Annual Report of the Research Institute for Hazards
in Snowy Areas, Niigata University, No.9, 1987

STUDIES ON THE HARDNESS OF WET SNOW AND ITS DECREASE DUE TO SOLAR RADIATION *

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Abstract

As wet snow plays one of the most important roles in the release of avalanches in temperate snowy districts, observations and experiments were made on the characteristics of hardness of wet snow in the field and laboratory.

By measuring Kinosita's hardness of natural wet snow over a wide range of snow density, a relation among hardness, dry density and free water content of wet snow was obtained for each snow type. As hardness of snow decreased with an increase in water content according to this relation, the lower limit of hardness of snow due to water content was obtained by immersing natural snow in 0℃ water. Unsaturated wet snow at the surface of a natural snow cover, having less hardness than the limit, was considered to have reduced its hardness due to solar radiation.

Laboratory and field experiments on hardness of snow showed that free water contained in snow decreased its hardness, and solar radiation further decreased its hardness down to a value below the limit caused only by water content. A relation between the amount of solar radiation absorbed by snow and decrease of snow hardness was quantitatively obtained. The mechanism of decrease in snow hardness caused by free water in snow and solar radiation were explained based on thin section analyses of snow.

From the obtained results, it was revealed that the weak wet snow layer of the sliding plane of some surface avalanches which occurred in Niigata Prefecture was formed by solar radiation.

Key words: wet snow, Kinoshita's hardness, water content, solar radiation, surface avalanche, weak layer

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Contents

I. Introduction

In the Hokuriku District of Japan, middle coastal district of Honshū Island facing the Sea of Japan, world famous heavy snowfall and deep snow accumulation occur in winter, e.g., snow depth attains up to 2.5 m in an average winter and 4 m in some heavy snow winter seasons at Tokamachi City (about 150 m a.s.l.), Niigata Prefecture.

For an ordinary snowfall, snow is generally wet as the climate of this district is temperate, around 0℃. But when a heavy snowfall caused by a cold air mass coming down from the north occurs, air temperature drops down to about -5℃ at ground level and the falling snow is dry. After snowfall, the air temperature at ground level rises over 0℃, and melt metamorphism proceeds from the snow surface.

A number of severe disasters have been brought on by avalanches in this district. Through general observation of such avalanches, it was presumed that wet snow played an important role in avalanche release in this district. Many studies have been made on the mechanical properties of dry snow, while those of wet snow are scarce. Studies on wet snow are very important to examine the mechanism of avalanche release in a temperate snow district.

In the present study, first, the mechanical strength of natural wet snow was researched over a wide range of snow density; second, a decrease in the mechanical strength of snow due to water saturation or solar radiation was studied both in a cold room and in the field. Finally, using the obtained results, the formation process of a weak wet snow layer which provided a sliding plane was investigated in regard to some surface avalanche accidents which recently occurred in Niigata Prefecture.

II. Hardness measurement of natural wet snow

For such a practical purpose as avalanche forecasting in the temperate snow district, it is important to study the mechanical strength of wet snow. In this study, Kinosita's hardness (Kinosita, 1960) was measured and used as an indicator of the mechanical strength of wet snow. Kinosita's hardness is defined as the average resistance of snow per unit area to vertical penetration of a gauge, a metal rod with a disk plate at the snow surface to be measured, driven by a drop hammer. Kinosita's hardness gauge is widely used for the snowpack observation in Japan. It is easy to handle it for field measurement even on a small snow sample. Furthermore, it shows a good correlation with other mechanical strengths. For example, Watanabe (1977) obtained the regression equation between Kinosita's hardness R and other mechanical strengths, tensile strength σ_t , shear strength σ_s and compressive strength σ_c, respectively, as follows :

$$\log \sigma_t = 0.842 \log R - 0.136 \qquad (0.97), \qquad (1)$$

$$\log \sigma_s = 0.796 \log R - 0.210 \qquad (0.95), \qquad (2)$$

$$\log \sigma_c = 0.765 \log R - 0.183 \qquad (0.96) \qquad (3)$$

where the unit is gw/cm^2 and numeral in parenthesis is the value of the correlation coefficient.

Hardness R ("hardness" indicates Kinosita's hardness in this paper), density ρ and free water content W of 208 natural wet snow samples in the snow cover were measured in the field in Hokkaido and Niigata Prefecture in the winter of 1981−1982. The free water content of the samples, measured with a newly designed calorimeter (Akitaya, 1978), was less than 22% in weight except for two samples which were almost water saturated.

Since hardness was supposed to depend mainly on the solid structure of snow, dry density ρ_d was calculated from density ρ and free water content W and used as a parameter in the analysis of the obtained data.

The wet snow samples were qualitatively classified into two types: I (coarse-grained granular snow) and II (new snow and fine-grained compact snow). Snow I is the snow with a snow grain diameter coarser than about 1 mm which has suffered a grain coarsening process (Wakahama, 1967) with a considerable amount of water. Snow II is the snow which contains a small amount of water and maintains almost the same texture of dry new snow or dry fine-grained compact snow before containing water.

In Fig. 1, ln R was plotted against ρ_d , where solid circles represent snow I and open circles snow II. Clearly, snow II was harder than snow I when the dry density was the same. This suggests that hardness of snow decreases by suffering a grain coarsening process, by which snow II metamorphoses into snow I.

Also ln R seemed to increase linearly with an increase in ρ_d for both types of snow. On the other hand, ln R of fine-grained compact snow (Snow II) was reported to decrease linearly with an increase in W (Akitaya and Endo, 1981). Hence, the dependence of R on W and ρ_d was assumed as,

$$\ln R = a - b\,W + c\,\rho_d \qquad (4\,a)$$

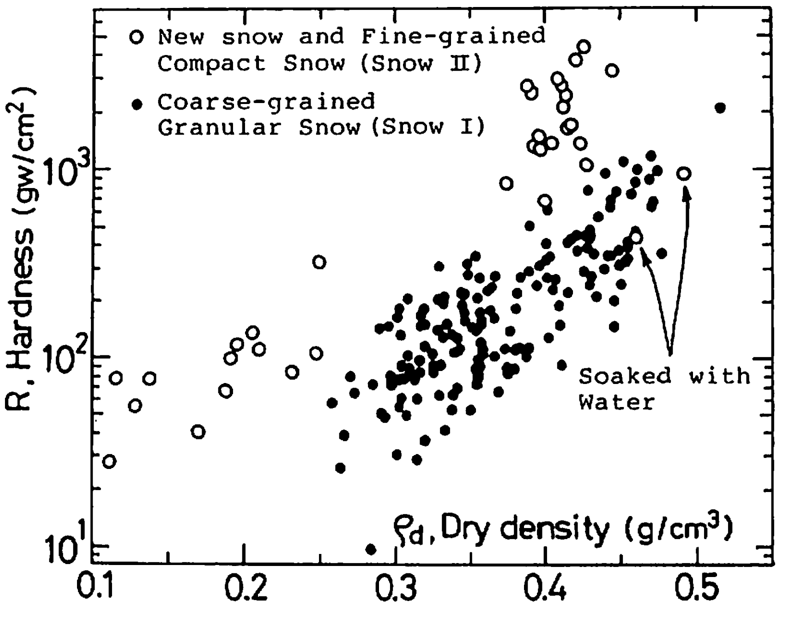

Fig. 1 Hardness and dry density of natural wet snow.

and the constants *a*, *b* and *c* were obtained by the mltipl regression method for each snow type. The results are :

$$\ln R = 1.00 - 0.0339\,W + 12.1\,\rho_d \quad \text{(snow I)}, \qquad (4\,b),$$

$$\ln R = 2.22 - 0.0517\,W + 14.0\,\rho_d \quad \text{(snow II)} \qquad (4\,c)$$

where R is in gw/cm^2, W in % and ρ_d in g/cm^3. The value of b and c of these relations were significant at less than 0.1 % level. The multiple correlation coefficients between ln R and (W, ρ_d) of these relations were high as shown in Table 1.

Table 1 Constants and multiple correlation coefficients (r) for $\ln R = a - bW + c\rho_d$.

Snow type	a	b	c	r
I (Coarse-grained granular snow)	1.00	0.0339	12.1	0.824
II (New snow and fine-grained compact snow)	2.22	0.0517	14.0	0.970

Field measurements of wet snow samples were continued throughout the winter periods of 1982 – 1983, 1983 – 1984, 1984 – 1985 and 1985 – 1986 principally in Niigata Prefecture. The hardness R, dry density ρ_d and free water content W of 667 natural wet snow samples were measured. In Fig.2, ln R was plotted against ρ_d over a wide range of dry density, where solid circles represented snow I (coarse-grained granular snow) and open circles snow II (new snow and fine-grained compact snow). The relation between hardness R and dry density ρ_d of wet snow was almost the same as that in Fig.1 over the range of dry density of 0.1 – 0.5 g/cm^3. The dotted curve and the dashed curves in Fig.2 show the $R-\rho_d$ relations obtained for dry new snow and dry fine-grained compact snow (Tusima, 1975), and for dry packed snow and ice crust on the road (Kinosita *et al*., 1970), respectively. In the dry density range more than 0.25 g/cm^3 wet snow showed smaller value of hardness than that of dry snow, and the hardness range of wet snow for a dry density decreased with an increase in dry density. In the dry density range less than 0.25 g/cm^3 several wet snow samples

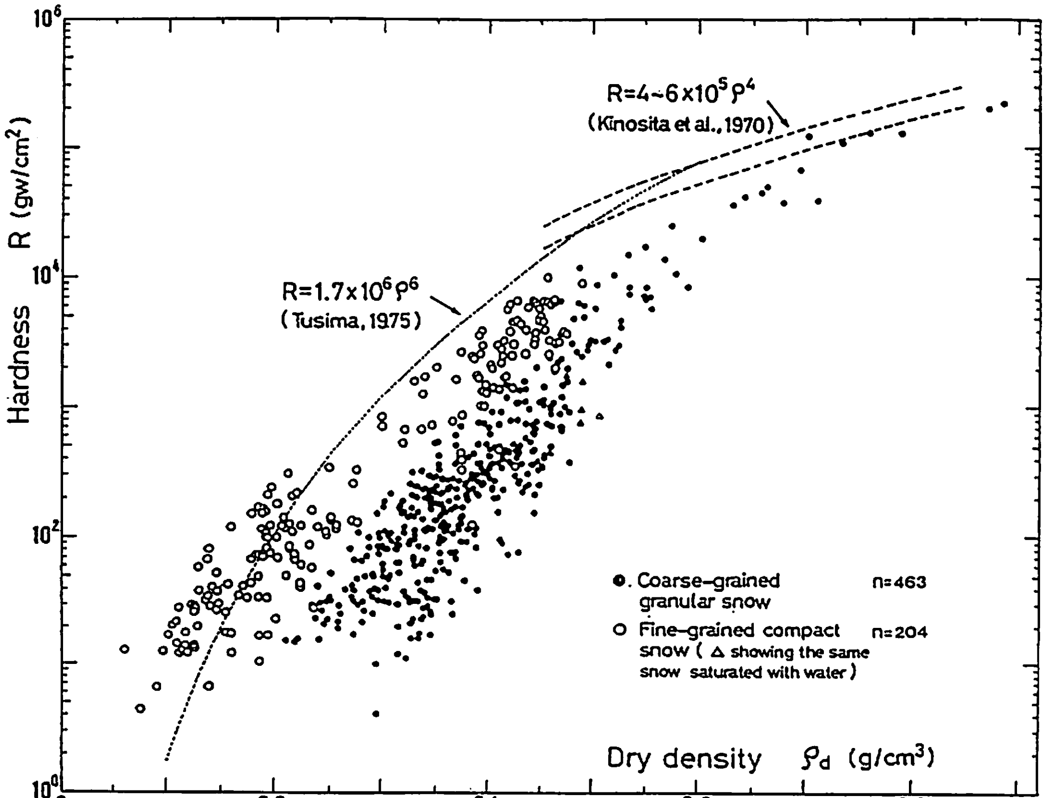

Fig. 2 Hardness and dry density of natural wet snow over a wide range of dry density. Dotted curve: a relation for dry new snow and dry fine-grained compact snow, dashed curves: relations for dry packed snow and ice crust.

showed larger values of hardness than those of dry snow. This is because the cohesive force due to water content has a considerable influence on the hardness of wet snow especially for small dry density values.

III. Decrease in hardness of snow due to water saturation

In the previous chapter, it was shown that Kinosita's hardness of wet snow decreased with an increase in free water content for a given dry density. According to this general relationship, the hardness of wet snow must have a minimum value when pore space in the snow is filled with water. Relating to problems such as the release of a wet snow avalanche, it is of basic importance to understand the mechanism of change in snow hardness and its minimum value when the snow contains free water. Thus the change in hardness of natural snow was measured by immersing it in water at 0 ℃.

III.1. Experimental procedure

Snow blocks uniform in structure were sampled from deep layers of the natural snow cover. A snow specimen, about 30 cm long, 20 cm wide and 10 cm high, cut out from a snow block, was placed in a plastic vessel and water at 0℃ was poured slowly into the vessel until the whole specimen was sufficiently submerged in the water. Then, hardness was measured intermittently on the surface of the specimen in a cold room at 1 ± 1 ℃ to avoid any freezing and to suppress active melting.

