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Permeability coefficient of water in snow and firn at the accumulation area of Yala Glacier, Nepal Himalaya

Shigeki MURAKAMI, Hisashi OZAWA and Tomomi YAMADA
Institute of Low Temperature Science, Hokkaido University,
Sapporo, 060 Japan

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Abstract

The permeability coefficient of water in snow and firn was measured for the first time *in situ* by means of ordinary falling head method using fresh core samples obtained at the accumulation area in Yala Glacier (5304 m a.s.l.), Nepal Himalaya on the post monsoon season of September to October 1987. The sample consisted of wet granular snow with a density of 370−760 kg/m^3. The surface of the glacier melts and melt water percolates into the glacier, thus the temperature of sample is 0°C. The measurement was carried out in a snow cave where the temperature was 0°C. After we took out the core sample, the permeability coefficient was measured promptly. We also made thin sections, and grain size and specific surface area were measured. A linear relation is found between density and the logarithm of the permeability coefficient while a discontinuity is seen at a density around 600 kg/m^3. The value of the permeability coefficient is discussed from the view point of grain size of the sample.

1. Introduction

Since 1981, glaciological and meteorological investigations have been continued in Langtang Himal with the aim of collecting basic data concerning glaciological, meteorological and hydrological processes relating to the cryospheric environment of the Nepal Himalayas. This work was made as a part of cooperative project with Nepalese researchers, so called "Glaciological expedition of Nepal Himalaya−Langtang Project".

Permeability coefficient of water in snow and firn is one of the most important elements for investigating the behavior of melting water through a glacier body, especially in the englacial aquifer. Air permeability and kerosene permeability were measured of natural fine granular snow and artificial compacted snow of high density in temperature below freezing point by previous investigators (Shimizu 1970; Kuroiwa 1968; Bender 1957). Because of the difficulty in the measurement of natural wet snow by using water at 0 ℃, its permeability coefficient still remained unknown. The measurement of permeability coefficient were made for the first time *in situ*, at drilling site at 5304 m a.s.l., the lower part of the accumulation area of Yala Glacier (28°15'N, 85°30'E), where snow melting occurred through the monsoon season and all the depth of the glacier is considered to be at the freezing point of 0°C. Corresponding to this environment, snow layers were completely metamorphosed into coarse grained granular snow by percolating meltwater and rainwater during the summer season. Yala Glacier lies between 5100 and 5700 m a.s.l. and the firn line is situated about 5250 m a.s.l..

In this paper, the permeability coefficient of water of coarse grained wet granular snow and firn naturally developed in the density range of about 370 to 760 kg/m^3 is discussed with consideration to its texture.

2. Method and samples

The measurements were made in the snow cave dug out near the drilling site which made an ideal laboratory for the measurements at a freezing point environment: both in the samples and in the water percolating them no melting and no freezing occurred. Cores of 13 m and 18 m in depth were drilled at two sites separated each other by only 10 m, which can be regarded as cores obtained in the same point. The cores contained many ice crusts and ice layers formed by refreezing of percolated water. The samples for measurement were chosen from the homogeneous parts of the cores. In the snow cave, each sample was arranged in a cylindrical shape of around 6 cm in diameter and 4 to 10 cm in length from a fresh core by a newly designed lathe constituted by an electric drill and a simple holder. For analyzing the texture of samples used for the measurement of permeability, photos of the thin section were also taken *in situ*. The distribution of grain size and specific surface area of each sample were obtained in the laboratory in Japan.

The measurements of permeability coefficient were made by the ordinary "falling water head method" as shown in Fig. 1. The cylindrical shaped sample is held by a rubber tube, which can be expanded by a pressure pump and is in tight contact with the sample for preventing leakage of water through the sides. The lower end of the sample is exactly set at the same water level of the surface of the saucer. Water at the temperature of freezing point of 0°C is poured to the cylinder. Water flows down through the sample and spills over to the saucer as the water level of the saucer is kept constant. The permeability coefficient can be calculated by measuring the time elapsed for the water head, h (m), to drop from h_1 (m) to h_2 (m). Three types of cylinder are used as shown in Fig. 1 : 20 cm, 5.6 cm and 1 cm in diameter depending on the decreasing rate of water head in the cylinder.

