Chinese Journal of Polar Science, Vol. 14, No. 1, 12 - 23, June 2003

Densification and grain coarsening of melting snow

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Receive June 1, 2001

Abstract A field work was conducted at Moshiri in Japan. The work included intensive snow pit work, taking snow grain photos, recording snow and air temperatures, as well as measuring snow water content. By treating the snow as a viscous fluid, it is found that the snow compactive viscosity decreases as the density increases, which is opposite to the relation for dry snow. Based on the measurements of snow grain size, it is shown that, similar to the water-saturated snow, the frequency distributions of grain size at different times almost have the same shape. This reveals that the water-unsaturated melting snow holds the same grain-coarsening behavior as the water-saturated snow does. It is also shown that the water-unsaturated melting snow coarsens much more slowly than the water-saturated snow. The *C* value, which is the viscosity when the snow density is zero, is related to the mean grain size and found to decrease with increasing grain size. The decreasing rate of *C* value increases with decreasing grain-coarsening rate.

Key words Melting snow, densification, grain coarsening.

1 Introduction

Snow densification is critical for calculations in engineering glaciology, snow avalanche forecasting, spring flooding, and other practical aspects. It is also important for interpreting ice core data including those taken from rather warm sites where surface layers experience melting, since it would affect the change of annual layer thickness with time. While extensive studies(e. g. Anderson and Benson 1963; Bader 1960, 1962; Kojima 1954, 1955, 1956, 1957, 1958, 1959, 1964; Keeler 1967; Gow 1975; Maeno and Ebinuma 1983; Qin 1990; Sturm and Holmgren 1998) have been reported on the densification of dry snow, few have been done in the densification of wet snow.

The rate of densification is generally considered to be a function of a variety of factors such as overburden load, density *per se*, snow temperature, grain size(including the distribution characteristics), liquid-water content and so on. They vary with time and height in a snowpack, so each layer has a unique loading history and a set of environmental conditions under which it compacts. They overlap and act on a given layer, and therefore it is very difficult to make clear the relations among them.

One of the methods is to treat all of these factors together by assuming that the snow behaves as a viscous fluid with a compactive viscosity. This work is to examine the relationship between the compactive viscosity and the density of the melting seasonal snow. Further analyses are also carried out on both the distribution characteristics of the particle size, and the relationship of the compactive viscosity with the grain size.

2 Methods

The field work was conducted at Snow Melting Research Station of Hokkaido University, Moshiri(44°23′N, 142°17′E), in the northern part of Hokkaido, Japan, where the snowpack was as thick as 180.1 cm on February 14 and its recorded lowest temperature was −17.3°C on February 7, 1998. On February 26, 1998, in the plain plot of the station, when the depth of the snowpack was 144 cm, 8 temperature sensors were inserted into a pit wall (filled after insertion) at different heights to record snow temperature variations throughout the observation period.

At a neighboring site, successive pits were dug almost every day from March 25 on which the whole pack became 0°C and its depth was 125 cm, to April 15 on which the depth of the pack was 41 cm and the field work ended. The pit work included: stratigraphical observations; snow temperature measurements by a portable sensor; snow sampling by a $4\times6\times7$ cm^3 sampler with a thickness of 4 cm continuously from the surface to the bottom of the pack; separating water from the snow by using a hand-driven centrifuge and measuring the water content of snow at different heights with a dielectric moisture meter; weighing snow samples, and taking particle photos of each sample using a camera with a magnifying lens.

By using the photos, the grain size of each sample was measured manually. On the average, about 20 particles were measured for each sample.

In order to calculate the densification, the snowpack has to be divided into layers. Although the landform of the experimental plot is rather plain, there are still fluctuations of several centimeters between two successive pits. Therefore, it is critical to identify the correspondent layers for different pits. Fortunately, there were slightly developed ice layers and some other stratigraphic marks like slightly-dark-colored stripes in the snowpack. They are used for the comparisons of different pit walls.

From the stratigraphical records(Figure 1), it is noted that the snow layers densified very slowly. For example, the range of thickness variations of the layer 16–78 cm(on Mar 25) was 6.5 cm. Therefore, in dividing the pack into layers, it is essential to keep a single layer thick enough so that the trend of densification is perceivable when comparing layers measured at different sites. Based on the stratigraphical records, the snowpack is divided into 5 layers. On March 25, heights of the layers(Figure 1) were

Layer A(LA): 94.5–122.5 cm;
Layer B(LB): 78–94.5 cm;
Layer C(LC): 40–78 cm;

Layer D(LD) : 16– 40 cm;

Layer E(LE) : 0– 16 cm.

The boundaries among LA, LB and LC were two ice layers. The boundary between LD and LE was a very clear line because LE was depth hoar which had a fragile structure and larger. As for the boundary between LC and LD, actually there was no very clear line as the ones above. Since the layer 16-78 cm(Mar. 25) was thick, and there were some differences, between its upper and lower part, in density (Figure 2) and grain size (Figure 3) , a line at the height of 40 cm was assumed to divide the layer into LC and LD throughout the period.