III.2. Change in handness of snow by immersion in water at 0 ℃

Time changes in hardness R for four immersed snow specimens are shown in Fig. 3 , as examples. Hardness R of the immersed snow decreased rapidly after the immersion and then reached a nearly constant value within three hours. This constant value of hardness which is indicated by R_s in Fig.3 was termed the water saturation hardness. This tendency of change in hardness was found in all of the 122 specimens independent of the snow type and the water content before immersion.

The relation between water saturation hardness R_s and dry density ρ_d of the original snow is shown in Fig.4, in which the lower limit of R_s is clearly found as indicated by the line $R_{s \cdot min}$. When the pore space in the snow is filled with water, wet snow reaches its minimum hardness R_s , and $R_{s \cdot min}$ indicates the minimum value of R_s for a dry density of snow regard-

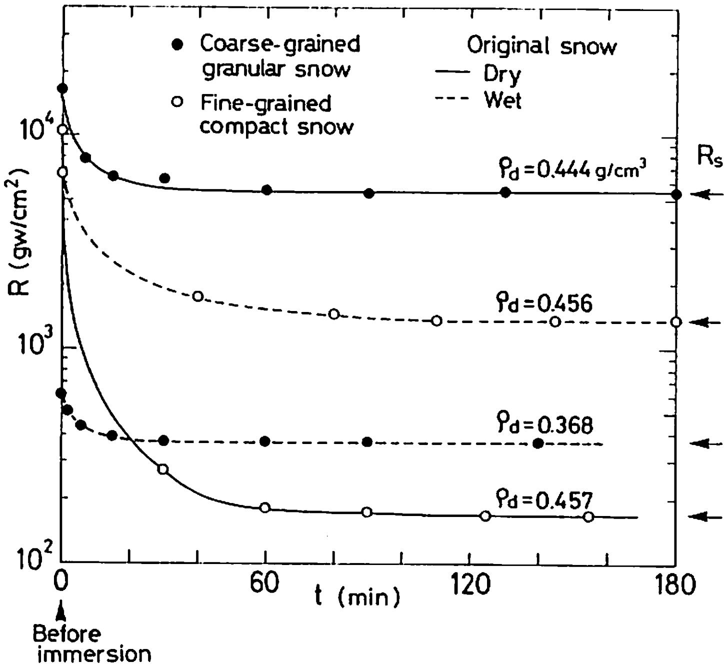

Fig. 3 Change in hardness R of snow by immersion in 0℃ water.

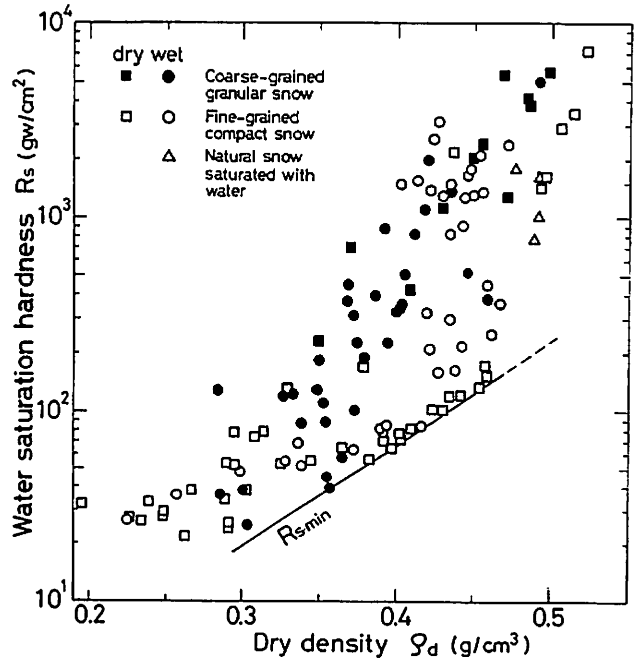

Fig. 4 Relation between water saturation hardness R_s and original dry density ρ_d. The line of $R_{s\cdot min}$ indicates the lower limit of R_s.

less of original snow type. Therefore, $R_{s.min}$ is considered to be the minimum value of snow hardness caused only by water content.

Ⅲ.3. A comparison between the hardness of natural wet snow and water saturated snow

Figure 5 shows the relation between hardness R and dry density ρ_d of natural wet snow over the density range of 0.22−0.62 g/cm³. This is in fact a part of Fig.2 which includes the line of $R_{s.min}$.

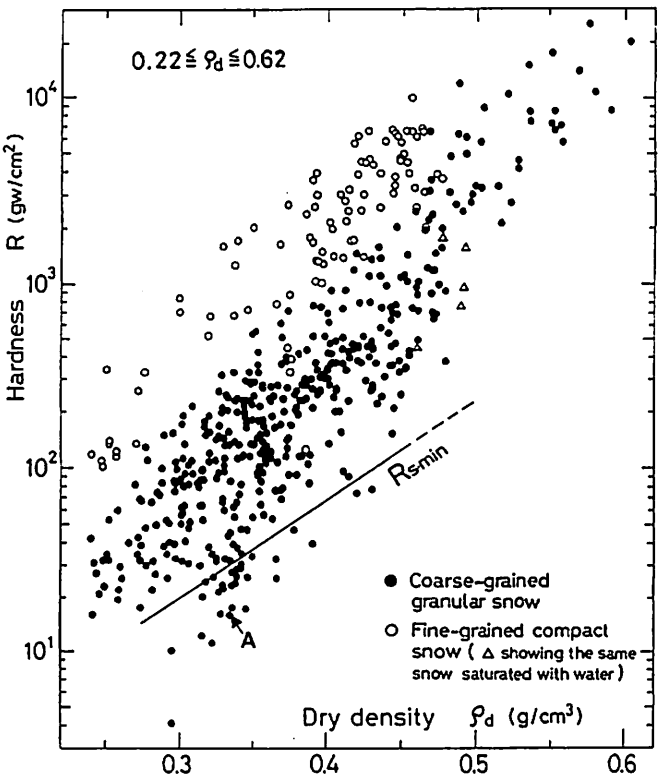

Fig. 5 Distribution of hardness and dry density of natural wet snow, and the line of $R_{s\cdot min}$.

In Fig.5, all of the natural wet snow retained a water content less than 13% in volume of pore space at most, except for the open triangles which correspond to fine-grained compact snow nearly saturated with water. If the decrease in hardness of wet snow is caused only by water content, hardness of unsaturated snow samples should be at least greater than $R_{s.min}$ for its corresponding dry density. But there are several plots of unsaturated snow specimens with lower values than $R_{s.min}$. These values of hardness must be caused by something other than water content.

All plots below $R_{s.min}$ were observed in surface snow layers which were supposed to be exposed to active solar radiation. In Fig. 5, point A is the value measured on the surface snow layer which slid as a wet surface avalanche and resulted in two casualties. This snow layer was found to have absorbed a large amount of solar radiation as will be mentioned later. Wakahama (1968) observed that hardness of snow at the surface layer decreased by two orders in magnitude due to strong solar radiation during daytime in the snowmelt season. Consequently it is considered that the decrease in hardness of wet snow to a value below $R_{s.min}$ was caused by solar radiation.

IV. Decrease in hardness of snow due to solar radiation

To study the mechanism of the decrease in hardness of snow caused by solar radiation, experiments were carried out in the laboratory and field.

IV.1. Laboratory experiments

IV.1.1. Experimental procedure

Snow blocks with uniform texture were cut out from deep layers of the natural snow cover where it was reasonably considered that solar radiation had scarcely influenced the snow texture. Two snow specimens of the same dimension, 20 cm × 20 cm in horizontal size and 6 − 17 cm in thickness, were prepared from a snow block at a time.

A specimen was set in a specially designed container with lateral walls of 0 ℃. The container was composed of crushed melting ice and a thermal insulator, with a draining pipe for meltwater at the bottom, as shown in Fig. 6, and was placed in a cold room at 1± 1 ℃.

Artificial solar radiation was provided by a light source composed of four 250 W flood lamps for color-photography by scattering the light with a frosted glass plate and a plastic tracing sheet. This artificial solar radiation had almost the same spectral characteristics of natural solar radiation.

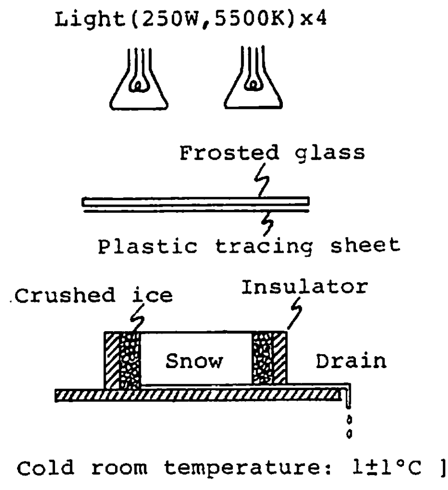

Fig. 6 Laboratory experimental system on the effect of solar radiation on snow hardness.

The artificial solar radiation was applied constantly to the specimen in the cold room to study its effect on snow hardness and snow texture. Let's name this experimental condition A (radiation). Intensity of the artificial solar radiation at the surface of the specimen was measured by a pyranometer before and after an experiment. The intensity ranged from 0.3−0.4 kw/m^2 which is often observed on fine mid-days in December and January in Niigata Prefecture.

Another snow specimen set in the specimen container was placed in a room at 24−25℃ keeping away from solar radiation, to study the effect of sensible and latent heat transfer on snow hardness and snow texture. Let's name this experimental condition B (nonradiation).

As snow specimens showed proper snow-melting according to the experimental conditions A and B, respectively, an observation layer (3 cm in thickness) was selected at a particular level inside the specimen. The surface level HS (cm) of the specimen, free water content W (%), dry density ρ_d (g/cm^3) and hardness R (gw/cm^2) of the observation layer were measured intermittently with time till the upper surface of the observation layer was exposed directly under solar radiation as the snow surface.

Ⅳ.1.2. Experimental results

Typical results of the comparative experiment on decrease in hardness of snow under/without solar radiation are shown in Fig.7. Initially, the snow specimen was wet fine-grained compact snow of $HS=10$ cm, $W=2.2\%$, ρ_d = 0.396 g/cm^3 and $R=1010$ gw/cm^2 (the observation layer was selected between the level of 3 and 6 cm from the bottom). Amount of artificial solar radiation applied to the specimen under condition A was 5.9 MJ/m^2 during 280 minutes.

The surface level of each specimen decreased from 10 cm down to 6 cm in the same manner with time. Free water content W and dry density ρ_d of the observation layer under the condition A (radiation) showed fairly close agreement with those under the condition B (nonradiation) respectively even with time. On the other hand, the hardness R_A and R_B showed a remarkable time variation difference with each other: hardness R_B of the observation layer decreased with time for the first three hours and then attained a constant value under the condition B (nonradiation), while R_A decreased more quickly and continuously until the end of the experiment under the condition A (radiation), finally reaching a value of approximately 20% of R_B. Therefore, it was presumed that this extraordinarily large decrease of hardness of snow under the condition A (radiation) was principally caused by the artificial solar radiation.

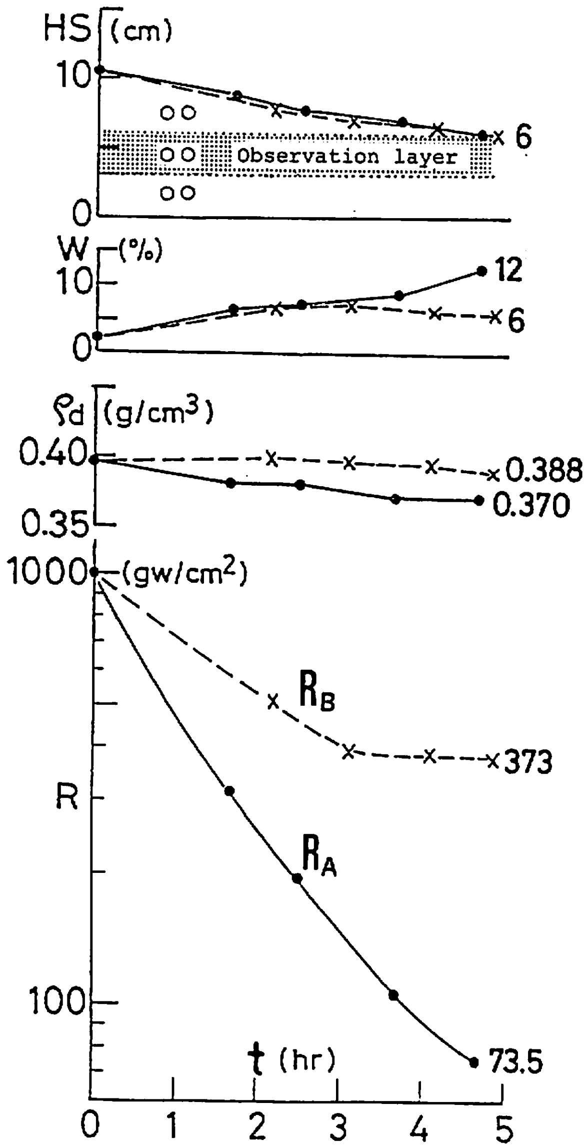

Fig. 7 Decrease in hardness R of snow at 0 ℃. —●— : under solar radiation, — × — : without solar radiation. HS : surface level of snow specimen, W: water content, ρ_d : dry density of snow.

