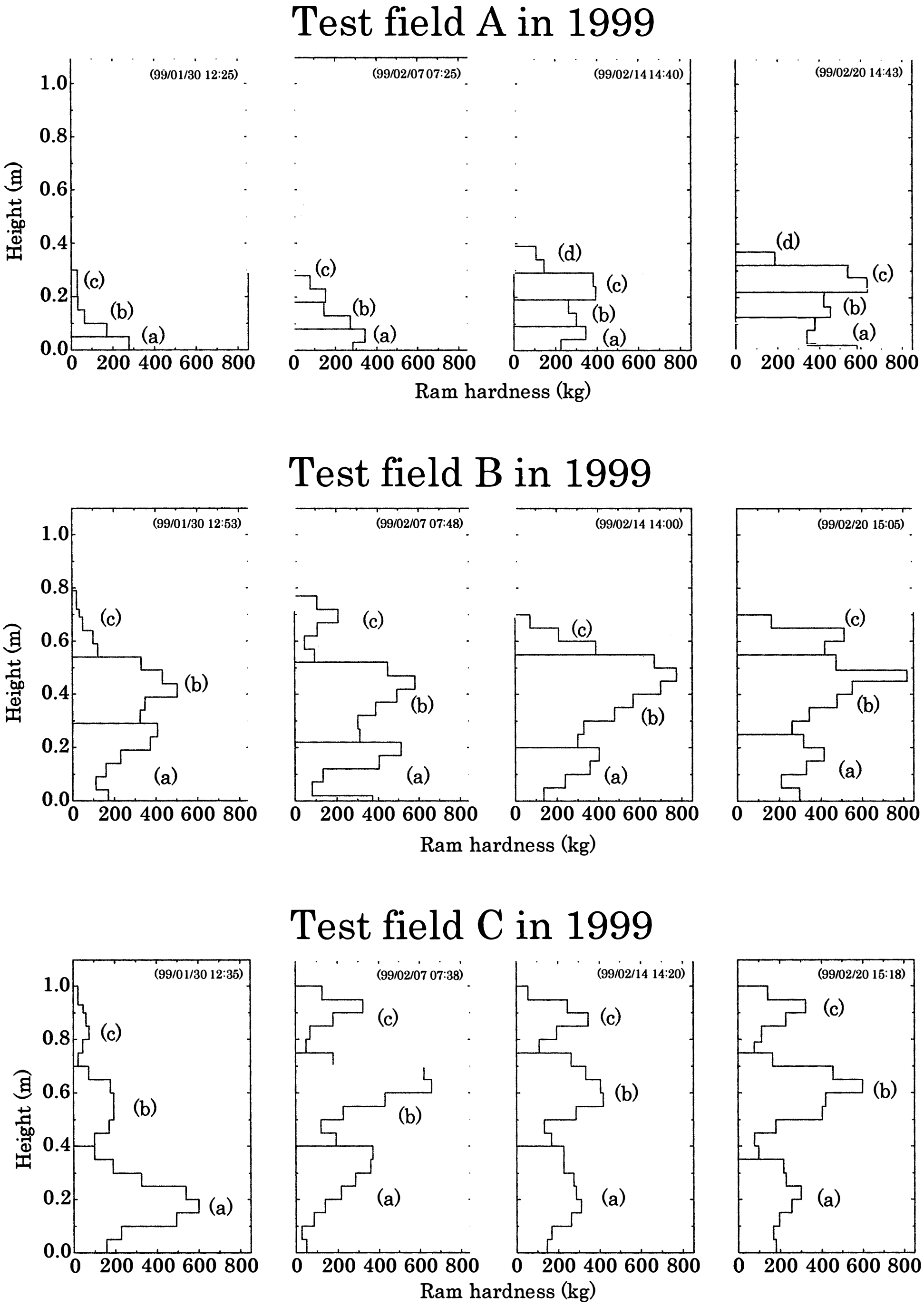

Fig. 5. Ram hardness profiles for test fields A, B, and C in 1999. Snow layers labeled (a) to (d) were deposited on January 16, 23, and 30 and February 7, respectively.

probably because the surface snow layer was mixed by the 0.05-m-long pawls of the bulldozer, thus leading to ineffective compression of the snow layer. Although the air temperature exceeded 0°C during the experiments, we did not observe any significant ice layers (>1 mm in thickness) in the test fields, and the layers with high ram hardness consisted solely of snow.