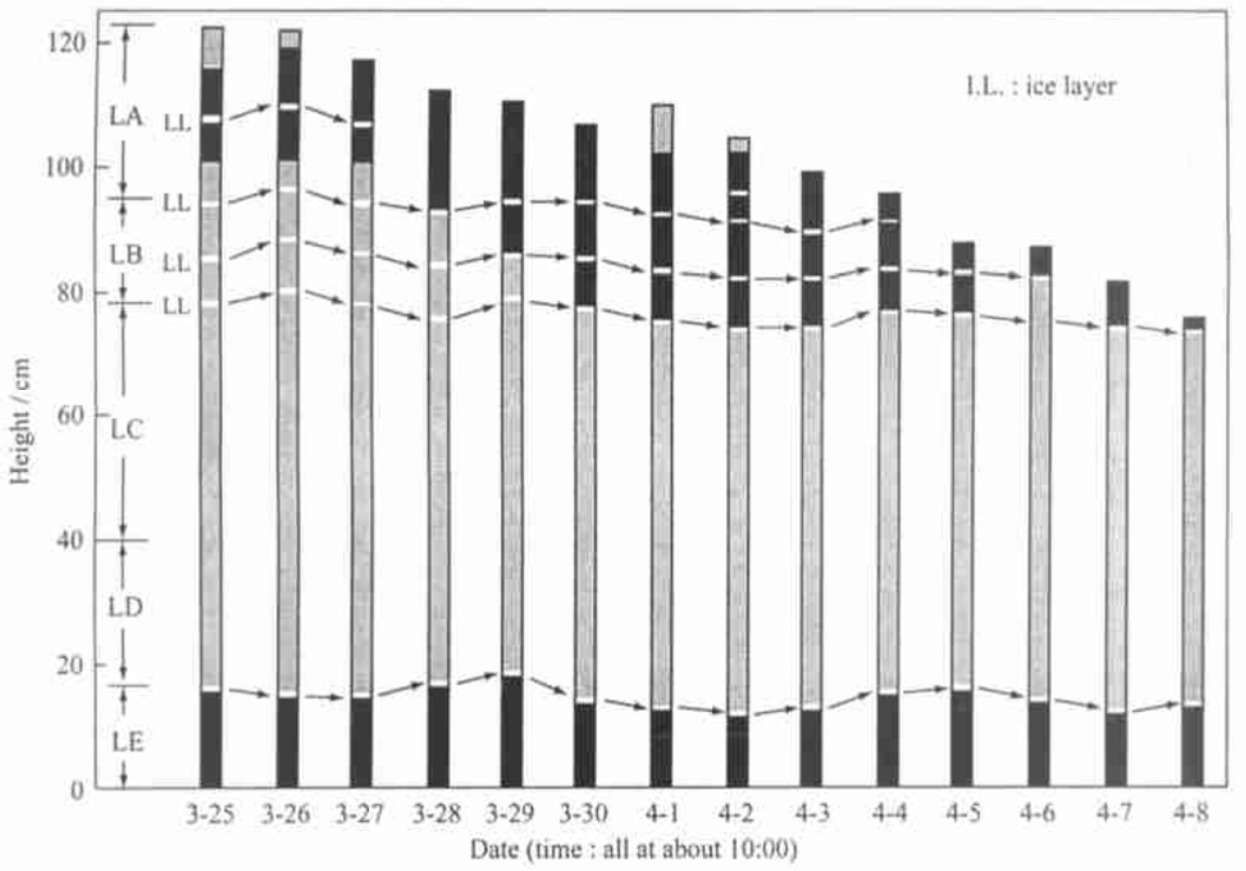

Fig. 1. Simplified sequence of developing stratigraphy. The light-colored parts show particle size not larger than 1 mm, the dark parts larger than 1 mm.

Since there were daily melt-freeze cycles at the surface of the snowpack during the melting season, only the layers beneath it were chosen for further analyses.

Temperature records of the above-mentioned sensors and the air temperature records provide the information of the frozen depths. Based on the records, it is determined that LC, LD and LE kept a constant temperature of 0°C until April 8 and LB kept until April 1. Since the thickness of LE varied by several centimeters among the pits because of landform fluctuations and there was a light melting at the bottom of LE because of the heat flux from the earth(Kojima and Motoyama 1985) , LE is less suitable for the study of densification, therefore LB(till April 1) , LC and LD(till April 8) are chosen for the next steps.