All other comparative experiments using this procedure showed the same tendency as indicated in Fig.7, and R_A finally reached a value of 80 − 10 % of R_B.

To clarify the reason of decrease in hardness of snow in these experiments, thin section analyses were made before and after the experiments. Vertical thin sections of the observation layer were prepared by the aniline method (Kinosita and Wakahama, 1959), and photographed under microscope by the use of polarized light.

Figure 8 shows the microtexture (0.3 mm thick) of the observation layer in the experiment shown in Fig.7. From Fig.8, it can qualitatively be seen that hardness of snow strongly depends upon the state of inter-grain ice bonding: the greater the number of ice bonds per unit area and the bigger the ice bond size, the stronger the hardness of snow.

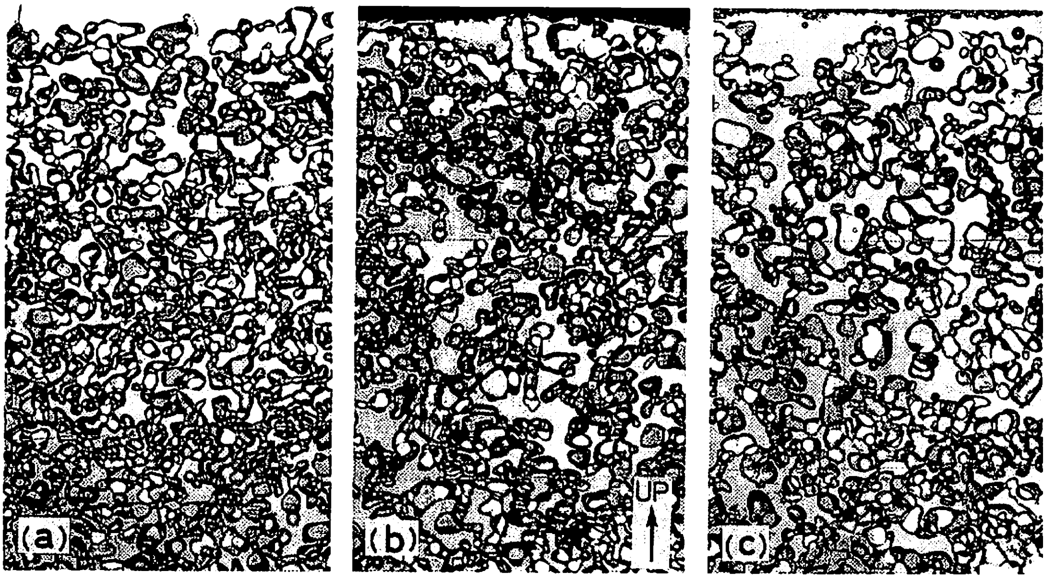

Fig. 8 Microscopic textures of vertical thin sections of fine-grained compact snow. (a) original, (b) after experiment without solar radiation and (c) after experiment under solar radiation.

To describe changes in snow texture quantitatively, 3 photographs of Fig.8 were analysed numerically by a image scanner. Measurements were made on grain area and bond area of the snow. Grain area was defined by the cross-sectional area of a snow grain which appeared on the surface of the thin section, and bond area by the cross-sectional area of a inter-grain ice bond on the assumption that the cross-section of an ice bond had a circular shape with a diameter equal to the neck width which appeared on the photograph.

Distribution of the grain area of the observation layer of the specimen, in the initial and final stage under the condition A (radiation) and B (non-radiation) are given in Fig.9. From this figure, it can generally be said that small grains (snow grains with a small grain area) decreased in number

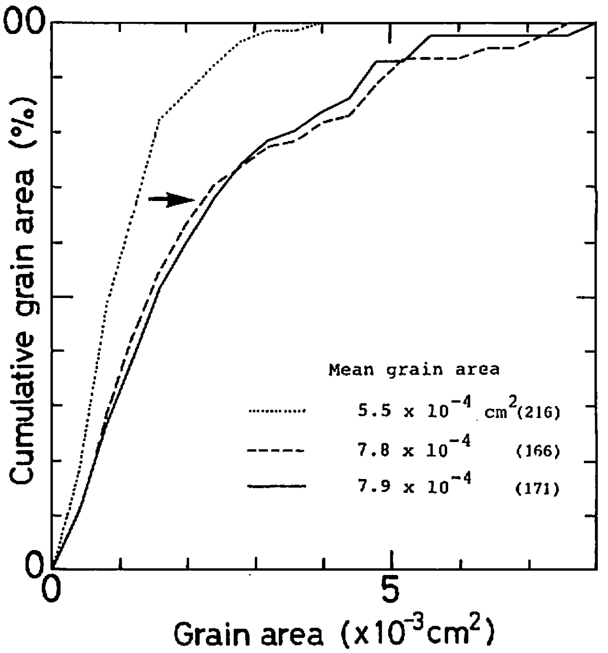

Fig. 9 Cumulative curves of grain area of snow. Dotted curve: intial, solid curve: after experiment under solar radiation (condition A), dashed curve: after experiment without solar radiation (condition B). Numeral in parenthesis is number of cross-sections of snow grains per square centimeter.

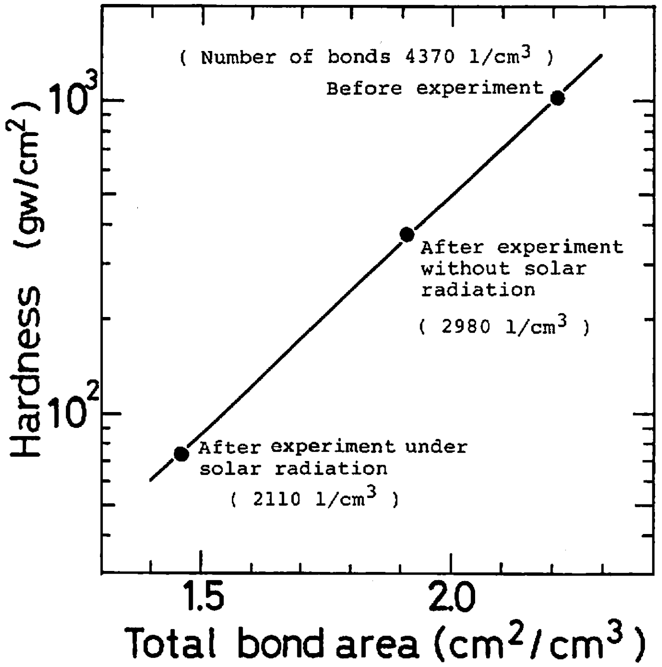

Fig. 10 Hardness and total bond area of snow.

while large grains increased and moreover larger grains than the largest ones of the initial stage were newly created through snow-melting process regardless of the experimental condition A or B. Such a change in grain size distribution was presumably caused by grain coarsening of snow whose water content increased. In fact, mean grain area in the specimen increased, and the number of snow grains per unit area decreased after the experiment regardless of the condition A or B, as seen in Fig.9.

Meanwhile, total bond area per unit volume obtained from the thin section photograph decreased under the condition B (nonradiation), and it decreased further greatly under the condition A (radiation), as shown in Fig.10. The diagram shows that the logarithm of hardness is proportional to the total bond area per unit volume of snow. It is found that a decrease in hardness of wet snow is caused by a decrease in total bond area, which depends mainly on the number of inter-grain ice bonds as shown in Fig.10.

The following mechanism of snow weakning by thermal process was presumed from these results :

The sensible heat transferred from air to snow surface and latent heat produced at the snow surface by condensation of water vapor in the air may cause snow-melting at the snow surface, even without solar radiation, and melt-water infiltrates into the snow. Snow which has increased its water content by melting decreases its hardness by the grain coarsening process, lessening the number of inter-grain ice bonds per unit volume with a decrease in the number of snow grains due to an increase in grain size. The amount of decrease in snow hardness depends upon the amount of water content increased. The maximum decrease in hardness will appear when the snow is saturated with water, reaching R_s.

Solar radiation penetrated into the snow cover is absorbed partially by snow grains, resulting in snowmelt even inside the snow cover and increase in water content if the snow temperature is 0 ℃. In this case, the grain boundaries absorb solar radiation predominantly. As a grain boundary very frequently exists at inter-grain ice bonds, an ice bond is easily thinned or cut off by solar radiation. The number of inter-grain ice bonds decreases due to such internal melting at the grain boundary in addition to the grain coarsening process. Consequently, hardness of snow greatly decreases due to solar radiation.

IV.1.3. Futher study on change in snow texture during application of solar radiation

A snow specimen of dry fine-grained compact snow with density of 0.390 g/cm³ at 0℃ was prepared. The artificial solar radiation was constantly applied to the surface of the specimen in the cold room at 1±1℃. Amount of artificial solar radiation applied to the surface of the specimen was 7.2 MJ/m² during 5.5 hours.

During the radiation experiment, three vertical thin sections (0.3 mm thick) of the observation layer were prepared intermittently at 1.5, 3.5, and 5.5 hours respectively after the start of the experiment. The results of texture analyses of them are given in Fig.11.

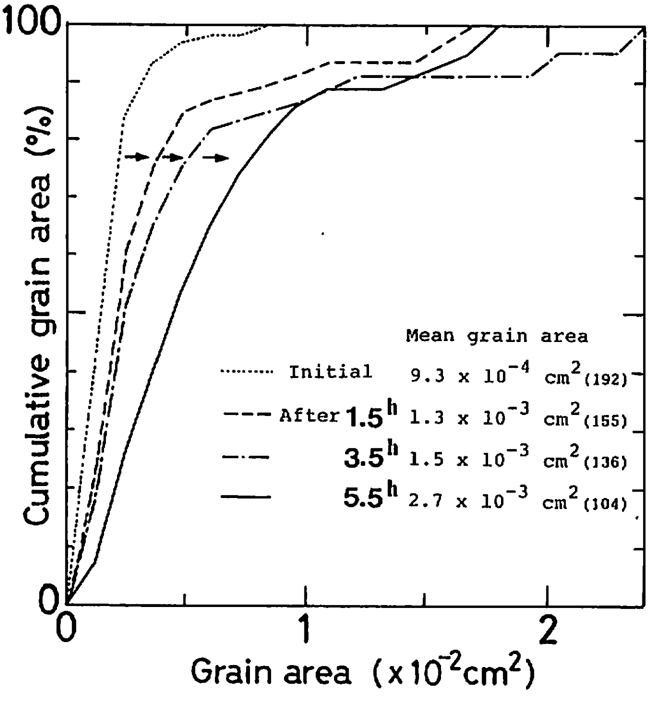

Fig.11 Cumulative curves of grain area of snow. Numeral in parenthesis is number of cross-sections of snow grains per square centimeter.

As is clearly seen in Fig.11, grain coarsening of snow proceeded in this experiment with radiation time, i.e., the fraction of small grains decreased while that of large grains increased and moreover larger grains than the largest ones of the initial stage were newly created. Such grain coarsening was caused by the increase of water content by snow-melting at the snow surface and inside the snow. Free water content of the observation layer increased to 5.5, 8.9 and 12.4% at 1.5, 3.5, and 5.5 hours after the start of the experiment, respectively.

Meanwhile, the total bond area U per unit volume obtained from the thin section analysis decreased with radiation time, as shown in Fig. 12. This figure shows that the logarithm of hardness, ln R, is proportional to the total bond area U. It is found that the hardness of snow during application of solar radiation decreases with radiation time due to the decrease in total bond area U, which depends mainly on the number of inter-grain ice bonds N per unit volume as shown in Fig.12.

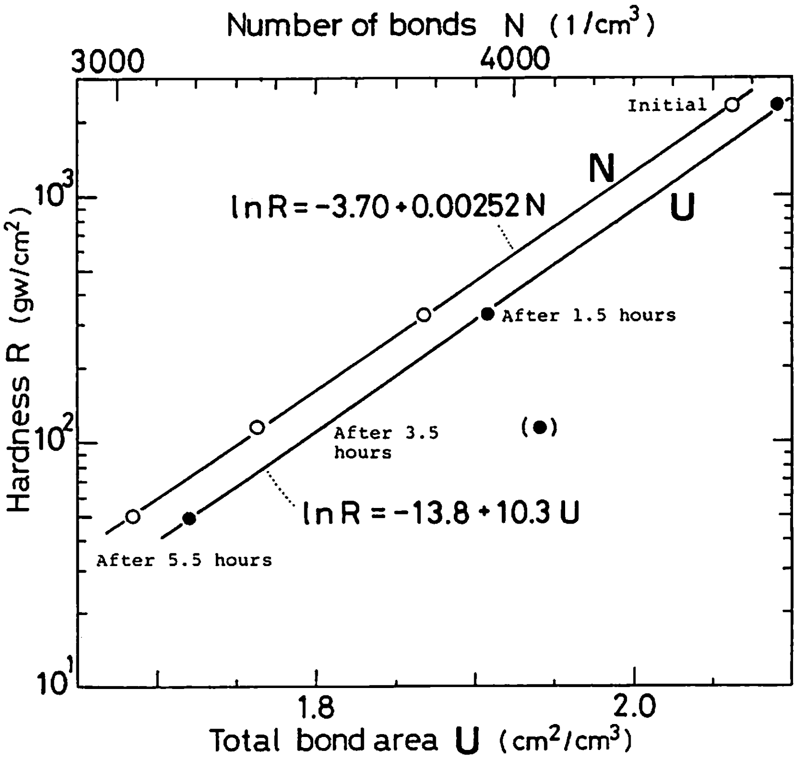

Fig.12 Change in hardness R, number of bonds N and total bond area U of snow with time, under solar radiation.