Figure 6 shows the snow densities of test fields A, B, and C on February 20. The average snow densities were 488, 494, and 518 kg m^{-3}, respectively. The heights above the compacted basal snow layer are also shown. These high densities were achieved by allowing the snow to fall freely from a height of approximately 3 m using a rotary snowplow (Fig. 3a) and by compacting it four times using a bulldozer (Fig. 3c). The low-density regions in test field C indicated by the arrows in Fig. 6 correspond to mechanically weak layers detected by the rammsonde. We think that these less compacted and mechanically weak layers were formed due to the deposition of thick snow layers (0.3–0.35 m) by the rotary snowplow. Because the pressure applied by the bulldozer at the snow surface decreased with the distance from the surface, these weak layers were formed.

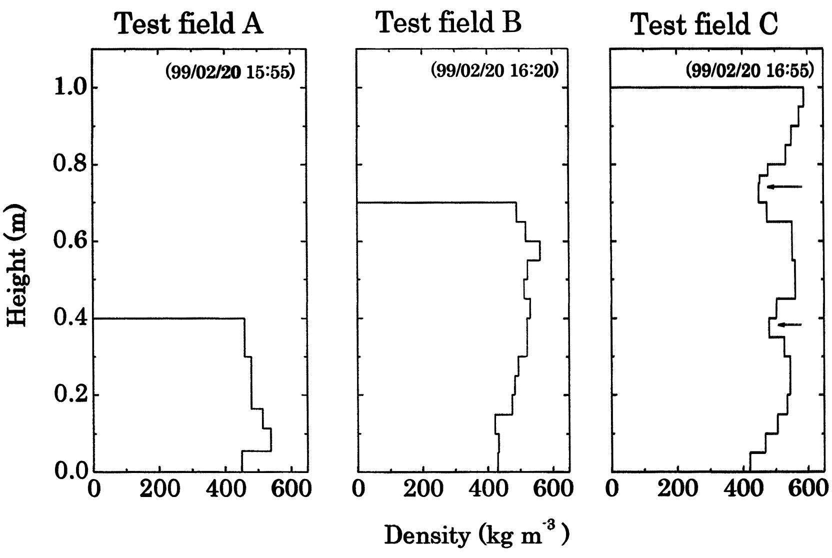

Fig. 6. Snow density distribution of test fields A, B, and C on February 20, 1999.

Figure 7a shows the snow structures at a height of 0.6 m above the basal snow layer in test field B, which was prepared by the aniline thin section method (Kinoshita and Wakahama, 1959) and from the same samples used for the density measurements. As shown in this figure, the snow particles are connected to form a network of small ice particles. Figure 7b shows the magnified view of the snow structure of the same sample. Further, the networks of bonded ice particles are clearly observed in this figure. These networks and the high density of snow layers are the main reasons for the high ram hardness observed in our test field. Thus, in order to construct a compacted-