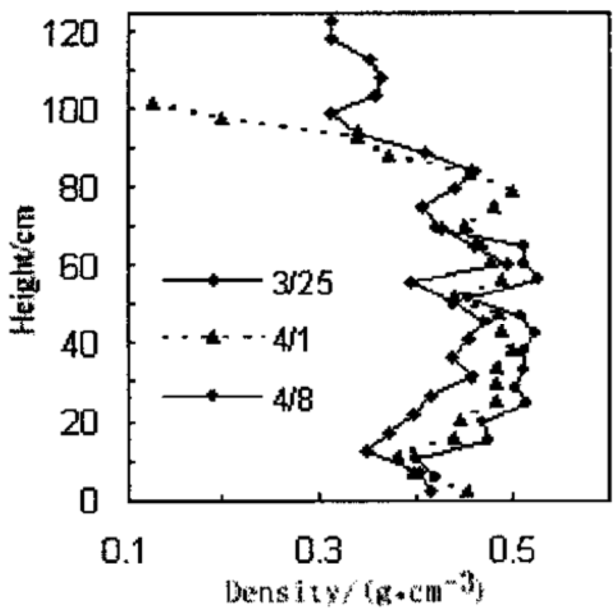

Fig. 2. Density evolution of the snowpack.

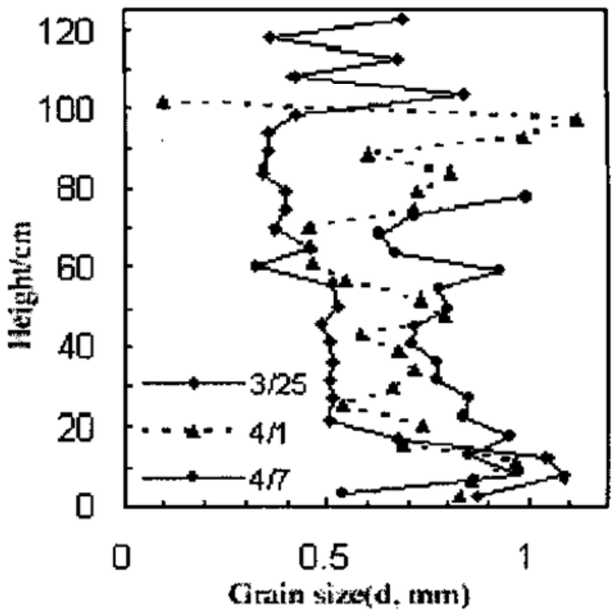

Fig. 3. Grain size evolution of the snowpack.

3 Compactive viscosity

The viscous model gives (Keeler 1967; Kojima 1967; Bergen 1978; Qin 1990; Sturm and Holmgren 1998):

$$-\frac{1}{h}\frac{dh}{dt}=\frac{1}{\rho}\frac{d\rho}{dt}=\frac{\sigma}{\eta_c} \quad (1)$$

where h is the thickness of a snow layer, t is time, ρ is density, σ is the load and η_c is the compactive viscosity. Since intensive density data are available, the density term of Equation (1), is used in the following calculations.

For wet snow, there are two kinds of density. One is the gross density which includes the liquid water, the other is the dry density which is obtained by subtracting the water content from the gross density. Figure 4 shows the averaged water content (weight%) for each of LB, LC and LD at the time when the correspondent density samples were taken (at about 10:00 every time). Figure 5(a) shows the mean dry density evolution for each layer. From the figure, it is clear that, if the compactive viscosity is calculated day by day by using Equation (1), then $d\rho$ would be minus in some days. Thus regressions are carried out to determine the density-time relations. According to the distribution of the dots, and the range of their values, the linear regressions are applied even though this might not be exactly of the physical properties. The regression lines are shown in the figure.

By using both the density profile and the stratigraphical data, the load evolution of each layer with time is calculated and shown in Figure 5(b). The curves in the figure are quadratic equations and the loads are averaged ones.

Substituting the equations for the lines and curves in Figure 5(a) and Figure 5(b) into Equation (1) respectively, then we get the $\eta_c - t$ (Figure 5(c)) and $\eta_c - \rho$ (Figure 6) curves.

Previous studies (Keeler 1967; Kojima 1967; Mellor 1975; Ambach and Eisner

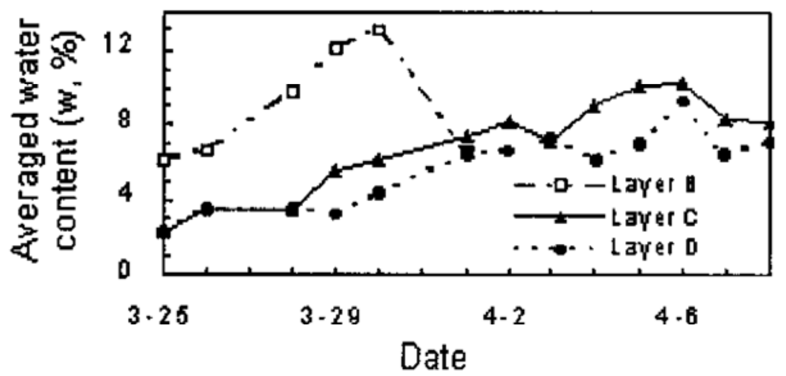

Fig. 4. Variations of water content for each of the three layers at the time when the density samples taken.