IV.1.4. Decrease in hardness of snow down to a value below $R_{s \cdot min}$

Four typical results on change in hardness of snow caused by solar radiation were summarized in Fig.13. The arrows indicate the change in hardness of each specimen from the initial to the final stage of the experiment. I and II are the results of experiments shown in Fig.7 and 12. In these cases, the final

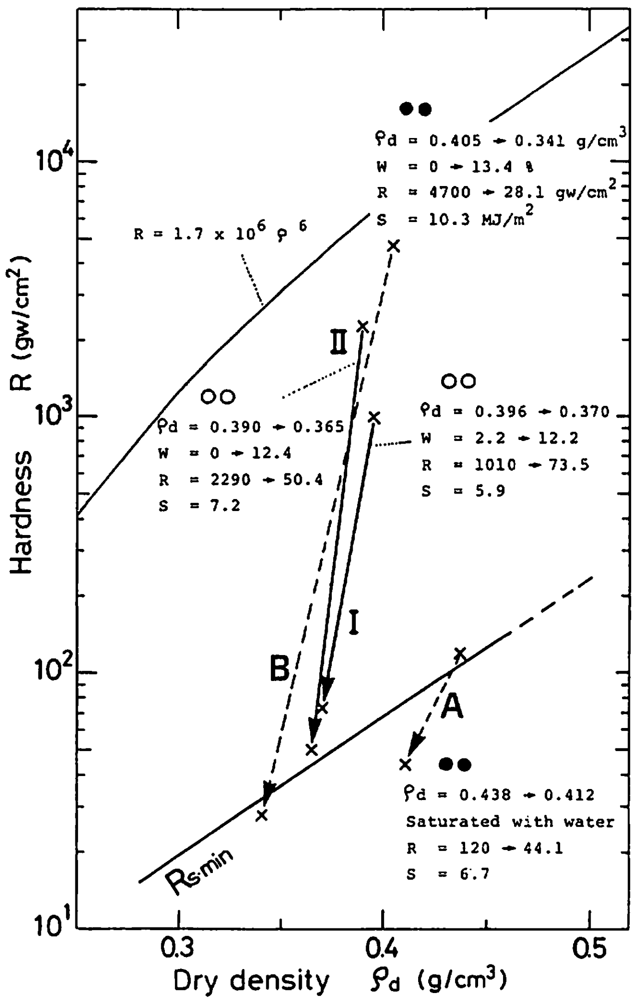

Fig.13 Change in hardness R and dry density ρ_d of snow under solar radiation, I. W: water content, S: applied solar radiation.

value of hardness was still larger than $R_{s.min}$. The reason for this fact would be attributed to a high value of hardness of the initial snow specimen, together with the small amount of artificial solar radiation applied.

To make clear the effect of these conditions on the decrease of snow hardness, two further experiments A and B were carried out.

Experiment A was made with water-saturated snow of dry density ρ_d = 0.438 g/cm^3. Its water saturation hardness was 120 gw/cm^2, which was very close value to $R_{s.min}$ for this dry density. Artificial solar radiation of 6.7 MJ/m^2 was applied on its surface. Then the hardness R of the snow decreased down to 44.1 gw/cm^2 which was below $R_{s.min}$ for the final dry density of 0.412 g/cm^3, as seen in Fig.13.

Experiment B was carried out with dry coarse-grained granular snow at almost 0℃ with dry density ρ_d =0.405 g/cm^3 and hardness R =4700 gw/cm^2, which was a much larger value than $R_{s.min}$ for this dry density. Then artificial solar radiation of 10.3 MJ/m^2 was applied on its surface: this amount of radiation was the largest one in laboratry experiments but approximately equivalent to the mean value of daily natural solar radiation in early March in Niigata Prefecture. As a result, hardness of the snow decreased down to 28.1 gw/cm^2 which was smaller than $R_{s.min}$ for the final dry density of 0.341 g/cm^3.

By these laboratory experiments described above, it was confirmed that by applying an artificial solar radiation, the hardness of snow could decrease to a value even below $R_{s.min}$ which was the minimum hardness attained only by water content.

Ⅳ.2. Relation between amount of solar radiation absorbed by snow and decrease in its hardness in laboratory experiments

Dominant fraction of incoming solar radiation into snow is reflected at the surface according to its albedo. The remainder is subject to absorption and scattering, so that its intensity is gradually reduced with depth. As it is usually assumed for simplicity that a snow mass acts as a homogeneous diffusing medium for radiation, solar radiation is considered to be attenuated according to the Bouger-Lambert law. Therefore, intensity of solar radiation I_z transmitted in the z-direction at depth z is given as,

$$I_z = (1-\alpha) I_0 \exp(-\mu z) \tag{5}$$

where α, μ and I_0 is albedo, extinction coefficient and intensity of incoming solar radiation at the snow surface, respectively. Absorbed solar radiation $q_{z_1 z_2}$ by a snow layer from depth z_1 to z_2 in a unit area and a unit time is given by,

$$\begin{aligned} q_{z_1 z_2} &= \int_{z_1}^{z_2} \mu (1-\alpha) I_0 \exp(-\mu z)\, dz \\ &= (1-\alpha) I_0 [\exp(-\mu z_1) - \exp(-\mu z_2)]. \end{aligned} \tag{6}$$

The amount of solar radiation Q absorbed by the snow layer during a certain period is calculated by time integration of eq.(6).

Thickness of an observation layer in the snow cover was selected as 3 cm, as the sampling thickness necessary for our measurements of density and water content of snow was 3 cm, respectively, and the depth affected by a penetration of Kinosita's gauge was within 3 cm to measure snow hardness. Therefore, a calculation of Q was made for the observation layer 3 cm thick.

Albedo α and extinction coefficient μ of snow was obtained by the results of field measurements on α (Kojima, 1979) and those of laboratory experiments on μ (Fukami *et al.*, 1980), respectively.

Solar radiation changes hardness R of snow, together with dry density ρ_d and water content W of it, as shown in Fig.7. To make clear the effect of solar radiation on snow hardness, the following analysis was made on the experimental results of hardness change of snow. Suppose that a snow specimen with dry density ρ_{d_0}, free water content W_0 and Kinosita's hardness R_0 was exposed under solar radiation, and finally attained ρ_{d_1}, W_1 and R_1, respectively. When ρ_{d_0} and W_0 of the snow change into ρ_{d_1} and W_1 without solar radiation, final hardness of the snow R_2 can be calculated by eqs. (4b) or (4c) as follows:

$$R_2 = R_0 \exp\left[0.0339\,(W_0 - W_1) + 12.1\,(\rho_{d_1} - \rho_{d_0})\right] \quad \text{(Snow I)}, \qquad (7a)$$

$$R_2 = R_0 \exp\left[0.0517\,(W_0 - W_1) + 14.0\,(\rho_{d_1} - \rho_{d_0})\right] \quad \text{(Snow II)}. \qquad (7b)$$

Then, to indicate the effect of only solar radiation on snow hardness, hardness ratio γ was defined as,

$$\gamma = R_1 / R_2 . \qquad (8)$$

If the snow was exposed under solar radiation for a long time, a large value of Q, R_1 becomes much smaller than R_2, missing a number of ice-bonds connecting snow grains by the radiation which results in a small value of γ. Figure 14 shows the relation between amount of absorbed solar radiation Q and hardness ratio γ in the case where original snow was dry at nearly 0℃. Figure 15 shows a similar relation in the case where original snow was wet.

The hardness ratio γ decreases exponentially with an increase in Q independent of snow type in both cases, Fig.14 and 15. Hardness of a snow layer at 0℃ after application of solar radiation can be approximately estimated from the amount of solar radiation absorbed by the layer and the initial hardness of it by the use of Fig.14 or 15.

Figure 14 indicates that γ for dry snow seems to tend to a value less than 1.0, let us say $\gamma = 0.7$ by a simple extrapolation, for $Q = 0$, while $\gamma = 1.0$ for wet snow for $Q = 0$. It is presumed that this discrepancy of γ of dry snow and wet snow indicates the abrupt decrease of hardness of dry snow at 0 ℃ by containing water (Tusima, 1970).

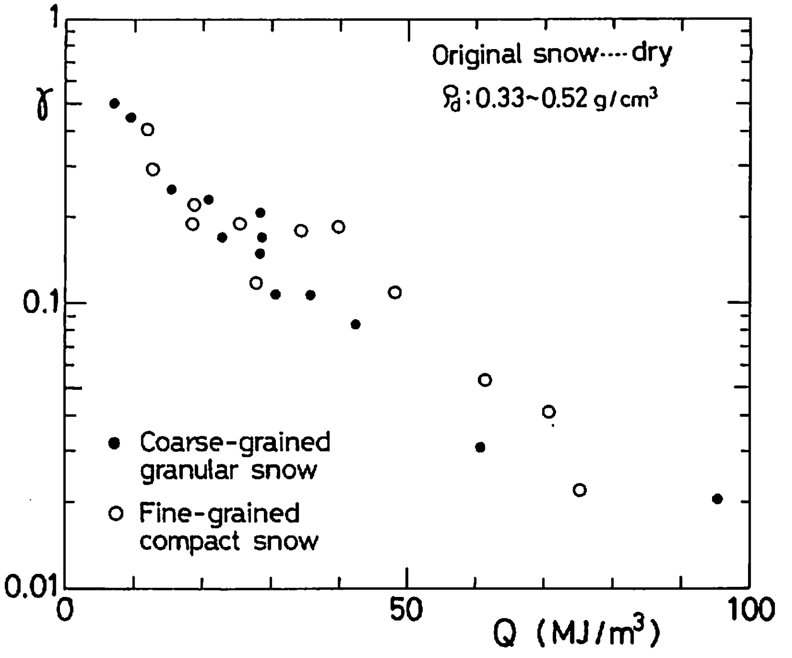

Fig.14 Relation between absorbed solar radiation Q and hardness ratio r. (original snow was dry)

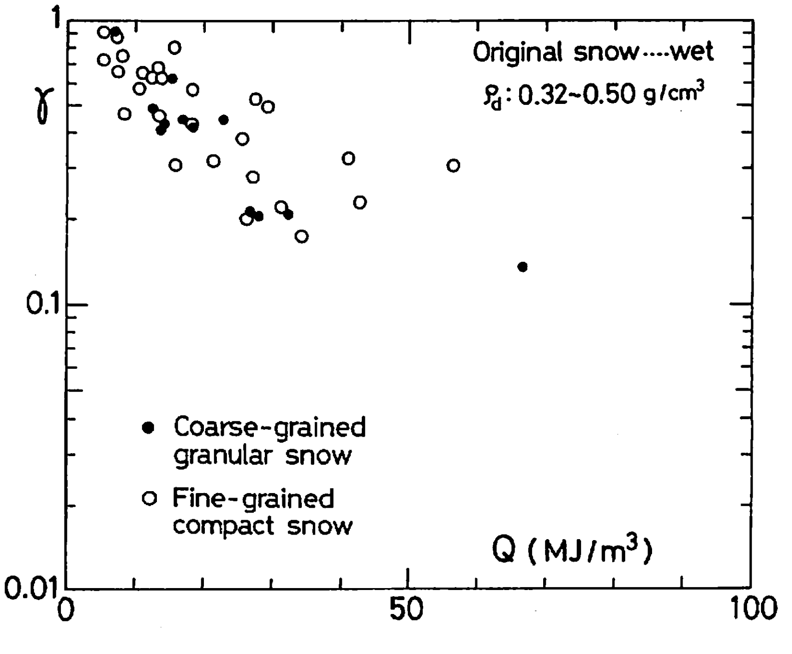

Fig.15 Relation between absorbed solar radiation Q and hardness ratio r. (original snow was wet)

Ⅳ.3. Field experiments and observations

Ⅳ.3.1. Procedure for field experiments

Field experiments on change in hardness of snow under natural solar radiation were carried out at Sapporo and Moshiri, Hokkaido, in March and April, 1986. To begin with, a uniform snow block was taken out from a depth in a snow cover where snow was scarcely influenced by solar radiation. A squared snow specimen of 30 cm×30 cm with 10 cm of thickness was cut out from the snow block. Then the specimen was set in a hole excavated on the surface of the snow cover tightly, making the upper surface of it the same level with that of the snow cover, and exposed under solar radiation in the daytime to study the effect of solar radiation on snow hardness and snow texture. As snow specimen showed proper snow-melting, an observation layer (3 cm thick) was selected at a paticular level inside the specimen before an experiment, and the experiment was continued until the upper surface of the observation layer was exposed directly under solar radiation. Surface level *HS* of the specimen, free water content *W*, dry density ρ_d and hardness *R* of the layer were measured before and after the experiment. Incoming solar radiation was measured by a pyranometer at the experimental site. The amount of solar radiation applied to the snow surface during the experiment ranged from 6.7−15.6 MJ/m^2. The value of albedo α and extinction coefficient μ of snow obtained by Kojima (1979) and by Fukami *et al.* (1980), respectively, was used basically for analysis, while α of several specimens were directly measured by an albedo-meter in the field.