Volume flow rate of water through the sample Q' (m^3/s) is directly proportional to the decrease rate of the water head by A' (m^2), the cross sectional area of cylinder:

$$Q' = -\frac{dh}{dt}A', \tag{1}$$

From Darcy's law, volume flow rate of water in the cylinder Q (m^3/s) is expressed as

$$Q = k\frac{h}{L}A, \tag{2}$$

where k (m/s) is the permeability coefficient of the sample, L (m) is the length of the sample and A (m) is the cross sectional area of the sample. From the condition of continuity Q' equals to Q :

$$-\frac{dh}{dt}A' = k\frac{h}{L}A. \tag{3}$$

When the water head decreases from h_1 to h_2 during the time t (s), we can integrate eq. (3) so that

$$-A'\int_{h_1}^{h_2}\frac{dh}{h} = k\frac{A}{L}\int_0^t dt, \tag{4}$$

then

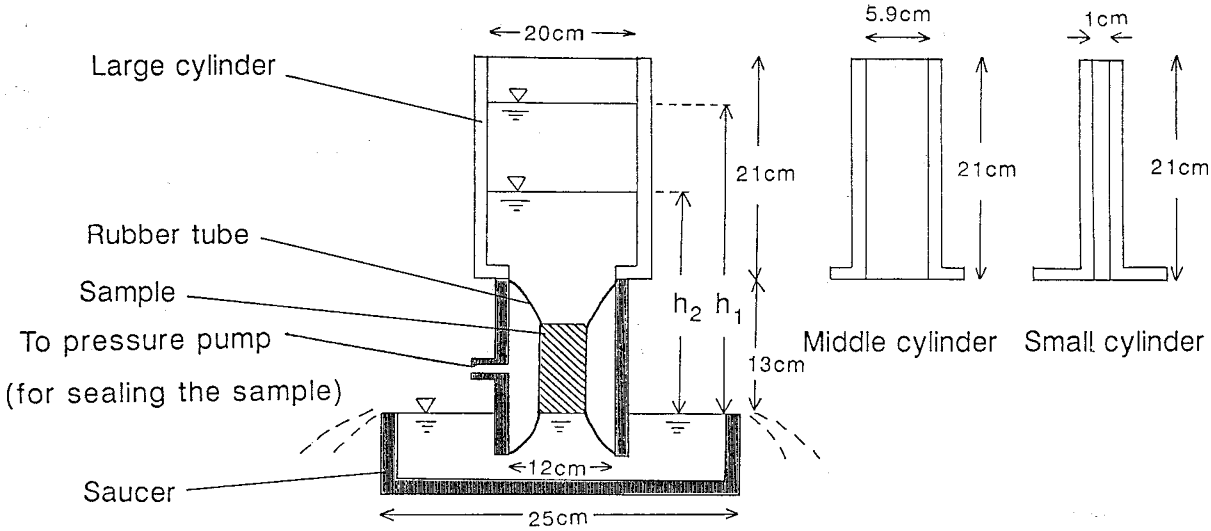

Fig. 1. Ordinary falling head apparatus with cylinders.

$$k = \frac{LA'}{tA} \ln \frac{h_1}{h_2} \qquad (5)$$

Here, the permeability coefficient k can be obtained by measuring the time t when h drops from h_1 to h_2.

To show the characteristics of the samples used, the density (or porosity) profile is shown in Fig. 2. Density increases linearly with increasing depth. The relation between grain size and specific surface area is illustrated in Fig. 3. Grain size ranges from 0.6 to 2 mm and it decreases with increasing specific surface area. In Fig. 4, specific surface area is plotted against density. Specific surface area is linearly decreasing with increasing density.

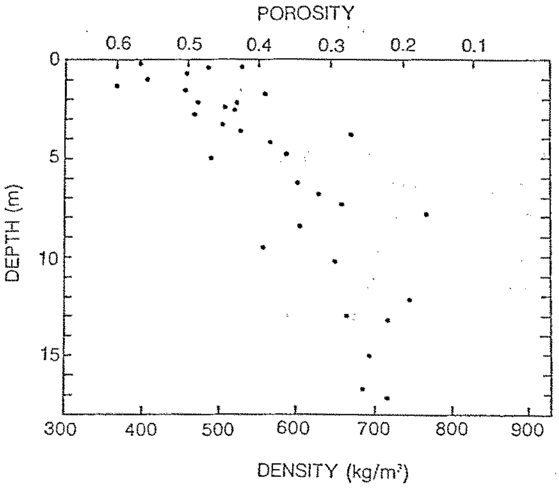

Fig. 2. Density (or porosity) profile of the samples employed for the measurement of permeability coefficient.

