

Dependence of the water retention curve of snow on snow characteristics

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ABSTRACT. The water retention curve (WRC), which shows the relationship between the volumetric liquid water content, θ_v , and suction, h , is a fundamental part of the characterization of hydraulic properties. Therefore, the formulation of the WRC as a function of snow characteristics is essential for establishing a model of water movement through the snow cover. In this study, we measured the WRC of several snow samples, which had different characteristics (grain size, bulk dry density and grain type), using a gravity drainage column experiment and then analysed these data using the Van Genuchten soil physics model (VG model). The shape of the WRC depended strongly on both the sample grain size, d , and bulk dry density, ρ . Therefore, we introduced the parameter ρ/d to model the WRC of snow. The relationships between the parameters α and n of the VG model and ρ/d change with grain type. For melt forms, α , which is related to the inverse value of the air-entry suction, increases quickly as ρ/d decreases, whereas n , which is related to the gradient of θ_v vs h , increases with ρ/d . Conversely, neither of these parameters of the VG model for rounded grains showed obvious dependence on ρ/d . These results suggest that water movement through snow cover can be modelled using grain size, bulk dry density and grain type based on the soil physics model.

1. INTRODUCTION

An accurate description of meltwater movement through snow cover is essential to improve the forecasting of disasters resulting from wet snow. Most water transportation processes in natural snow cover occur under unsaturated conditions because water usually drains from the snowpack before saturation is reached. Therefore, it is important to determine the unsaturated hydraulic conductivity, K , based on the snow characteristics. However, directly measuring K of snow is very difficult and only a few attempts have ever been made for a limited set of snow samples (Sugie and Naruse, 2000; S. Yamaguchi and A. Sato, unpublished information). Consequently, fundamental questions regarding how to model K of snow remain unanswered.

The water retention curve (WRC) shows the relationship between the volumetric water content, θ_v , and matric potential, ψ , or suction, h , and is a fundamental part of the hydraulic properties in porous media (Klute, 1986). In soil physics, K is commonly modelled based on WRC measurements (e.g. Mualem, 1976). Several studies have reported measured WRCs of snow (e.g. Colbeck, 1974, 1975; Wankiewicz, 1979), which may be useful for modifying soil physics models to establish a model for K of snow, but only if the hydraulic properties of snow behave similarly to those of soil. Yamaguchi and others (2010) measured the WRCs of snow with the same density but various grain sizes using a gravity drainage column. They found many similarities between the WRCs of snow and sand, on the basis of which they applied widely used soil physics models to analyse the characteristics of the WRC of snow. Using these results, they suggested that the WRC of snow can be described as a function of grain size using soil physics models. Moreover, based on their results, Hirashima and

others (2010) introduced a new scheme for calculating water movement through snow cover under unsaturated conditions in the numerical snow-cover model, SNOWPACK, developed by the WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland (Bartelt and Lehning, 2002; Lehning and others, 2002a,b). They succeeded in reproducing the appearance and disappearance of layers with a high water content in seasonal snow. Although these studies contributed to our understanding of the mechanism of water movement in snow and improved the modelling of water movement through snowpack, Yamaguchi and others (2010) examined only one grain type and one bulk dry density (550 kg m^{-3}), which was high relative to that of natural wet snow. To improve understanding of the dependence of snow's hydraulic properties on its physical characteristics, we examined the WRCs for different bulk dry densities and grain properties. Based on our findings, we discuss the possibility of modelling the WRC of snow as a function of grain size, bulk density and grain type.