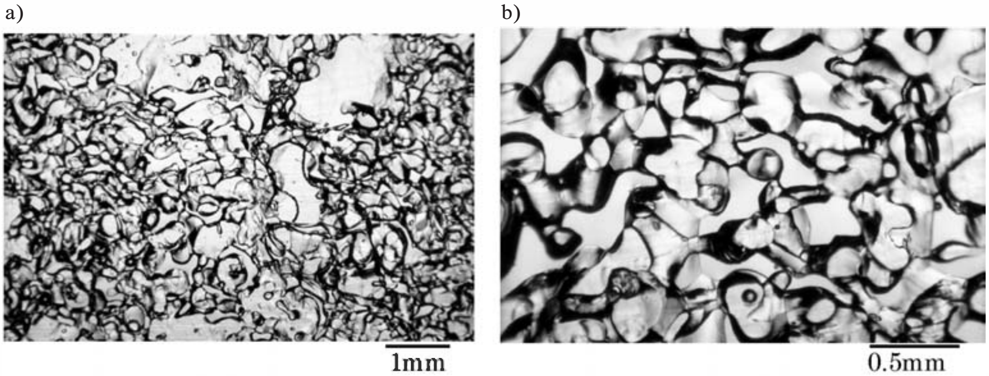

Fig. 7. Microscopic photograph of a hard compacted-snow layer. (a) Snow structure at a height of 0.2 m in test field B and (b) magnified view of the photograph shown in (a).

snow runway on the Antarctic ice sheet, it is essential to produce high-density snow layers with connected ice particles, as shown in Fig. 7b.

4.2. Feasibility of the construction of snow runways in East Antarctic sites

U.S. and Russian scientists have examined the criteria for the safe landing and takeoff of aircrafts on the compacted-snow runways in Antarctica and Greenland. Using a large amount of experimental data, Abele (1990) determined the snow hardness

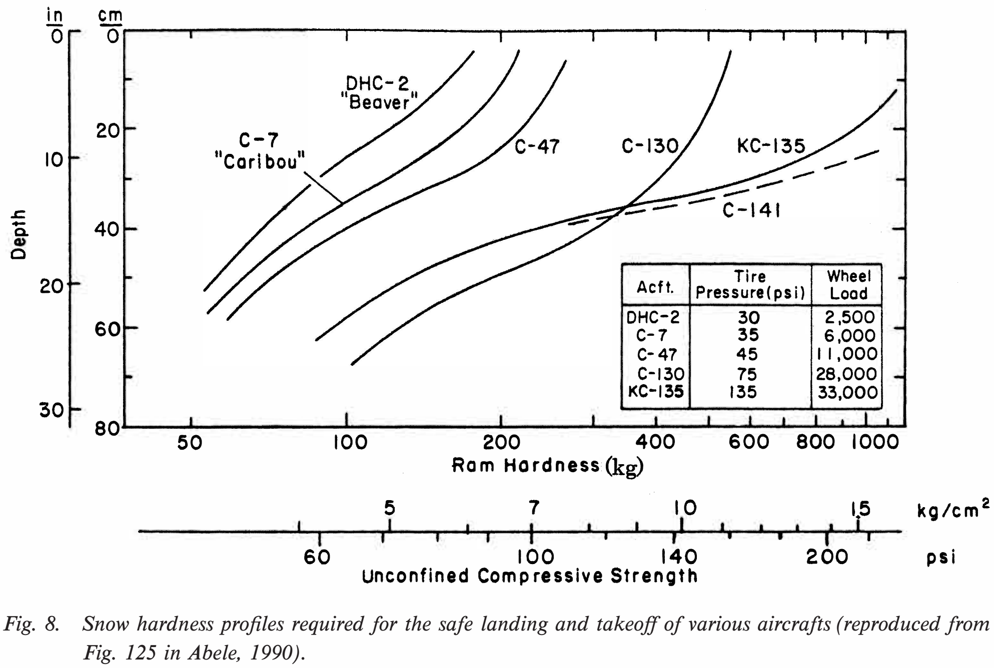

Fig. 8. Snow hardness profiles required for the safe landing and takeoff of various aircrafts (reproduced from Fig. 125 in Abele, 1990).

profiles required for the safe landing and takeoff of various aircrafts (Fig. 8). It is clear that the minimum thickness of the compacted-snow layer for the landing of a wheeled C-130 is about 70 cm. Figure 9 compares our final results (February 20, 1999) for the three test fields with the profile of the C-130 shown in Fig. 8. It is evident that the snow hardness profile of test field A is larger than that required for the C-130, but the thickness is insufficient. This is because test field A was constructed from four 10-cm-thick snow layers. The profile of test field B nearly coincides with that required for the C-130. On the other hand, the profile of test field C is generally smaller than that required for the C-130, because it was constructed from 0.3–0.35-m layers that were relatively thick and contained mechanically weak layers to some extent.