3. Result

The data obtained for each measurement of the sample are listed in Table 1. The permeability coefficient decreases exponentially with increasing depth as shown in Fig. 5 because density increases with depth and conversely porosity decreases with depth. Fig. 6 shows the relation between the permeability coefficient and density (or porosity). Solid values indicate the data obtained in this study. The permeability coefficient decreases exponentially with increasing density, while the logarithm of decreasing rate discontinuously shifts from small to large values at a density of around 600 kg/m³.

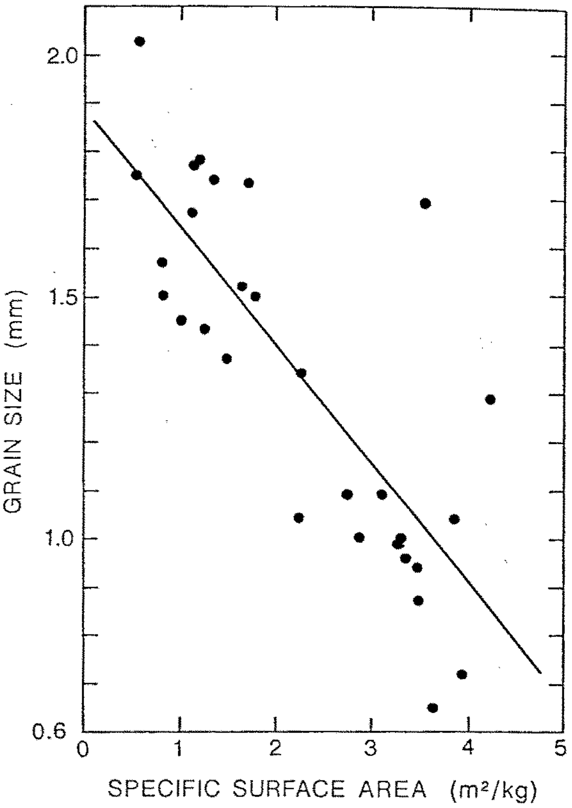

Fig. 3. Relation between grain size and specific surface area.

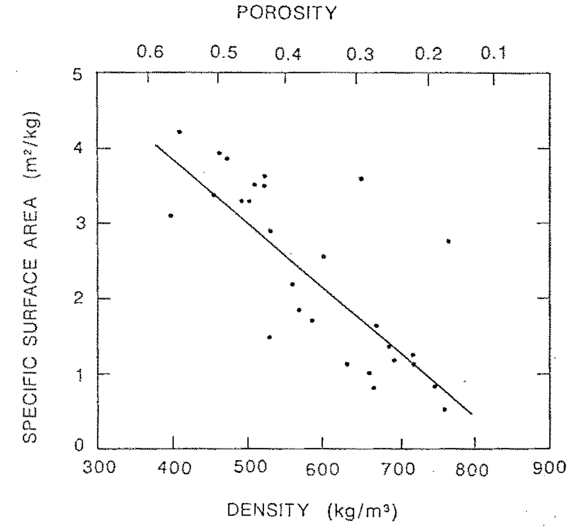

Fig. 4. Relation between specific surface area and density (or porosity).

Table 1. List of data obtained by the measurements of each sample.