2. METHODS

2.1. Properties of snow samples

We used two types of snow sample: screened refrozen melt forms kept in a cold room at -20°C for 1 year (S-sample hereafter) and natural snows obtained in the field at the Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, Japan (N-sample hereafter). The S-samples had high grain-size uniformity because they were fragmented and screened through several fine-meshed sieves with progressively smaller meshes. The N-sample experiments were conducted on the same day that each snow sample was obtained. To determine the grain

size, at least 500 individual grains in each sample were photographed through a microscope, and the area of each grain was determined using the ImageJ software developed at the US National Institutes of Health. Then each equivalent grain diameter, which was defined as the diameter of a circle with the same area, was calculated. In this study, the representative grain size for each sample was assumed to be the average diameter, d , in the sample (Table 1). Table 1 also presents the uniformity coefficients (UCs), which are a measure of the relative dispersion. Values of UC close to 1 indicate a high level of uniformity. The S-samples had small UCs, whereas the N-samples had large UCs, reflecting a marked difference in uniformity of grain size between the S- and N-samples.

Snow for each S-sample was packed into a sample column that consisted of several acrylic rings (20 mm high, 50 mm in diameter) taped securely together. The bulk density, which is determined by the volume of the sample column and the weight of snow added, was controlled by tamping the snow sample. The S-sample density was high relative to that of the normal seasonal snow density because of repacking. The bulk density of N-samples packed into a sample column without tamping was the same as under natural conditions. To examine the influence of density change, we also performed experiments using N-samples that were tamped to increase the density. If a snow sample was wet, the water content was measured using part of the sample prior to performing the experiment, and the bulk dry density was calculated from the measured bulk density. The dry bulk densities of all the samples are also listed in Table 1.

2.2. Measurement of water retention curve of snow

The WRC of snow was measured using a gravity drainage column method (Yamaguchi and others, 2010). First, the column holding the sample was submerged in water with ice at 0°C in an insulated box until the snow was saturated (30 min in this study). The water was then removed from the insulated box using a pump until a defined water-table level was reached, and the column was allowed to settle until a steady state was reached at 0°C (60 min in this study). Finally, the volumetric water content, θ_v , for each acrylic ring and the corresponding suction value, h , which was defined as the central height of each ring from the final water-table level, were measured to obtain the WRC.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Influence of grain size and bulk dry density on the WRC of snow

Figure 1a shows the WRCs and the relationship between the volumetric water content, θ_v , and suction, h , for S1-2 (black circles) and S4-2 (white triangles). The figure also gives the plotted data number (DN). The two S-samples had similar dry bulk densities (S1-2 = 555 kg m⁻³, S4-2 = 547 kg m⁻³) but different grain sizes (S1-2 = 0.5 mm, S4-2 = 2.1 mm) (Table 1). The shapes of the WRCs differed markedly for the two samples. We used a soil physical model to analyse the measured WRCs. Yamaguchi and others (2010) applied two widely used soil physics models, the Brooks and Corey model (BC model; Brooks and Corey, 1964) and the Van Genuchten model (VG model; Van Genuchten, 1980), to determine the shape of the WRC of snow. Based on a comparison of the results of the models, they concluded that the VG model reconstructed the distribution of the measured

WRC of snow better than the BC model did, although both models were in good agreement with the experimental WRC for snow. Therefore, we adopted the VG model to analyse the measured WRCs of snow in this study.

The VG model is as follows:

$$S_e = \frac{\theta_v - \theta_v^r}{\theta_v^s - \theta_v^r} = (1 + |\alpha h|^n)^{-m}, \quad (1)$$

where S_e is the effective saturation water content, h is suction, θ_v is the volumetric water content, and θ_v^r and θ_v^s are the residual and saturated volumetric water content, respectively; these parameters determine the relationship between θ_v and S_e , whereas α , n and m are parameters that affect the shape of the WRC. Although several formulas for the relationship between n and m have been suggested (Van Genuchten, 1980; Van Genuchten and Nielsen, 1985), we adopted the standard relationship $m = 1 - (1/n)$. To fit the VG models to the measurements, we must determine the parameters θ_v^r , θ_v^s , α and n . In this study, we adopted $\theta_v^r = 0.02$ and $\theta_v^s = 10\%$ less than the porosity for all samples based on Yamaguchi and others (2010). Finally, parameters α and n of the VG models were determined by applying the models to the experimental results using the Retention Curve (RET) software (Van Genuchten and others, 1991). The results of the VG model simulation were in good agreement with the experimental results (Figs 1a and 2a), indicating that the VG model is suitable for describing the WRC of snow.