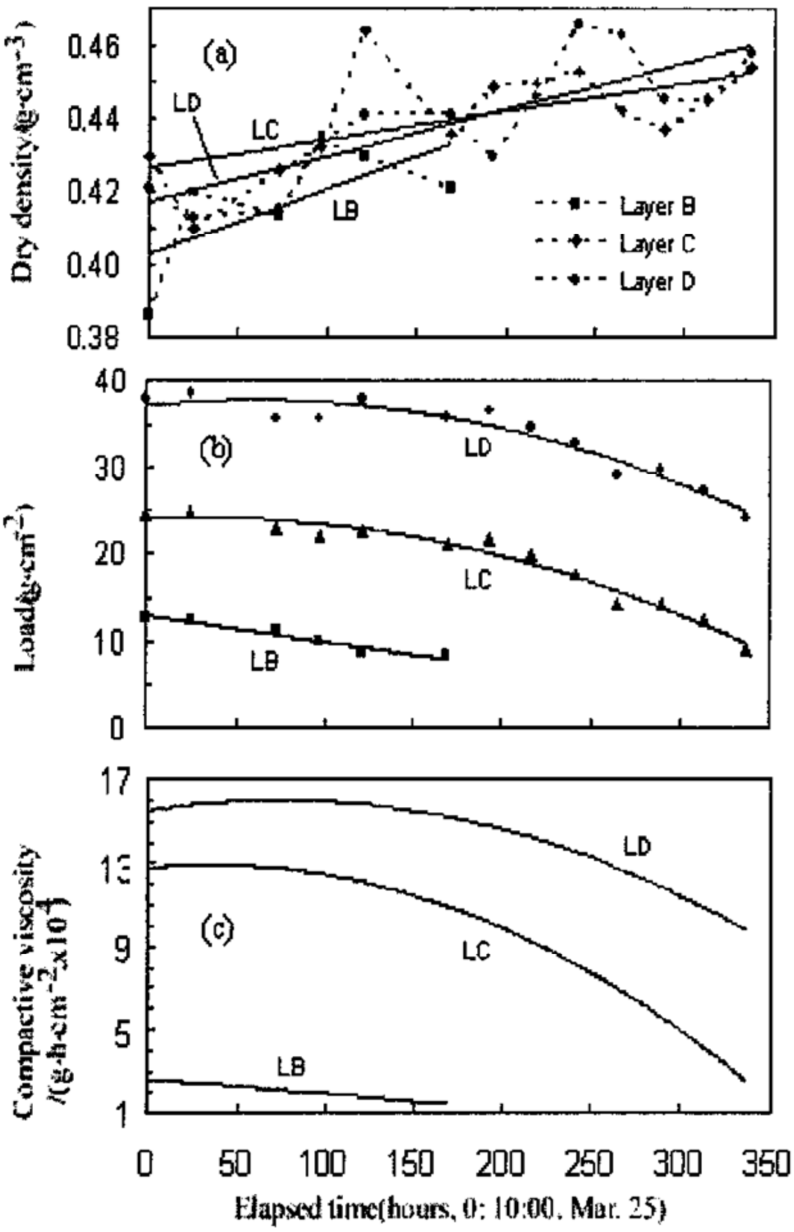

Fig. 5. The evolution of averaged dry density (a), load (b) and compactive viscosity (c) for each layer.

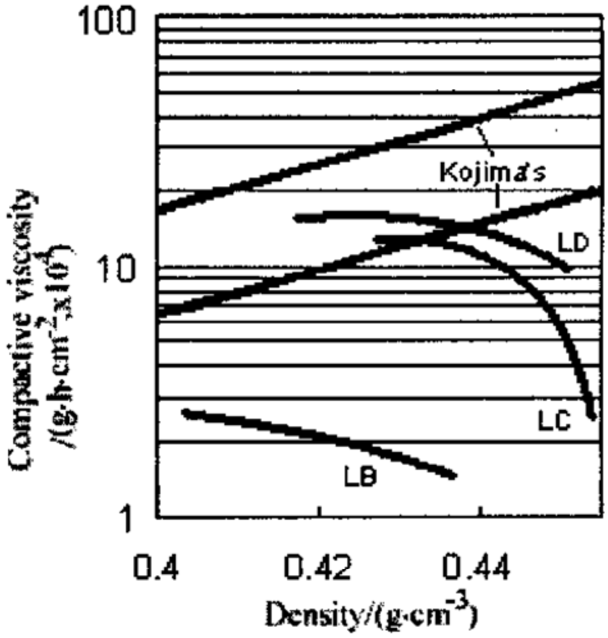

Fig. 6. Compactive viscosity vs density for each of the three layers.

1985) show that, although the combined results scatter, individual sets of data are usually fitted with

$$\eta_c = Ce^{k\rho} \quad (2)$$

where C is the viscosity at ρ equals zero, a factor which is dependent on snow temperature and the initial type of snow crystals(Kojima 1967), k is a factor that depends on the type of snow, its temperature and whether it is wet (Sturm and Holmgren 1998). In a density-viscosity figure (Figure 6), C stands for the intercept of a line and k stands for the slope of the line.