Depth (m)	Density (kg/m³)	Permeability coefficient (m/s)	Specific surface area (m²/kg)	Average grain size (mm)
0.09	398	2.47	3.10	1.09
0.38	529	2.33	1.49	1.37
0.40	485	1.55	–	–
0.65	459	1.57	3.93	0.73
0.97	408	2.83	4.22	1.29
1.15	369	2.08	–	1.45
1.41	454	1.84	3.35	0.96
1.68	559	1.74	2.26	1.34
2.08	471	1.52	3.85	1.04
2.21	522	1.42	3.47	0.94
2.38	507	1.33	3.49	0.87
2.55	521	0.96	3.62	0.65
2.88	467	1.92	–	–
3.02	490	1.67	3.30	1.00
3.23	502	1.35	3.23	0.99
3.66	527	1.30	2.89	1.01
3.89	668	0.37	1.63	1.52
4.24	567	1.22	1.78	1.50
4.81	587	1.04	1.71	1.73
6.31	601	0.57	2.55	1.04
6.82	629	0.67	1.13	1.77
7.30	656	0.86	1.00	1.45
8.43	603	0.74	–	–
9.46	556	1.23	–	–
10.22	649	0.39	3.59	1.69
* 10.55	759	1.7×10^{-4}	0.53	1.75
12.19	745	0.11	0.83	1.51
13.01	664	0.25	0.80	1.57
13.13	716	0.12	1.25	1.43
15.00	692	0.12	1.18	1.78
16.74	685	0.12	1.35	1.74
17.06	716	0.083	1.13	1.67

* This value is not plotted in any figure.

4. Discussion

Although there is no previous data of permeability coefficient of water in snow and firn, only Kuroiwa (1968) has obtained liquid permeability using kerosene in natural fine grained compacted snow (density is less than 550 kg/m³) and artificially compressed snow for high density range (density is more than 550 kg/m³) at the temperature of −5°C. The texture of his samples was much different from the present samples. For assessing the effect of the texture on the permeability coefficient, let's compare our data with Kuroiwa's. First of all, his data is converted to permeability coefficient of water by consideration of kerosene and water viscosity. We can get the permeability of kerosene at 0°C by multiplying the permeability at −5°C by the ratio of kerosene viscosity at −5°C to 0°C. The permeability coefficient of water at 0°C can be obtained by multiplication of the kerosene permeability by the ratio of kerosene to water viscosity at 0°C. The converted values are shown in Fig. 6; the dot−dashed line indicates his mean values; broken lines show its upper and lower limit. As seen in the figure, Kuroiwa's values show almost one order less than the present values obtained, while the kink in the relation of the permeability coefficient with density is found at a density of around 550 kg/m³.

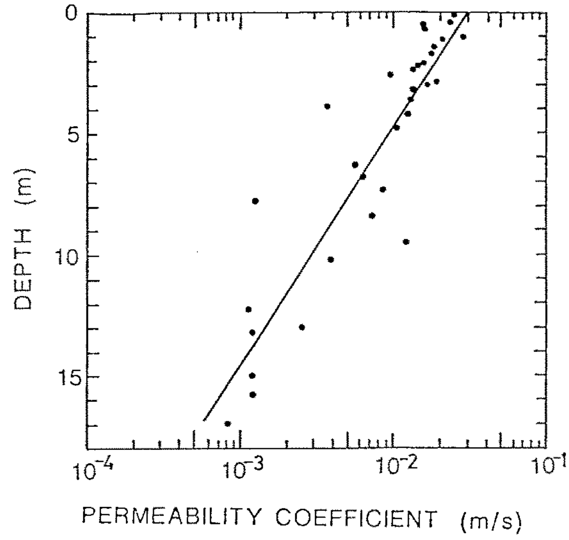

Fig. 5. Relation between depth and permeability coefficient.

For clarifying the dependency on grain size of the sample on the permeability coefficient, the relation among grain size, density (or porosity) and permeability coefficient are shown in Fig. 7. The small solid circles indicate a permeability coefficient smaller than 0.01 m/s, the middle ones from 0.01 to 0.02 m/s and the large ones greater than 0.02 m/s. As seen around the density of 520 kg/m³ in Fig. 7, the permeability coefficient tends to increase with increasing grain size. It means that snow/firn with larger grain size possesses greater permeability coefficient at a given density. Grain size of the samples which Kuroiwa employed was around 0.3 mm in diameter but that of the present samples of wet granular snow was from 0.6 to 2 mm in diameter. Therefore, the one order discrepancy in the value of permeability coefficient is attributed to this difference in grain size.