Ⅳ.3.2. Decrease in hardness of snow caused by solar radiation in the field

Change in hardness and dry density of snow under solar radiation in the field are summarized in Fig.16. Initial hardness of snow (● coarse-grained granular snow and ○ fine-grained compact snow) and its final hardness (×) in the experiment were connected with an arrow (a solid arrow indicated the field experiment, while a broken arrow the laboratory experiment), in the figure. As a general tendency of the experimental results, dry density ρ_d decreased with decrease of snow hardness except for low density range. When the dry density of the initial snow was less than 0.35 g/cm^3, the final dry density increased slightly. This is considered to be caused by densification of snow with small dry density during the application of solar radiation.

As is seen in Fig.16, more than half of the field experiments showed hardness decrease to below $R_{s.min}$. It was proved that snow hardness could decrease to the value below $R'_{s.min}$ also under natural solar radiation.

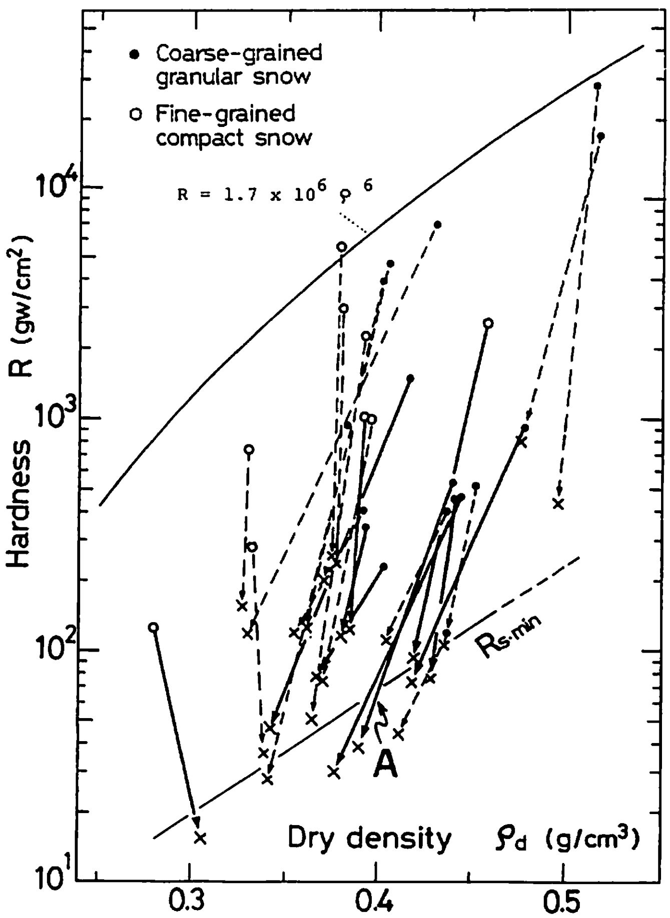

Fig.16 Change in hardness and dry density of snow under solar radiation, II.
Solid arrow: field, broken arrow: laboratory.

Detail of field experiment A in Fig.16, was given in Fig.17. The specimen was wet coarse-grained compact snow with free water content $W=8.8\%$ and dry density ρ_d $=0.440$ g/cm³. Amount of solar radiation applied to the snow surface was 7.0 MJ/m² during 8 hours of the experiment. Albedo α of the snow was directly measured as $\alpha=0.60$ and extinction coefficient μ was taken value of $\mu=0.35$ from the experimental result of Fukami *et al*. (1980). The observation layer was selected 1.5 cm below the snow surface when the experiment was started.

Hardness of snow decreased from 541 gw/cm² down to 39.0 gw/cm² which was clearly less than $R_{s\cdot min}$ for the final dry density of 0.390 g/cm³, in this experiment. At the same time, ρ_d and W of the obsevation layer changed resulting

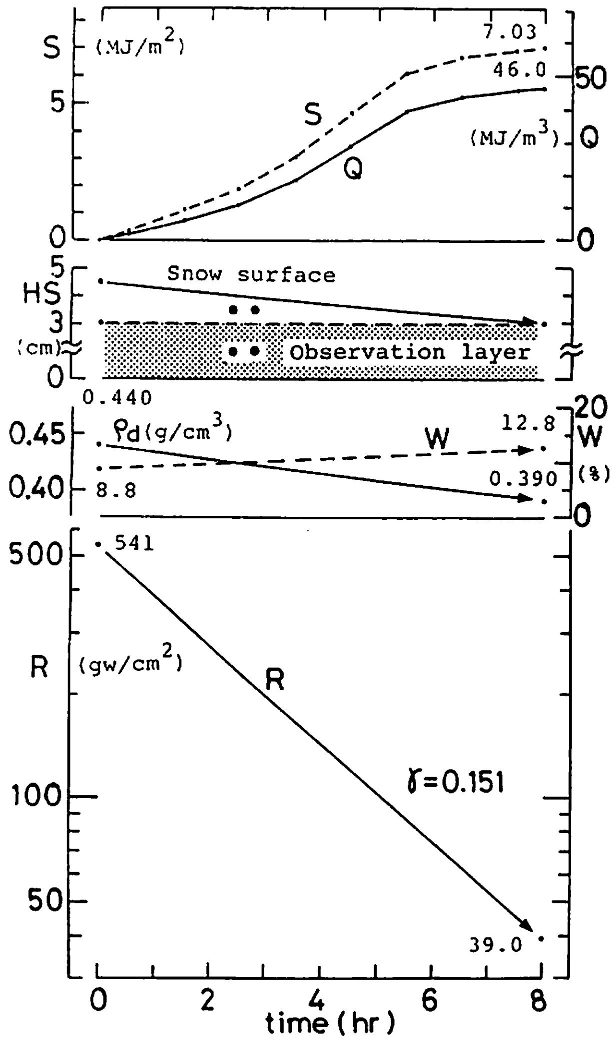

Fig.17 Change in hardness R of an observation layer in a snow cover, under natural solar radiation. S: cumulative solar radiation, Q: solar radiation absorbed by the layer, HS: level of snow surface. W, ρ_d : water content and dry density of the layer.

in $r = 0.15$, i.e., hardness of snow decreased down to 1/7 of the initial value only by solar radiation, in this case.

Change in texture of the observation layer in this solar radiation experiment is shown in Fig.18. They are micro-photographs of vertical thin sections of 0.7 mm thick respectively, under polarized light. In the initial stage, picture (a), large snow grains composed of several single ice crystals which were generated by melt-freeze metamorphism can be seen here and there. But their number decreased considerably while small grains increased relatively,

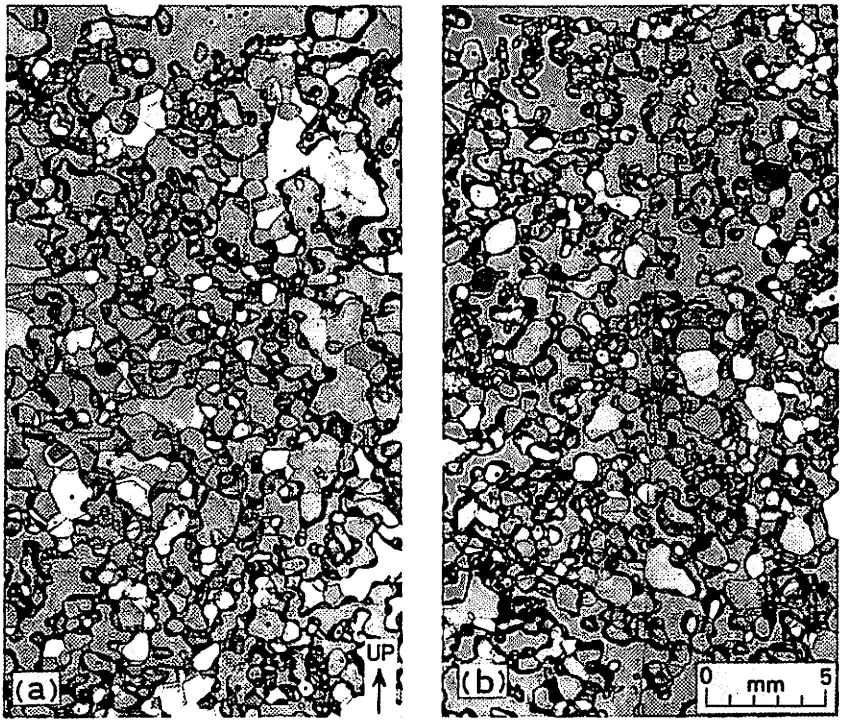

Fig. 18 Microscopic textures of vertical thin sections of coarse-grained granular snow. (a) original, (b) after appling solar radiation. Photographs were taken by polarized light.

in the final stage (b).

To study such change in distribution of grain size quantitatively, grain area on the photographs of Fig. 18 were analysed by the image scanner. Cumulative curves of grain area in the initial and final stage of the observation snow layer were given in Fig. 19. It can clearly be seen from this result that the fraction number of large grains decreased remarkably while that of small grains increased by this solar radiation experiment. This change in snow texture was principally caused by internal melting of snow at the grain boundaries of polycristalline snow grains by the solar radiation. As a result, big polycrystalline snow grains were disintegrated into small single crystals. Actually, the number of cross-sections of snow grains increased after the experiment as indicated in Fig. 19.

Similar phenomena can be observed on a thin ice layer near the surface in a snow cover, especially in snowmelt season. The thin ice layer absorbs solar radiation sufficiently, and is disintegrated into small pieces of single crystal and polycrystalline ice plate along grain boundaries, and scarcely appears on the surface of snow as a sheet of thin ice.

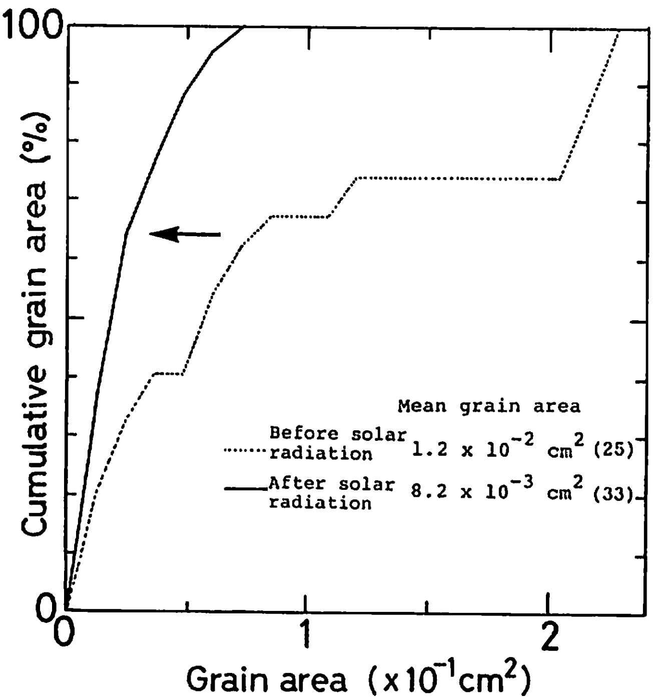

Fig.19 Cumulative curves of grain area of snow. Dotted curve: original, solid curve: after appling solar radiation. Numeral in parenthesis is number of cross-sections of snow grains per square centimeter.

IV.3.3. Field observations

As the snow surface descends by snow-melting, an inner snow layer of the snow cover comes closer to the surface step by step. As a result, the inner layer is gradually exposed under solar radiation through the upper snow layer. Change in amount of absorbed radiation and hardness of an inner snow layer under such condition were observed in the field at Moshiri, Hokkaido in April 1986.

An example of such observation is given in Fig.20. The observation layer was selected 16 cm below the surface in the initial stage of the observation. Snow type of the layer was coarse-grained granular snow. The amount of solar radiation absorbed by the snow cover was calculated from upward and downward solar radiation measured by two pyranometers respectively, at the experimental site. Extinction coefficient μ of the snow was taken value of $\mu = 0.30$ from the experimental result of Fukami *et al.*(1980).