Since the average air and snow temperature conditions of the experiments in Rikubetsu are similar to those at H68 during the period from December to January, we can conclude that the parameters of test field B (deposition of 0.2–0.25-m-thick snow layers that are compacted four times using a bulldozer) are the optimum conditions for constructing a compacted-snow runway at H68 for a large wheeled aircraft (*e.g.*, C-130 Hercules). However, in order to construct a hard compacted-snow runway at H68, we must take great care not to form less compacted and mechanically weak layers during the formation of the hard compacted layer. This is the key issue to construct a hard compacted-snow runway on the ice sheet.

If we apply this result to a warmer place such as S17, the procedures applied in test field B will be sufficient. On the other hand, if we apply these results to a colder place on the Antarctic ice sheets, a more effective compaction method should be employed. For example, (1) the thickness of the snow layer deposited using the rotary snow plow should be reduced (less than 0.2 m), (2) a higher snow compaction pressure should be

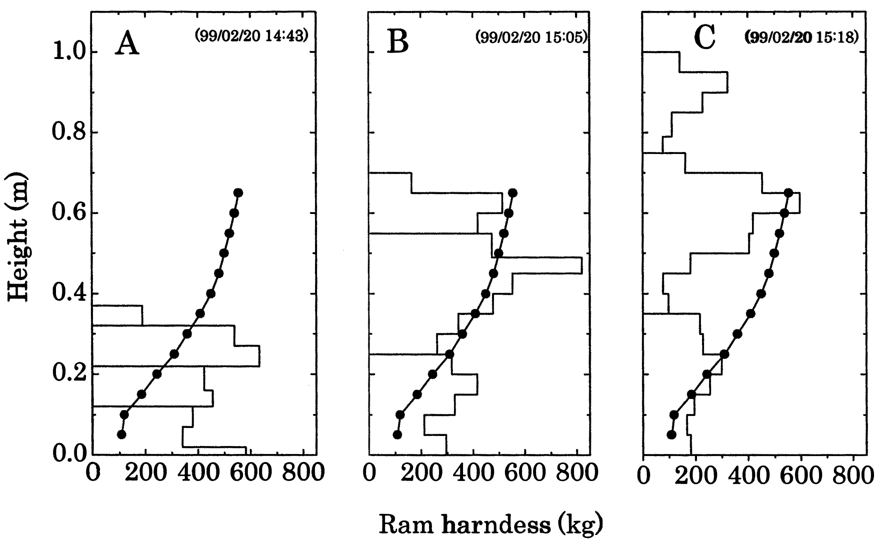

Fig. 9. Comparison of our final results for test fields A, B, and C obtained in 1999 with the profile of the wheeled C-130 shown in Fig. 8 (line with solid circles).

applied using a special type of bulldozer, (3) the number of compaction processes should be increased, and (4) the snow temperature should be increased by providing additional heating.

5. Concluding remarks

We constructed a 0.4–1.0-m-thick hard compacted-snow runway using a rotary snowplow, excavator, and bulldozer during the winter of 1999 in Rikubetsu, Japan. In order to satisfy the criteria by Abele (1990) for constructing a compacted-snow runway for a large wheeled aircraft (*e.g*., C-130 Hercules), the maximum height of the deposited snow layers using the rotary snowplow should be 0.2–0.25 m, and the snow should be compacted four times using a bulldozer. This whole process should be repeated at least three times to obtain hard compacted snow with a thickness of 0.7 m. Since the air and snow temperature conditions during the experiments were similar to those at H68 (1204 m a.s.l.)—located on the East Antarctic ice sheet—from December to January, we can conclude that the above mentioned procedures are applicable at H68, where JARE plans to conduct a feasibility study on the construction of hard compacted-snow runways.

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