The kink found on the permeability-density curve

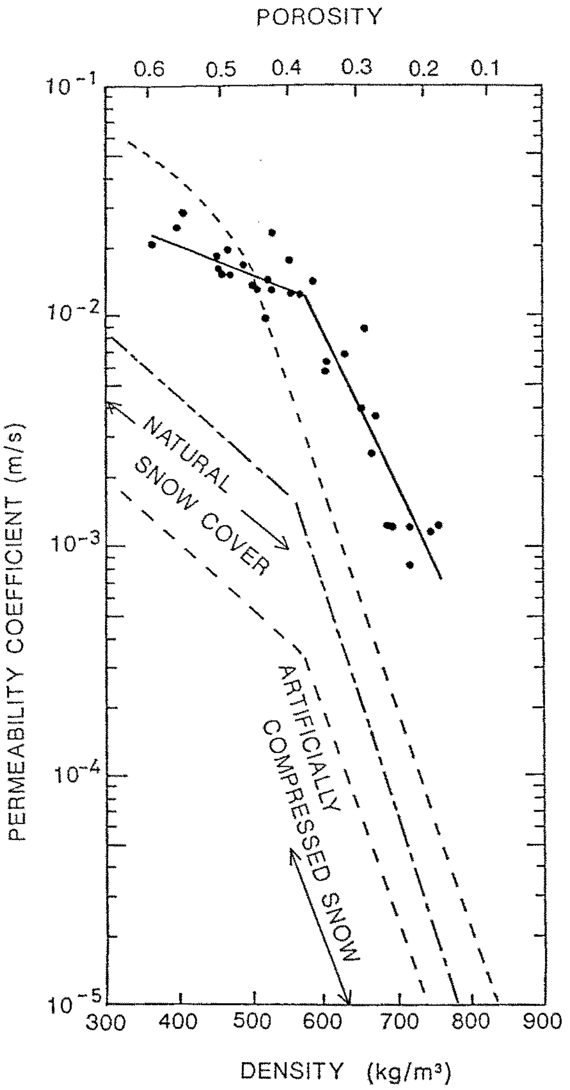

Fig. 6. Solid line: relation between permeability coefficient and density (or porosity) of this study, dot–dashed line: the data obtained by Kuroiwa 1968, broken lines: which indicate the range of scattering in Kuroiwa's data.

in Fig. 6 has been pointed out in other physical properties of snow/firn by previous investigators: Yamada (1978) revealed the kink at the density of 650 kg/m³ for Mizuho cores, Antarctica in the relation between ultrasonic wave velocity and density; Mellor (1975) at 550 kg/m³ in the density dependency of fracture strength of snow. In the present case,the kink is found at around 600 kg/m³. As a result, density where the kink is found seems to be in the range of 550 to 650 kg/m³. During this density range, densification process of snow changes from mechanical packing to plastic flow (Ebinuma and Maeno 1985). According to this change of densification, snow texture drastically changed. Consequently, the physical properties sensitive to snow texture should change their density dependency. In the drilling site of the accumulation area in Yala Glacier, snow texture was concluded to change gradually from a permeable one to a semi–permeable one at a density of around 600 kg/m³, corresponding to a depth of around 3 m.

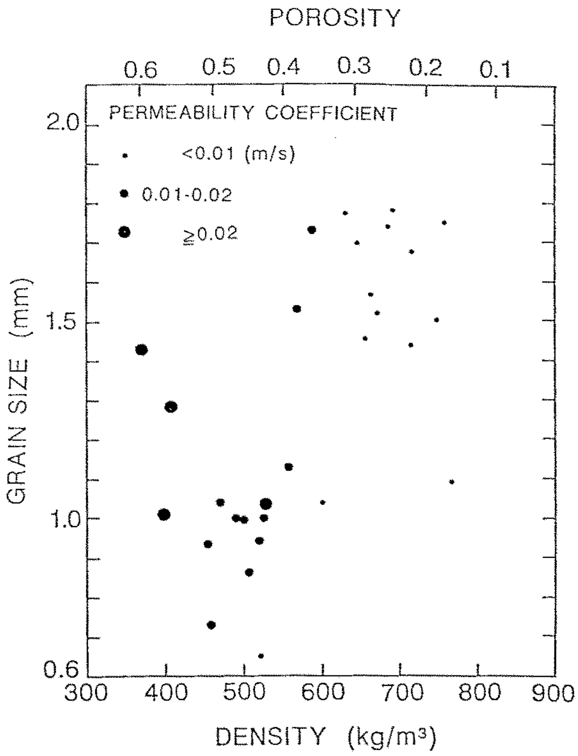

Fig. 7. The relation among grain size, density (or porosity) and permeability coefficient.

Acknowledgments

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