Snow-melting proceeded moderately before April 23, and actively thereafter as seen in Fig.20. Amount of solar radiation Q absorbed by the observation layer was only 1.7 MJ/m^3 for the former period, April 21, 16:30 − April 23, 11:20, while 33.6 MJ/m^3 for the latter period, April 23, 11:20 − April 25,

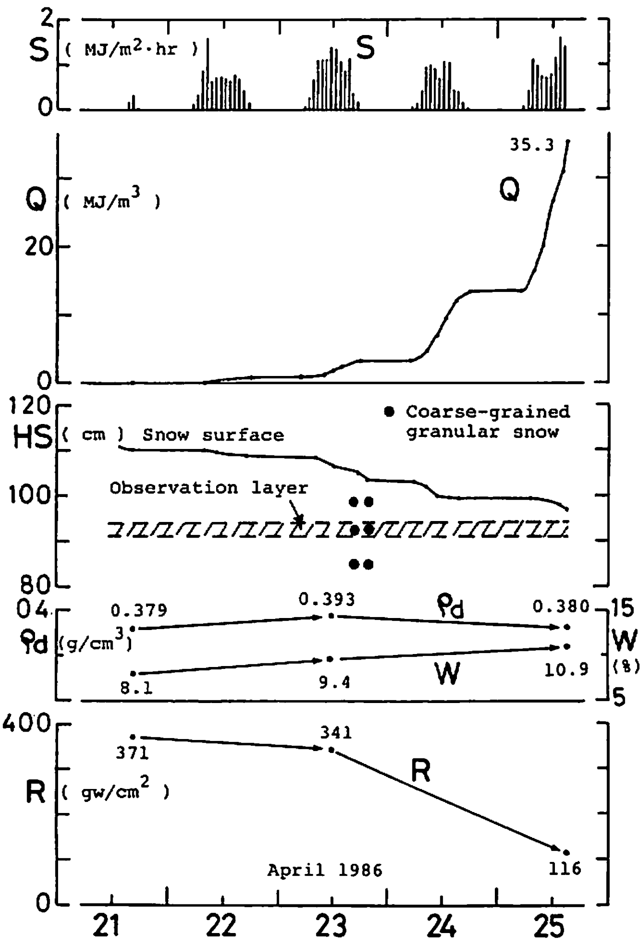

Fig. 20 Decrease in hardness R of a snow layer in a snow cover during absorption of natural solar radiation. S : solar radiation, Q : solar radiation absorbed by the layer, HS : level of snow surface. W, ρ_d : water content and dry density of the layer.

14:50. Snow hardness of the observation layer scarcely changed in the former period, but it decreased from 341 gw/cm² down to 116 gw/cm² which was about 1/3 of 341 gw/cm² and gave $\gamma = 0.42$ in the latter period, i.e., this decrease of snow hardness was mostly caused by solar radiation.

The result of such field observation reveals that solar radiation has a predominant effect to decrease snow hardness. Moreover, it was experimentally confirmed that the effect of solar radiation on decreasing hardness of snow could penetrate about 10 cm into the snow from the surface: the thickness of the surface snow layer which suffers from the effect of solar radiation varies depending upon amount of solar radiation, albedo and extinction coefficient of snow.

By such manner, solar radiation can form a very fragile snow layer beneath the snow surface which occasionally provides a sliding layer for surface avalanches with or without an overlaid snow accumulation.

IV.3.4. Relation between amount of solar radiation absorbed by snow and decrease in its hardness in the field

Figure 21 shows the relation between the amount of solar radiation Q absorbed by snow and the hardness ratio γ of the snow measured in the field and in laboratory (Fig.15). The hardness ratio γ of wet snow in the field decreased exponentially with an increase in Q regardless of snow type. This relation obtained in the field coincides with that obtained in laboratory, as shown in Fig.21. This fact also indicates that the artificial solar radiation used in laboratory had almost the same influence on snow hardness as natural solar radiation.

Regression equation for all plots of Fig.21, which gave $\gamma = 1$ for $Q = 0$, was obtained as,

$$\gamma = \exp(-0.0368\,Q). \tag{9}$$

This equation indicates that hardness of snow decreases down to 1/5 and 1/10 of the initial value by absorption of solar radiation of 44 MJ/m^3 and 63 MJ/m^3, respectively.

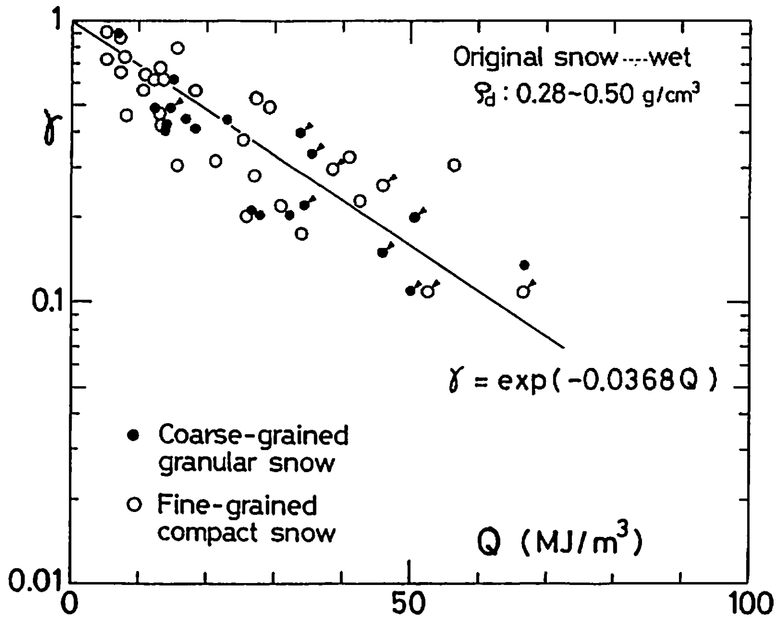

Fig. 21 Relation between absorbed solar radiation Q and hardness ratio γ. ●, ○ (flagged): field experiments, ●, ○: laboratory experiments.

V. Application of the experimental results to actual avalanches

V.1. Recent accidents caused by avalanches in Niigata Prefecture

In the Hokuriku District of Japan, especially in Niigata Prefecture, a tremendous amount of snow accumulates in winter, with a distinct feature: snow frequently contains water even in mid-winter. We have had a number of accidents caused by avalanches with a sliding plane of wet snow in the prefecture. Generally, avalanches caused by wet snow can be classified into 4 types as shown in Fig.22, i.e., (A) dry surface type (surface avalanche of dry snow released by a sliding plane in a wet snow layer), (B) dry full-depth

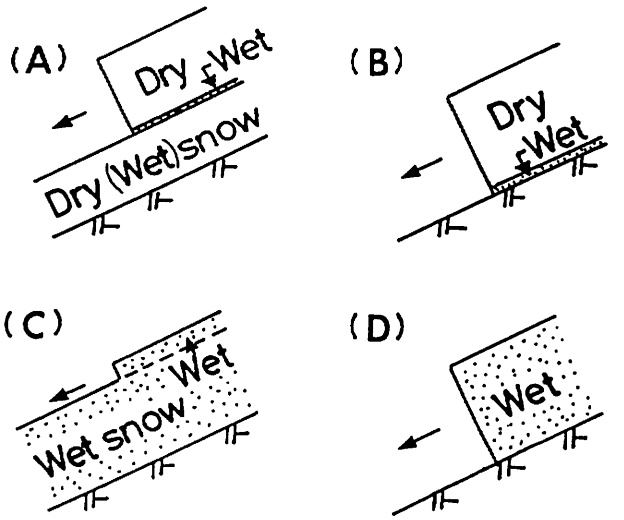

Fig. 22 Four types of avalanches having a sliding plane of wet snow. (A): dry surface type, (B): dry full-depth type, (C): wet surface type. (D): wet full-depth type.

type (full-depth avalanche of dry snow released by a basal sliding plane of wet snow), (C) wet surface type (thin surface avalanche of wet snow), (D) wet full-depth type (full-depth avalanche of wet snow). Brief description and location of typical accidents, caused by the avalanches of these four types which occurred in recent years, are given in Table 2 and Fig.23.

As the type (A) avalanche is basically a dry surface avalanche, it occasionally becomes a big scale powder avalanche running over an incredible long distance with an immense snow quantity and speed, during a heavy snowfall. Therefore, it brings on severe disaster. The type (C) avalanche sometimes results in an accident, although it is generally on a very small scale.

Table. 2 Recent accidents caused by avalanche which had a sliding of wet snow in Niigata Prefecture.

	Avalanche type	Location (Fig.23)		Date	Volume(m³)	Deaths
(A)	Dry surface	Ohkura, Sumon	(1)	Jan. 7, 1981	1.5×10^5	8
		Maseguchi, Nou	(2)	Jan. 26, 1986	$1 \sim 2.5 \times 10^5$	13
(B)	Dry full depth	Simo-oritate, Yunotani	(3)	Jan. 18, 1981	9.6×10^3	6
(C)	Wet surface	Aoshima, Koide	(4)	Mar. 9, 1985	$2 \sim 3$	2
(D)	Wet full depth	Yamamoto, Ojiya	(5)	Mar. 18, 1984	3×10^2	—

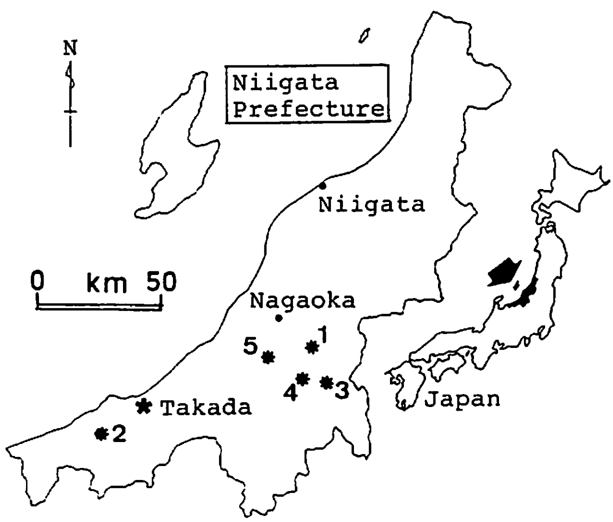

Fig. 23 Location of the avalanche accidents in Table 2.

Two avalanches of type (A) and (C) which occurred in recent years and resulted in disasters will be discussed respectively in the following sections, as it is reasonably presumed that a weak layer of wet snow which provided the sliding plane for both avalanches was formed by the same mechanism caused by solar radiation.

V.2. Maseguchi avalanche, 1986 (type A)

A big scale dry surface avalanche which broke out on the east slope of Mt. Gongen (1,108 m a.s.l.) assaulted Maseguchi, Nou, Niigata Prefecture, around 11:00 p.m., January 26, 1986. Thirteen people were killed, 9 injured, 8 houses crushed and 3 partially destroyed by this avalanche.

Relative height of Mt. Gongen to Maseguchi was 800 m and horizontal distance between them 2,000 m. The profile of the avalanche track was concave, composed of a steep mountain slope and a gentle mountain foot, as shown in

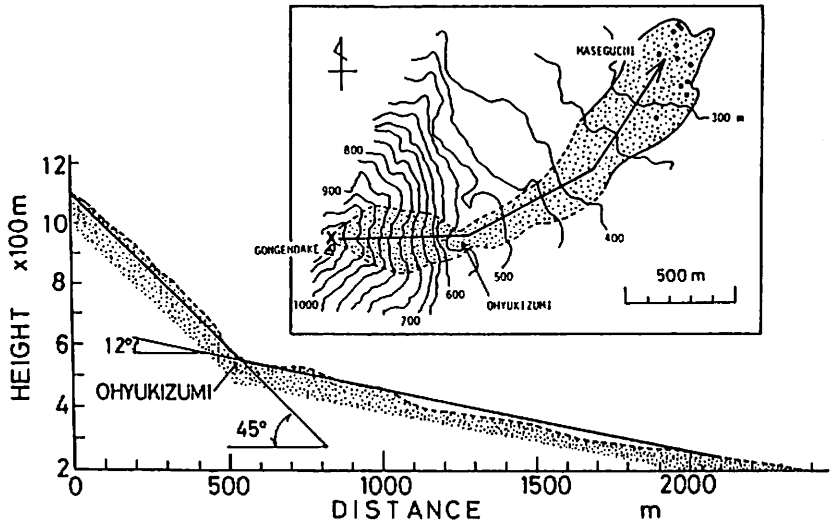

Fig. 24 Track profile of Maseguchi Avalanche, 1986 (Kobayashi, 1986).

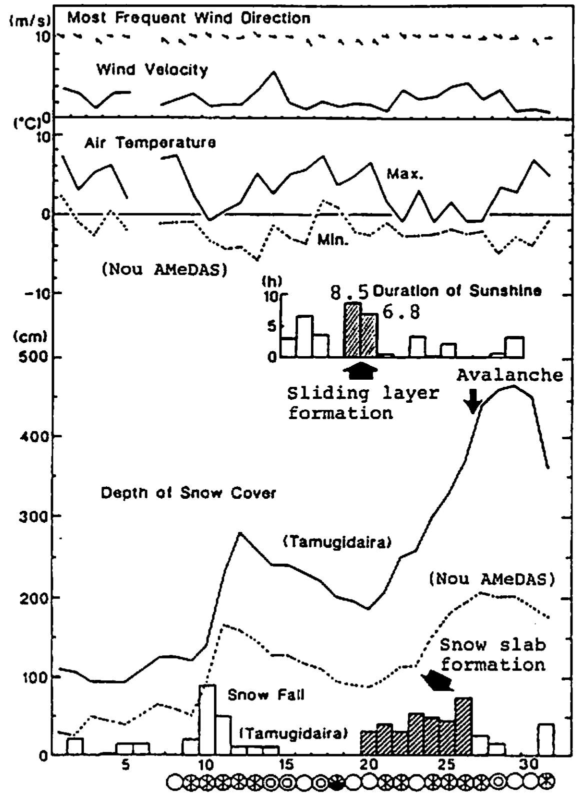

Fig. 25 Daily meteorological data at Nou AMeDAS station and Tamugidaira village observatory (Kobayashi, 1986). ○, ◎, ❄ and ◓ indicate fine, cloudy, snowy and sleety weather respectively, at Tamugidaira at 9:00 a.m.