The WRC of a porous medium can be conceptualized using the capillary bundle model, in which pores are treated as a bundle of capillary tubes of varying sizes. Although this model differs in several ways from water flow in real media, it contains many of the properties of a real medium and may be used to understand the relationship between the WRC and the geometry of porous media (Jury and Horton, 2004). Thus, we attempted to explain the difference between the WRC of two samples using the capillary bundle model theory. Because S_e becomes 0 with the minimum capillary tube radius $r_{\min} = 0$ and becomes 1 with the maximum capillary tube radius r_{\max} , the probability density function of the contribution of each capillary tube, r , to the WRC, $p(r)$, is defined as the differentiation of S_e by r as follows:

$$p(r) = \frac{dS_e}{dr} = \frac{1}{\theta_s - \theta_r} \frac{d\theta}{dr} = \frac{1}{\theta_s - \theta_r} \frac{d\theta}{dh} \frac{dh}{dr}. \quad (2)$$

The relationship between capillary tube radius, r , and suction, h , is described by the Laplace equation

$$h = -\frac{2\gamma \cos \beta}{\rho_w g r}. \quad (3)$$

Here γ is the surface tension of water (0.0073 J m⁻²) and β is the contact angle between water and ice particles (0°C). Introducing Eqns (1) and (3) into Eqn (2), $p(r)$ for the VG model is defined as (Mualem, 1976; Kosugi, 1996; Sakai and Toride, 2009)

$$p(r) = \frac{2\gamma}{\rho_w g r^2} \frac{\alpha^{nm} (-h)^{n-1}}{[1 + (-\alpha h)^n]^{m+1}}. \quad (4)$$

Finally, the ratio of capillary tubes with a diameter of r to all capillary tubes, $F(r)$, is

$$F(r) = [p(r) \times dr] \times 100. \quad (5)$$

Figure 1b shows $F(r)$ calculated from the VG model simulations. The position of the peak of tube (pore) radius r for S1-2 (0.09 mm) is smaller than that for S4-2 (0.25 mm),

Table 1. Sample information. Snow type is according to the International Classification for Seasonal Snow on the Ground (Fierz and others, 2009)

Sample type	Snow type	d 10^{-3} m	UC	Sample name	ρ kg m^{-3}	Comment
S-sample	Refrozen melt forms	0.5 ± 0.0	1.5	S1-1	502	Screened
				S1-2	555	Screened
		1.1 ± 0.3	1.7	S2-1	523	Screened
				S2-2	548	Screened
				S2-3	594	Screened
		1.5 ± 0.4	1.7	S3-1	502	Screened
				S3-2	519	Screened
				S3-3	550	Screened
		2.1 ± 0.4	1.4	S4-1	500	Screened
				S4-2	547	Screened
		3.1 ± 0.3	1.3	S5-1	497	Screened
				S5-2	550	Screened
		3.9 ± 0.5	1.1	S6-1	456	Screened
				S6-2	476	Screened
				S6-3	502	Screened
		4.6 ± 0.6	1.2	S7-1	456	Screened
				S7-2	501	Screened
5.8 ± 0.9	1.2	S8-1	500	Screened		
		S8-2	424	Screened		
		S8-3	456	Screened		
N-sample	Melt forms	2.2 ± 0.7	1.7	N1-1	431	Natural
				N1-2	488	Light compacted
				N1-3	631	Hard compacted
		1.1 ± 0.4	1.7	N2-1	421	Natural
				N2-2	492	Light compacted
				N2-3	575	Hard compacted
		1.8 ± 0.6	1.8	N3-1	361	Natural
				N3-2	621	Hard compacted
		2.0 ± 0.7	1.8	N4-1	458	Natural
				N4-2	608	Hard compacted
		2.1 ± 0.7	1.8	N5-1	396	Natural
				N5-2	508	Hard compacted
		1.6 ± 0.6	1.8	N6-1	378	Natural
				N6-2	478	Light compacted
				N6-3	636	Hard compacted
		4.1 ± 1.6	1.8	N7-1	370	Natural
				N7-2	551	Hard compacted
		2.2 ± 0.7	1.8	N8-1	513	Light compacted
				N8-2	635	Hard compacted
		1.4 ± 0.5	1.8	N9-1	399	Natural
				N9-2	462	Light compacted
				N9-3	489	Light compacted
				N9-4	590	Hard compacted
		1.8 ± 0.6	1.8	N10-1	461	Natural
				N10-2	463	Natural
		2.0 ± 0.7	2.0	N11-1	565	Light compacted
		2.1 ± 0.7	2.0	N12-1	388	Natural
		N12-2	509	Light compacted		
		N12-3	607	Hard compacted		
	Rounded grains	0.4 ± 0.1	1.8	N13-1	381	Natural
				N13-2	480	Light compacted
				N13-3	508	Hard compacted
0.9 ± 0.4		1.8	N14-1	366	Natural	
			N14-2	618	Hard compacted	
0.3 ± 0.1		1.8	N15-1	363	Natural	
			N15-2	431	Hard compacted	
0.3 ± 0.1		1.9	N16-1	390	Natural	
			N16-2	401	Hard compacted	
0.4 ± 0.1	1.9	N17-1	309	Natural		
		N17-2	363	Light compacted		
		N17-3	483	Hard compacted		