From Figure 5(c) and Figure 6, it can be seen that while the η_c value of LB keeps decreasing with time and density, the η_c values of both LC and LD increase very slightly at the beginning (in the first 35 hours for LC and 75 hours for LD), but after that, they decrease gradually, and the decreasing rates become larger as the time or density increases until the end of the period. By adding the above results into Kojima's figure (Kojima 1967) (Figure 6), it is shown that, for LC and LD, our results fall well in the area of Kojima's data at the beginning, but as the density or time increases, they differ from each other with the former(Kojima's) decreasing and the latter(LC's and LD's) increasing; and that for LB, the η_c value also decreases with increasing density, but all the values are smaller than Kojima's in the same density.

4 Grain coarsening and properties of grain size distributions

Kojima's data(Figure 6, Kojima 1967), which are largely from dry snow and fitted well with Equation (2) except two series of very wet snow(the water content: 35% and 12%), show the same k value, but different C values for different layers. Compared with Kojima's data, our data belong to the same snow type (even the same place) and in the same temperature range, but different in grain size and water content. The water content in Kojima's data (wet snow) is less than 5%, but that in ours exceeds 5% in most time (Figure 4 and Figure 7) and varies in the period for a given layer; the grain size in Kojima's data is almost the same for a given layer in a period because the dry snow coarsens very slowly, but that of ours changes remarkably (Figure 3). Thus it is reasonable that the change of water content and grain size of LB, LC and LD gives rise to the decrease of the compactive viscosity as the density increases, which differs from Kojima's data (Figure 6). For the water content, no enough data are available, moreover, unlike the steady coarsening of grains, it varies much from day to day (Figure 4) and hour to hour (Figure 7). Therefore, we can only analyze the relationship between compactive viscosity and grain size.

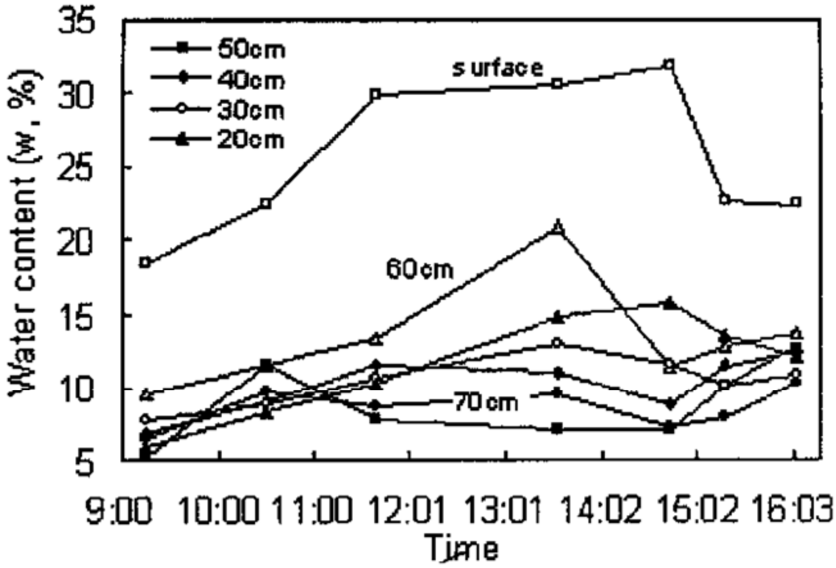

Fig. 7. Water content variations at different heights of the snowpack on Aprill 7.

For the grain size, first the properties of grain size distributions have to be examined.

Raymond and Tusima (1979) made an experiment by saturating about 400 g of dry, natural, new snow with about 500 ml distilled water and keeping the sample in a 0°C chamber. Then by scooping from it a small subsample of about 0.5 g total ice weight at different times ranging from 1 to 170 hours, further examinations were made on the size distributions of the subsamples. For convenience, the cumulative distribution Ψ is defined as the fractional number of grains with size greater than or equal to a specific size. These cumulative distributions decrease monotonically from a value of 1 at zero size to a value of 0 for maximum size. Grain diameter d and volume v are chosen as alternative size parameters, assuming the grains are spherical.

By plotting Ψ_d measured for subsamples taken at various times in their experiment, they found that, on a logarithmic scale of diameter, the size distributions at different times all had about the same shape. Figure 8 is the same kind figure of our data for LB. Two others, for LC and LD respectively, are very similar. For the figures, although the size distributions have less similarities than Raymond and Tusima's, they are roughly in the same shape.