Fig.24 (Kobayashi, 1986), resulting in an average slope angle of 21.8°.

In the winter of 1985 – 1986, heavy snowfall occurred twice in January in the western Niigata Prefecture, e.g., snow depth at Tamugidaira (village observatory), 0.6 km SE of Maseguchi, reached 465 cm on January 29 which was the 2nd highest recorded there for January (Fig. 25). Snowfall stopped and the sun shone occasionally from January 15 to 20. Successive heavy snowfall started late on January 20, and snow depth reached 440 cm at Tamugidaira at 9:00 a.m., January 27.

A pit observation of natural snow cover on flat ground was made at Maseguchi on January 30, 4 days after the avalanche. The snow cover was 384 cm in thickness and the upper half of it was composed of dry snow. At the level between 151.5 cm and 154.5 cm above the ground, a very fragile wet snow layer was observed as shown in Fig.26 and 27, and it was termed the weak layer. The weak layer was 3 cm in thickness, composed of wet coarse-grained granular snow, with 7.3% of water content, 0.33 g/cm^3 of dry density and 22 gw/cm^2 of Shear Frame Index. Also, Ram hardness profile of the snow cover showed a remarkable

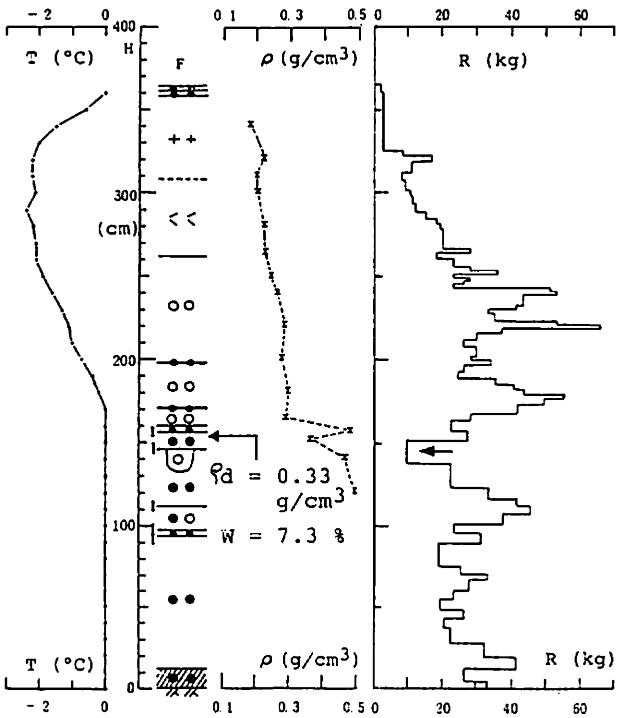

Fig. 26 Pit observation of the snow cover on flat ground at Maseguchi (Kobayashi, 1986). *T*: snow temperature, *ρ*: snow density, *R*: Ram hardness, *W*: water content, *F*: snow stratification (ref. Appendix), *H*: snow height.

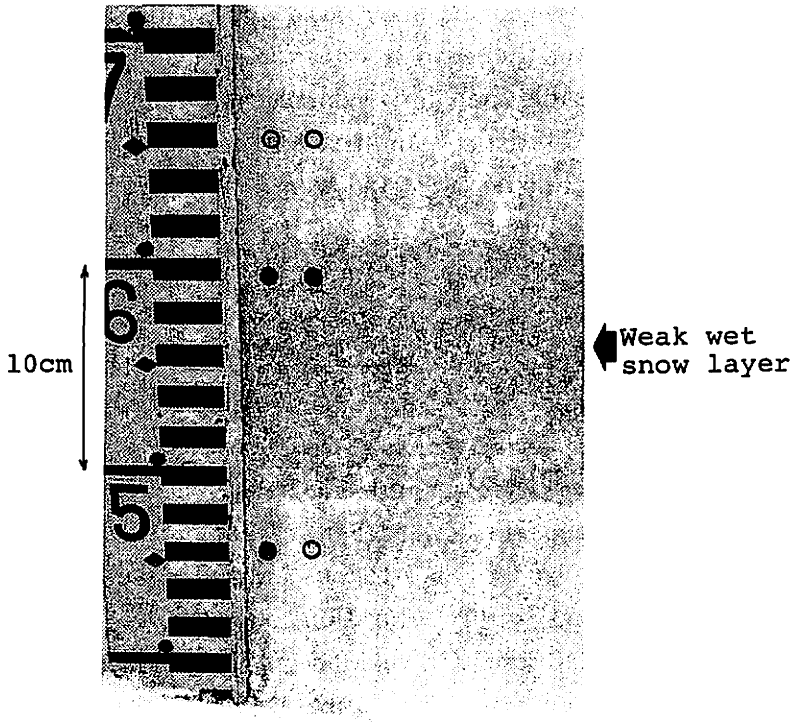

Fig. 27 Weak layer of wet coarse-grained granular snow appeared on the pit-wall at Maseguchi on Janualy 30, 1986. Solid circle: coarse-grained granular snow, open circle: fine-grained compact snow.

depresssion at this level, suggesting clearly the existence of a weak layer here. It was presumed that this weak layer provided the sliding plane in the starting zone of the avalanche.

Mechanical balance of the snow slab in the avalanche starting zone was estimated as follows: from the pit observation at Maseguchi, height and load of the snow slab above the weak layer was presumed to be 250 cm and 41.2 gw/cm^2, respectively, in the starting zone. As the slope angle θ there was $40-50°$, shear stress τ working across the weak layer caused by the upper snow was estimated as,

$$\tau = 41.2 \times \sin\theta \times \cos\theta = 20-21 \text{ gw/cm}^2. \quad (10)$$

Meanwhile, the Shear Frame Index of this weak layer was SFI = 22 gw/cm^2. Stability of a snow slab on a weak layer was defined by Roch (1966) as,

$$SI = SFI / \tau \quad (11)$$

where SI is the Stable Index of the snow slab and τ the shear stress working across the weak layer. And he gave a criterion that if SI$<$4, the snow slab on the weak layer is unstable, and an avalanche is easily released.

Perla (1977) made a statistical analysis on SI data at the fracture point of 80 avalanches in several districts of the world, and obtained an average value of 1.66 with a standard deviation of 0.98. He gave a new criterion for avalanche release as SI$<$1.5. This criterion is used in practice for avalanche forecasting at Rogers Pass, Canada.

Applying this criterion to SI data of the Maseguchi Avalanche, SI =1.05−1.10, it can reasonably be said that the snow slab on the weak layer was very unstable and dangerous enough to cause an avalanche release.

Formation of the weak layer was presumed as follows, by the use of meteorological data in the vicinity of Maseguchi : Tamugidaira village observatory provided snowfall and snowdepth data, Nou AMeDAS* station (6 km NNW of Maseguchi) wind, air temperature, duration of sunshine and snowfall data, Takada Weather Station (18 km ENE of Maseguchi) global solar radiation.

During a 6-day break of heavy snowfall, from January 15 to 20, occasional sunshine and high air temperature up to +7℃ occurred, which resulted in snow-melting and transformed the whole snow cover to wet. The weak layer became coarse-grained by melt metamorphism. Then it was affected by solar radiation mainly on January 19 and 20, when the depth of the layer from the snow surface became 10 cm or less by surface melting, just before the successive snowfall started late on January 20. The influence of solar radiation on the weak layer before January 19 could be neglected quantitatively. Let's estimate the amount of solar radiation absorbed by the weak layer during January 19 and 20.

Figure 28 shows the relation between the duration of sunshine (hr/day) and daily solar radiation ($MJ/m^2 \cdot day$) at Takada during the period of January 14 −21, 1986. Daily solar radiation at Maseguchi during January 19 and 20, 1986 was estimated putting the duration of sunshine at Nou on those days in the relation given in Fig.28. Albedo and extinction coefficient of the weak layer and wet coarse-grained granular snow layer over the weak layer were taken as 0.6 and 0.35, respectively.

Finally, the amount of solar radiation absorbed by the weak layer was estimated as 4.3 and 15.3 MJ/m^3 for January 19 and 20, respectively, 19.6 MJ/m^3 in total, taking account of the absorption of radiation by the snow layer over

* Automated Meteorological Data Acquisition System

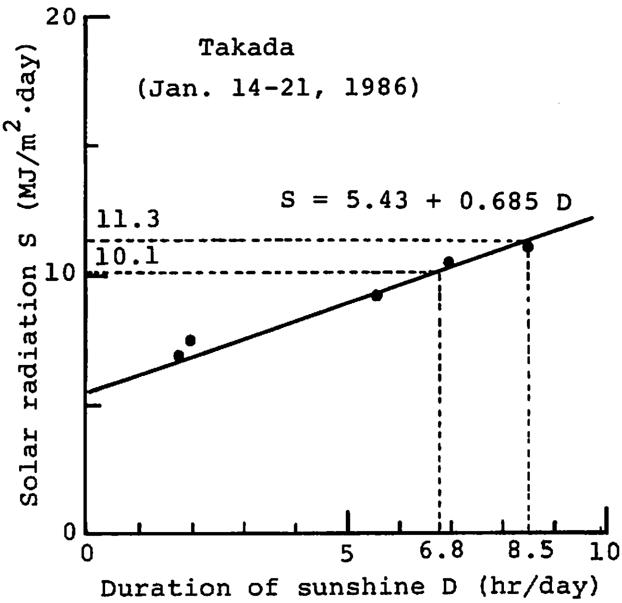

Fig. 28 Relation between daily solar radiation and duration of sunshine at the weather station of Takada during January 14-21, 1986.

the weak layer which was refreezed by the successive cold snowfall and hardened.

Previously, it was suggested by eq.(9) that wet snow decreased its hardness down to 49% (γ =0.49) of the original value by absorbing a solar radiation of 19.6 MJ/m^3. The hardness of the weak layer was 89 gw/cm^2, obtained by the shear strength (Shear Frame Index), using eq.(2). Therefore, the original hardness of the weak layer was presumed to have been 182 gw/cm^2(= 89 / 0.49) before the absorption of solar radiation during these two days, under a simple assumption neglecting changes in water content and dry density of the snow. Wet coarse-grained granular snow with dry density of 0.33 g/cm^3 and hardness of about 180 gw/cm^2 is commonly observed in the snow cover, as seen in Fig.2.

Regarding the Maseguchi Avalanche, 1986, the following process of unstable slab formation was reasonably presumed. During a break of heavy snowfall from January 15 to 20, 1986, the snow cover turned into wet coarse-grained granular snow as snow-melting proceeded. The surface snow layer just before the successive snowfall greatly decreased its hardness by the absorptin of a large amount of solar radiation. As a result, surface of the snow cover was furnished with a very fragile wet coarse-grained granular snow layer several centimeters thick. Then successive snowfall started late on January 20, depositing new snow, possibly more than 250 cm at the starting zone of the avalanche, upon the wet coarse-grained granular snow layer which was refreezed gradually from the upper surface beneath the newly accumulated cold snow. But the lower part of it remained as a wet weak layer till the avalanche. As the newly accumulated snow increased its thickness, the snow slab above the weak layer became unstable.

It was presumed that the Maseguchi Avalanche was released as a climax avalanche on January 26, after a 6−day heavy snowfall, the weak wet snow layer formed by solar radiation providing the sliding plane.

With regard to the Ohkura Avalanche, 1985 (Table 2), the same type as the Maseguchi Avalanche, formation process of the weak wet snow layer of the sliding plane was also examined. As a result, it was revealed that this weak layer was also formed by solar radiation when it existed near the snow surface.

V.3. Aoshima Avalanche, 1985 (type C)

On March 9, 1985, a wet surface avalanche of about 10 cm thickness was released on the south slope of the hill called Yukiyama, Aoshima, Koide, Niigata Prefecture (Fig.29), where three children were playing with snow sleds, and two of them were buried by the avalanche debris and killed by suffocation.