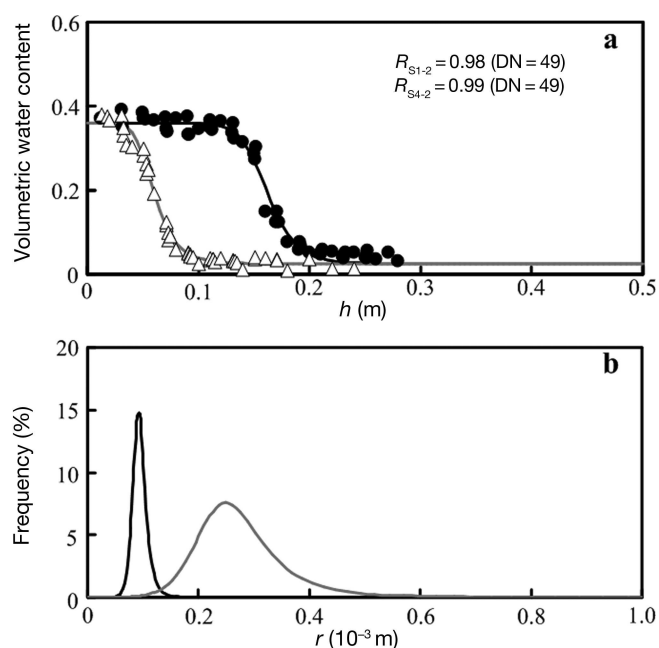


Fig. 1. Experimental and simulation results for samples with the same density but different grain sizes. (a) Experimental results with the modelled water retention curves. Black circles: measured results for S1-2 ($d=0.5$ mm, $\rho=555$ kg m⁻³). Black line: VG model simulation for S1-2. White triangles: measured results for S4-2 ($d=2.1$ mm, $\rho=547$ kg m⁻³). Grey line: VG model simulation for S4-2. (b) Frequency of the capillary tube plotted against all capillary tubes calculated from the VG model simulation. Black line: simulation for S1-2. Grey line: simulation for S4-2. DN is plotted data number.

and these values are approximately one order of magnitude smaller than the respective values of mean grain diameter d . Comparing the shapes of both $F(r)$ distributions, the concentration ratio of r for S1-2 is narrower than that for S4-2, although both samples have the same bulk dry density. These calculated results imply that an increase in grain size causes an increase in pore size and a decrease in the uniformity of pore size.