The approximate invariance of shape on a logarithmic size scale indicates that all of the distributions shown can be approximately represented by a single distribution, which is scaled to some characteristic size. Raymond and Tusima chose the median diameter

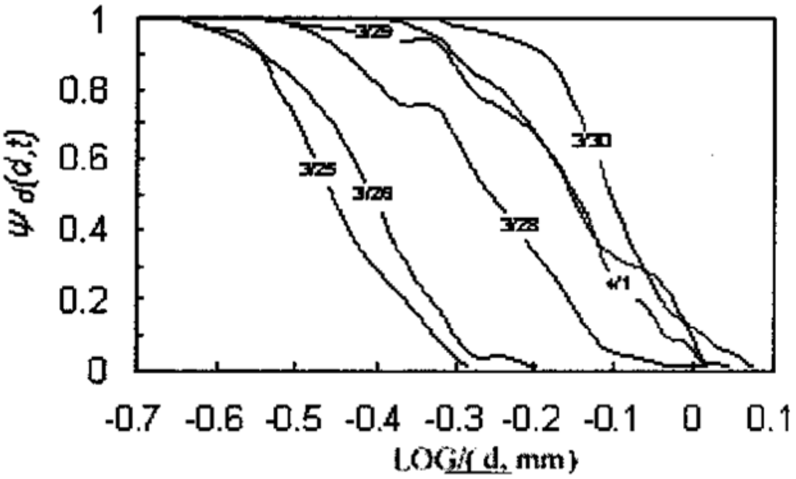

Fig. 8. Cumulative distribution of particle diameters for Layer B.

(d_m) as the characteristic size. By plotting the distribution v/v_m (v_m is median volume) for all of the above-mentioned distributions ($\Psi_d(d, t)$), it is shown that, except for some apparent deviations of the early distributions and local deviations of some irregular distributions, all of the distributions fall in a narrow band which defines $\Psi_v^*(v/v_m)$. It was found that these measurements were fitted quite well with

$$\Psi_v^*\left(\frac{v}{v_m}\right) \cong \left(1-\frac{av}{bv_m}\right)^{\frac{1}{a}}, \tag{3}$$

where $a = 0.23$ and $b = 1.55$. It predicts zero probability for grains larger than a maximum volume of $v_m b/a = 6.8 v_m$.

Figure 9 show comparisons of our measured data, for LB, with the line of Equation (3). Two others, for LC and LD respectively, are also very similar. It is clear that both basically agree with each other, but they are apparently different for those grains that are much larger or much smaller than the median volume. This is because of our slight preference of measuring more grains close to the mean size. Considering this, both should agree better. This agreement indicates that the water-unsaturated snow has the same grain coarsening behavior as the water-saturated snow.

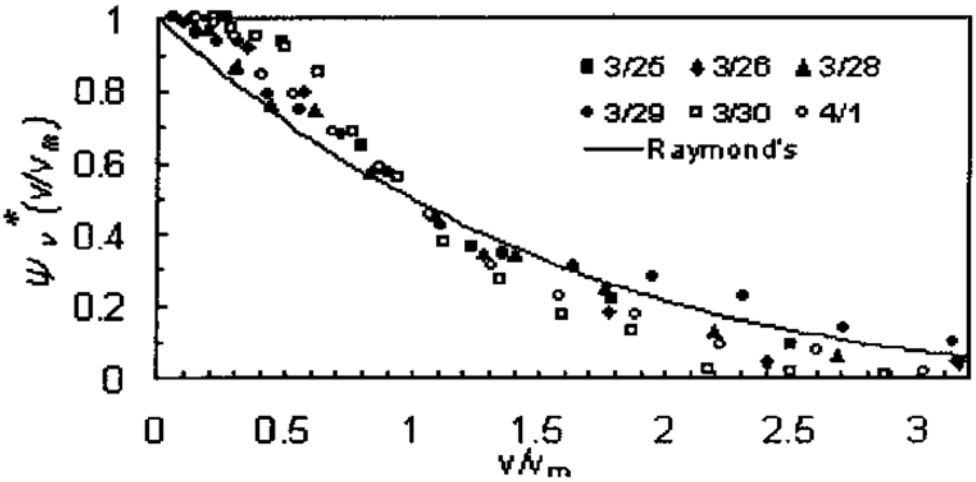

Fig. 9. A comparison of our data with Raymond's on the cumulative distribution of particle volumes in units of median volume for Layer B.

A consequence of the similarity of the size distribution shapes is that there is an approximately unique relationship between median size and mean size, so

$$\bar{d}/d_m = k' \quad (4)$$

where $\bar{d}$ is mean diameter. Raymond and Tusima's data give $k' = 1.013 \pm 0.009$. The k' values of our data range from 1.038 to 1.107 for LB, 0.983 to 1.112 for LC and 0.993 to 1.068 for LD. All the ranges are larger than Raymond and Tusima's because of the less similarity of the size distributions.

Based on the above, the mean grain size is a good choice for the analysis of the relationship between compactive viscosity and grain size.