In December and January of that winter heavy snowfall and deep snow occurred in Niigata Prefecture. In February, air temperature rose highly and

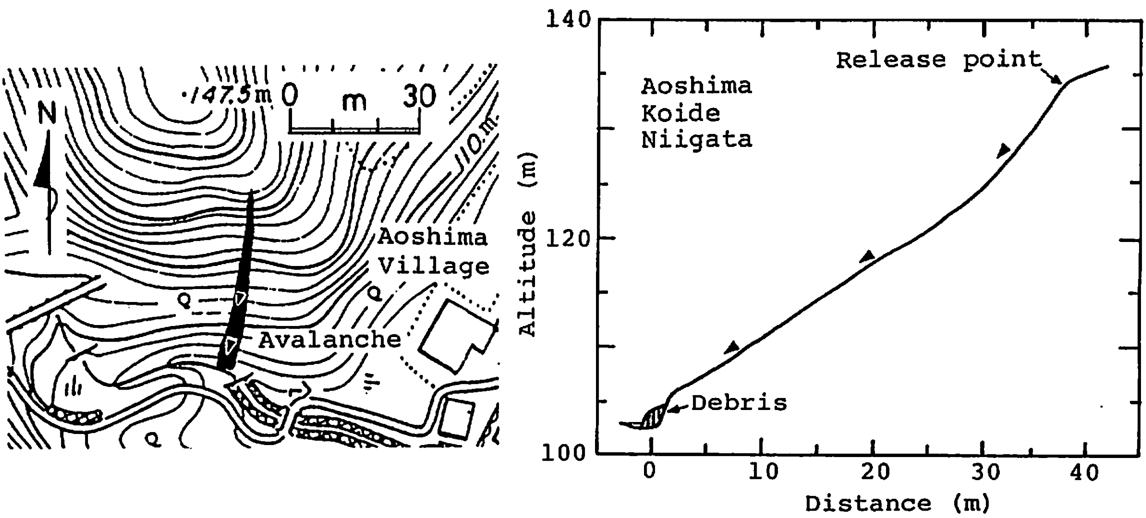

Fig. 29 Track profile of Aoshima Avalanche, 1985.

extraordinarily active snow-melting proceeded. Such a meteorological condition made the whole snow cover sufficiently soaked, and the snow metamorphosed into coarse-grained granular snow. New snow which was deposited on the old snow cover in middle and late February also metamorphosed into coarse-grained granular snow.

On March 10, the day after the avalanche accident, a pit observation of the snow cover was made on flat ground at Aoshima. The result is shown in Fig.30. The snow cover was mostly composed of wet coarse-grained granular snow. Just beneath the new snow layer 4 cm thick which was deposited after the avalanche, an extremely fragile layer of wet coarse-grained granular snow 12.5 cm thick was found. This was the surface snow layer which avalanched on March 9. Dry density, water content and hardness of the 3 cm thick upper part of this fragile layer, which was the weakest part of this layer, was 0.33 g/cm^3, 15.3% and 16.2 gw/cm^2, respectively. This hardness given by mark A in Fig.5 was below $R_{s.min}$. Therefore, the effect of solar radiation on weakening snow was considered for the formation of this fragile layer, by the use of meteorological data in this region and its vicinity.

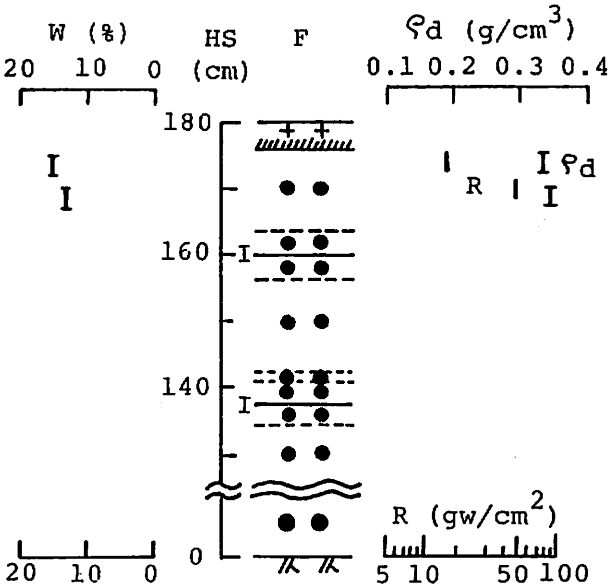

Fig. 30 Pit observation of the snow cover on flat ground at Aoshima on March 10, 1985, one day after the Avalanche. *W*: water content, *HS*: Snow height, *F*: snow stratification (ref. Appendix), ρ_d : dry density, *R*: Kinoshita's hardness.

Hourly meteorological data at Koide AMeDAS station, 2.5 km NNE of Aoshima, during the period of March 3−9, is given in Fig. 31. From these data it can be seen that on March 9 this fragile layer became the surface layer by rapid melting of the snow over it. Therefore, this layer absorbed solar radiation mainly on March 8 and 9.

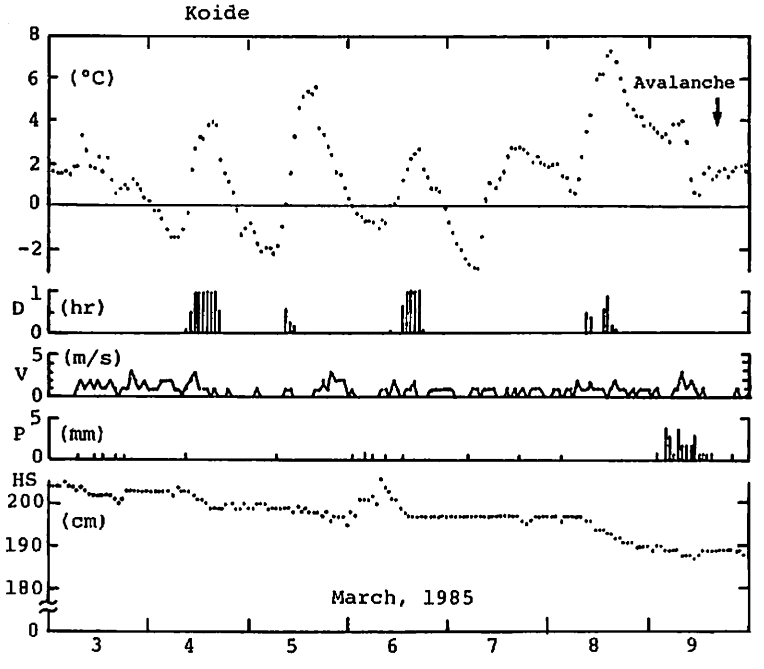

Fig. 31 Hourly meteorological data at Koide AMeDAS station, during March 3−10, 1985. *T*: air temperature, *D*: duration of sunshine, *V*: wind speed, *P*: precipitation, *HS*: snow height.

The amount of solar radiation absorbed by the 3 cm thick upper part of this fragile layer was estimated by duration of sunshine at Koide AMeDAS station and daily solar radiation at Takada Weather Station, 63 km WSW of Aoshima. Figure 32 shows the relation between duration of sunshine (hr/day) and daily solar radiation ($MJ/m^2 \cdot day$) at Takada during the period of February 23−March 10, 1985. Daily solar radiation at Aoshima on March 8 and 9, 1985 was estimated putting the duration of sunshine at Koide on these days in the relation given in Fig. 32. Albedo and extinction coefficient of the fragile snow layer were taken as 0.55 and 0.35 respectively.

Finally, the amount of solar radiation absorbed by the upper 3 cm of the fragile layer was estimated as 10.0 and 34.7 MJ/m^3 for March 8 and 9 respectively, 44.7 MJ/m^3 in total, taking account of the absorption of the snow on the fragile layer which had melted away during these two days.

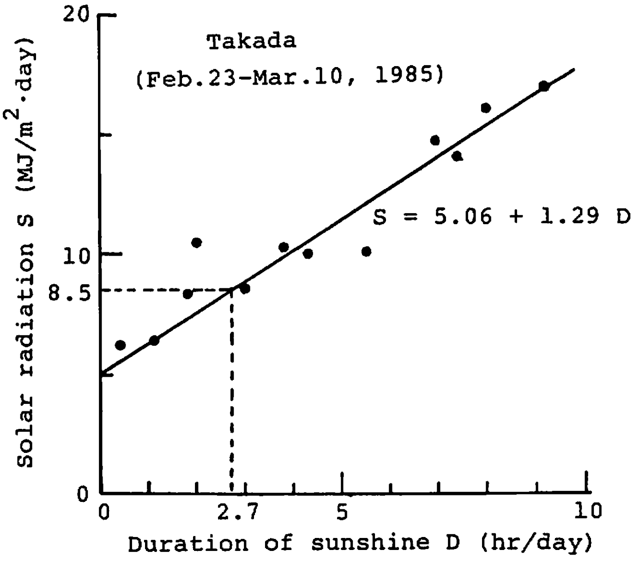

Fig. 32 Relation between daily solar radiation and duration of sunshine at the weather station of Takada from February 23 to March 10, 1985.

Previously, it was suggested by eq.(9) that wet snow decreased its hardness down to 19% (γ = 0.19) of the original by absorbing a solar radiation of 44.7 MJ/m³. The hardness of the upper part of the fragile layer was 16.2 gw/cm². Therefore, the original hardness of this part was presumed to have been 85 gw/cm² (=16.2 / 0.19) before absorption of solar radiation during those two days, under a simple assumption neglecting changes in water content and dry density of the snow. Wet coarse-grained granular snow with dry density of 0.33 g/cm³and hardness of about 85 gw/cm² is commonly observed in the snow cover, as seen in Fig. 2.

Shear strength of the upper part of the fragile layer was estimated from its hardness by the relation between Kinosita's hardness and shear strength of snow, eq.(2). The calculated value from eq.(2) was 5.7 gw/cm². The mean inclination was 40° at the starting zone of the Aoshima Avalanche. Vertical snow load to generate shear stress working across the sliding plane equivalent to this shear strength is 12 gw/cm² on the slope of 40°. If snow density is 0.4 g/cm³, this value of snow load needs the vertical snow height of 30 cm on the sliding plane.

Consequently, it can be concluded that the Aoshina Avalanche, 1985 was triggered by the sledding of the children because the sliding layer about 10 cm thick of the avalanche was very fragile due to the absorption of solar radiation, but not weak enough to cause a slide spontaneously. In fact, no other wet surface avalanche could be seen in the vicinity of Aoshima on that day.

VI. Conclusions

The author carried out a study on mechanical strength of wet snow through observations, measurements and experiments both in the field and laboratory. The research focused on the effects of free water and solar radiation on Kinosita's hardness of snow, as an indicator of mechanical strength of snow. The results were summarized as follows.

1) Through the field measurements of wet snow, a relation among hardness, dry density and free water content of wet snow was obtained for two snow types respectively: equation (4b) for coarse-grained granular snow, equation (4c) for new snow and fine-grained compact snow. These equations indicate that hardness of wet snow exponentially decreases with an increase in water content of the snow.

2) Mechanism of decrease in snow hardness by free water content was considered as follows: when water content of snow increased, number of snow grains decreases with an increase in grain size by grain coarsening process. Therefore, the number of inter-grain ice bonds is lessened, resulting in a decrease in snow hardness.

3) When snow was immersed in water at 0℃, hardness of the snow decreased rapidly and attained a constant value, water saturation hardness R_s of the snow, within three hours. The lower limit of R_s obtained for a given dry density was termed $R_{s.min}$, which increased with an increase in dry density. $R_{s.min}$ indicates the minimum hardness of snow caused only by water content.

4) In the field, unsaturated wet snow in the surface layer of the snow cover occasionally showed a lower value of hardness than $R_{s.min}$ for its dry density. From field conditions, it was presumed that such a low value of snow hardness was caused by solar radiation.

5) In the field and laboratory, it was experimentally confirmed that under solar radiation, hardness of snow at 0 ℃ showed a large decrease which is inexplicable only by the changes in water content and dry density, and could decrease to a value below $R_{s.min}$ depending on the conditions.

6) Mechanism of decrease in hardness of snow at 0 ℃ by solar radiation was considered as follows: solar radiation penetrated into snow is absorbed predominantly by grain boundaries at inter-grain ice bonds and local snow-melting takes place there. This results in decrease in hardness of snow firstly by thinning or missing of inter-grain ice bonds and secondly by the effect of an increase in water content as is described in 2).

7) Rate of decrease in hardness of wet snow caused by solar radiation was given by a function of the amount of solar radiation absorbed by the snow. This indicates that hardness of snow decreases exponentially with an increase in the amount of solar radiation absorbed by the snow.

8) Finally, in regard to the two typical surface avalanches which occurred in Niigata Prefecture, a formation process of the weak snow layer which provided the sliding plane was studied by the use of meteorological and snow observation data in situ. The results revealed that those weak layers were formed by solar radiation.

Acknowledgements

The author would like to express his thanks to Drs. S. Kinosita, H. Shimizu, G. Wakahama and E. Akitaya of the Institute of Low Temperature Science, Hokkaido University, for their helpful discussions and encouragement throughout the study. He is also grateful to Drs. D. Kobayashi, H. Narita and N. Ishikawa of the Institute and Dr. S. Kobayashi of the Research Institute for Hazards in Snowly Areas, Niigata University for their valuable advice.

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Appendix

Classification of deposited snow by Japanese Society of Snow and Ice (1967)

Denomination of deposited snow	Graphic symbol
New Snow	+ +
Lightly compact snow	＜ ＜
Fine-grained compact snow	○ ○
Coarse-grained granular snow	● ●
Solid-type depth hoar	□ □
Skeleton-type depth hoar	∧ ∧
Ice crust	I