5 *C* value and grain size

For Equation (2), if Kojima's k value of 21 cm^3/g is adopted, then

$$C = \frac{\eta_s}{e^{21\rho_s}}. \quad (5)$$

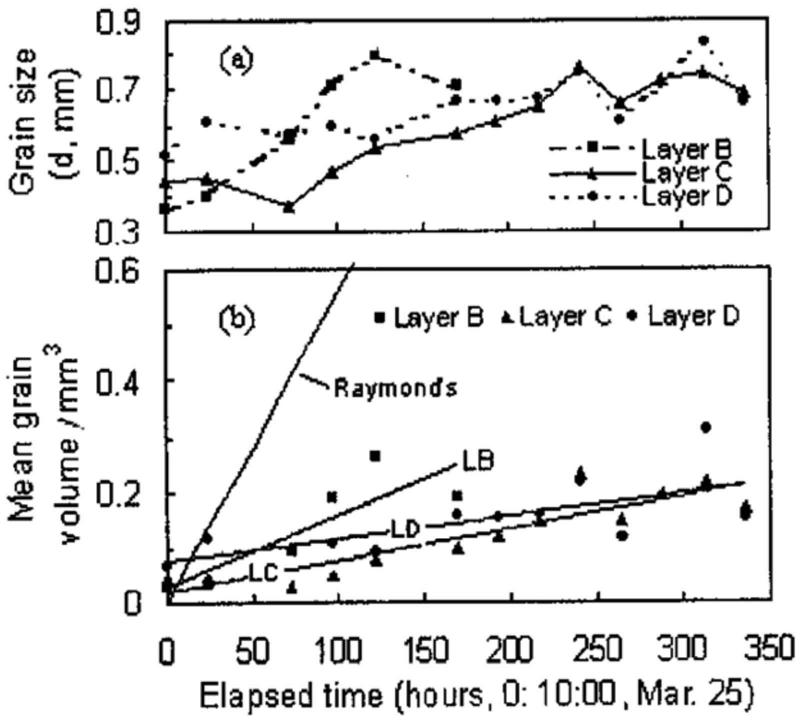

Fig. 10. Mean grain size evolution for each layer(a) and a comparison of the grain coarsening rates with Raymond's(b).

C's change reflects the change of grain size and water content. As mentioned above, here we analyze the relationship between C and the grain size.

Figure 10(a) shows the evolution of mean grain size (grain diameter) with time for each layer. According to Raymond and Tusima (1979), for the water-saturated snow, the mean volume of the snow grains increases linearly with time. We assume the same law for our data. Also assuming the grains are spherical, regression (Figure 10(b)) and substitution give $d = f(t)$ for each layer where d is the grain diameter.

The relationship between C and d for each layer can be obtained by first substituing equation $\rho = f(t)$ (Figure 5(a)) and equation $\eta = f(t)$ (Figure 5(c)) into Equation (5), here expressed by $C = f(t)$, then relating equation $d = f(t)$ to $C = f(t)$. Thus $C = f(d)$ (Figure 11) is obtained.

From Figure 11 and Figure 10(b), it can be seen that the C value of each layer decreases as the grain size increases, but the decreasing rates are different. The decreasing rate of C value increases with decreasing grain-coarsening rate.

6 Discussion

It is reasonable that the compactive viscosity of melting snow would be less than that of dry snow in the same conditions, since the water acts as a lubricator. As for the grain size, although it was suggested (Bucher 1956) that the viscosity of snow increased with increasing grain size, the published literature is somewhat contradictory (Sturm and Holmgren 1998). For our data, from Figure 5(c) and Figure 10, it can not be judged whether the decreasing rate of compactive viscosity increases or decreases as the grain coarsening rate increases. Since the water content is always accompanied by grain coarsening, the variation of compactive viscosity depends on the correspondent increasing (or decreasing for water content) rates of both water content and grain size given equal other conditions. In the case of our observation, the water content seems holding a rough increasing trend in the whole period, which can be slightly perceived by Figure 4. If so, and if the compactive viscosity is much more sensitive to water content than that to the correspondent grain coarsening, then it might be the water content that causes the decrease of compactive viscosity which is shown by Figure 5(c) and Figure 6. If so, our results, as shown in Figure 11, do not reflect the intrinsic nature of the relation. Nevertheless, from Figure 4 and Figure 10(b), it seems that the grain coarsening rate increases as the water content increases. If so, the grain size does serve as an indictor of water content, and thus the relationship shown by Figure 11 is still meaningful.

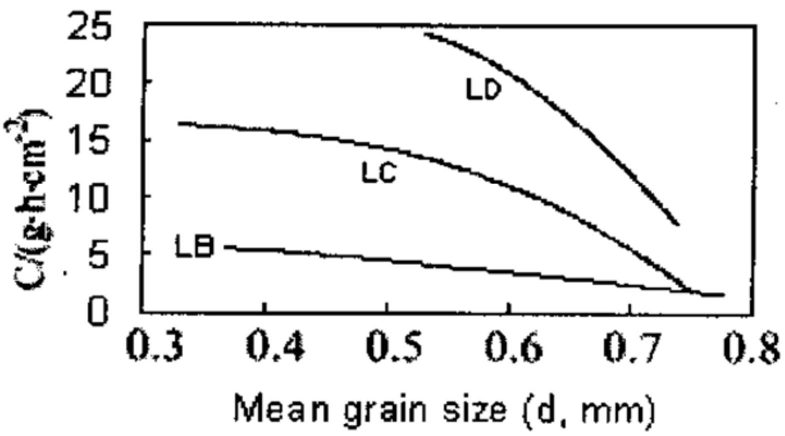

Fig. 11. C vs grain size for layers.

7 Conclusions

This study examines the densification of melting seasonal snow. It is shown that the snow compactive viscosity decreases as the density increases, which is opposite to the relation for dry snow. This arises from grain coarsening and probably larger water content. By looking into the grain coarsening, it is found that, similar to the water - saturated snow, the distributions of grain size at different times almost all have the same shape. This reveals that the water - unsaturated, seasonal melting snow holds the same grain - coarsening behavior as the water - saturated snow does. It is also shown that the water - unsaturated melting snow coarsens much more slowly than the water - saturated snow. The C value, which is the viscosity when the snow density is zero, is related to the mean grain size and found to decrease with increasing grain size. The decreasing rate of C value increases with decreasing grain - coarsening rate.

Acknowledgments This work was supported by the Ministry of Education, Science, Sports and Culture of Japan, and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry of China.

References

Ambach W, Eisner H (1985): Rheological properties of temperate firn. PoLarforschung. 55(2): 71 - 77.

Anderson DL, Benson CS(1963): Densification and diagenesis of snow. In Kingery WD ed., Ice and Snow, M.I.T. Press, Cambridge, Mass., 391 - 411.

Bader H(1960): Theory of densification of dry snow on high polar glaciers, 1. SIPRE Res. Rept., 69: 1 - 8.

Bader H(1962): Theory of densification of dry snow on high polar glaciers, 2. CRREL Res. Rept., 108: 1 - 18.

Bergen JD(1978): Some measurements of settlement in a Rocky Mountains snow cover. J. Glaciol., 20(82): 141 - 148.

Bucher E(1956): Contribution to the theoretical foundations of avalanche defense construction. SIPRE Transl. 18.

Gow AJ (1975): Time-temperatnre dependence of sintering in perennial isothermal snow packs. International Association of Hydrological Sciences Publication 114(Symposium at Grindelwald 1974- Snow Mechanics), 25 - 41.

Keeler CM (1967): Some observations on the densification of alpine snow covers. CRREL Tech. Rep., 197.

Kojima K(1954): Visco-elastic properties of snow. Low Temp. Sci., Al2, 1 - 13(In Japanese with English summary).

Kojima K(1955): Viscous compression of natural snow-layer, iv. Low Temp. Sci., Al4, 77 - 79(1n Japanese with English summary).

Kojima K(1956): Viscous compression of natural snow-layer, ㊆. Low Temp. Sci., Al5, 117 - 136(In Japanese with English summary).

Kojima K(1957): Viscous compression of natural snow-layer, ㊃. Low Temp. Sci., Al6, 167 - 196(1n Japanese with English summary).

Kojima K(1958): Viscous compression of natural snow-layer, IV. Low Temp. Sci., Al7, 53 - 64(In Japanese with English summary).

Kojima K(1959): The influence of temperature gradient upon the grain texture, settling rate, and brittleness of snow. Low Temp. Sci., A18, 29 - 46(1n Japanese with English summary).

Kojima K(1964): Densification of snow in Antarctica. In Antarctic Snow and Ice Studies(Mellor M. ed), Antarcti Res. Ser. 2; Amer. Geophys. Union, Washington, D. C., 157 - 218.

Kojima K(1967): Densification of seasonal snow cover. In physics of snow and ice(Oura, H., ed). Vol. 1, Part 2. Sapporo, Hokkaido University. Institute of Low Temperature Science, 929 - 952.

Kojima K, Motoyama H(1985): Melting and heat exchange at the bottom of a snow cover. Annals of Glaciology, 6: 276 - 277.

Maeno N, Ebinuma T (1983): Pressure sintering of ice and its implication to the densification of snow at polar glaciers and ice sheets. J. Phys. Chem., 87(21): 4103 - 4110.

Mellor M(1975): A review of basic snow mechanics. International Association of Hydrological Sciences Publication 114(Symposium at Grindelwald 1974– Snow Mechanics), 251 - 291.

Qin Dahe(1990): Densification process within the near-surface layer of the Antarct. ice sheet. Antarct. Res., 2 (1): 10 - 19.

Raymond CF, Tusima K(1979): Grain coarsening of water-saturated snow. J. Glaciol., 22(86): 83 - 105.

Sturm M, Holmgren J(1998): Differences in compaction behavior of three climate classes of snow. Annals of Glaciology, 26: 125 - 130.