Figure 2a shows the measured WRCs of the N-samples (N3-1 and N3-2) with the VG model simulations. Both N-samples originated in the same snow layer (melt forms and $d=1.8$ mm), but their densities were different because N3-2 was tamped to obtain higher density. The bulk dry densities, ρ , of samples N3-1 and N3-2 were 361 and 621 kg m⁻³, respectively (Table 1). The WRCs for the two samples differed markedly, although the grain size was the same. Figure 2b shows the $F(r)$ calculated from each VG model simulation. The r peak of N3-1 (0.63 mm) is larger than that of N3-2 (0.17 mm). Their values are smaller than d (1.8 mm), but the position of the r peak of N3-2 is approximately one order of magnitude smaller than d , which is the same trend as for S1-2 and S4-2, whereas that of N3-1 is only one-third smaller than d . These differences should be due to the bulk dry density difference: N3-1 is less dense than S1-2 and S4-2, whereas N3-2 is similar to S1-2 and S4-2. Therefore, the relationship between the position of r and d depends strongly on the sample bulk dry density. Comparing the shapes of $F(r)$, the concentration ratio of r for N3-1 is wider than that for N3-2. This difference may result from the fact that large pores are most easily crushed as density increases with compaction.

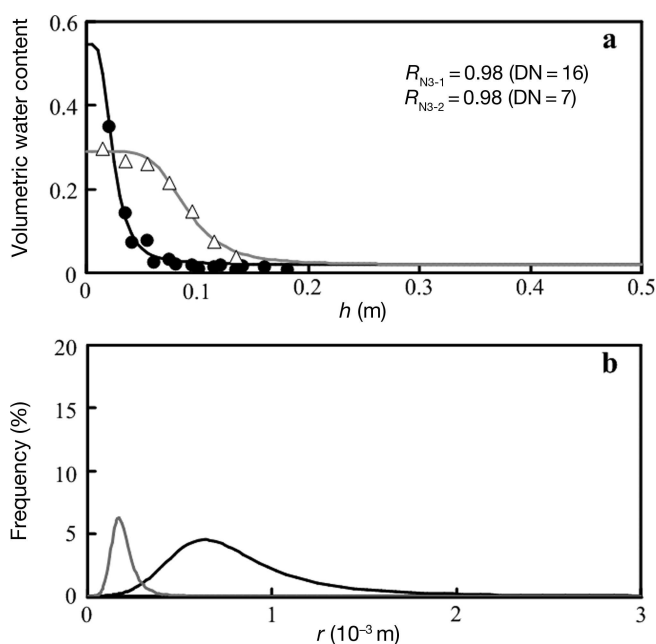


Fig. 2. Experimental and simulation results for samples with the same grain size but different densities. (a) Experimental results with the modelled water retention curves. Black circles: measured results for N3-1 ($d=1.8$ mm, $\rho=361$ kg m⁻³). Black line: VG model simulation for N3-1. White triangles: measured results for N3-2 ($d=1.8$ mm, $\rho=621$ kg m⁻³). Grey line: VG model simulation for N3-2. (b) Frequency of the capillary tube plotted against all capillary tubes calculated from the VG model simulation. Black line: simulation for N3-1. Grey line: simulation for N3-2. DN is plotted data number.

3.2. Description of WRC of snow using grain size and bulk dry density

Having discussed that the WRC of snow changed with its grain size, d , and dry bulk density, ρ , we now consider the possibility of describing the WRC of snow using d and ρ . Coléou and Lesaffre (1998) introduced the parameter d/ρ to model the air-entry suction, h_{air} , of snow, which is the point at which air enters a sample. Similar to their idea, we introduced a parameter ρ/d and examined its relationships to the parameters in the VG model. We adopted the inverse function compared to that of Coléou and Lesaffre (1998) because α in the VG model is related to the inverse of h_{air} . To discuss the relationship between the parameters in the VG model and ρ/d , we examined the results for the S-samples with uniform grain size because some of the N-samples had various grain sizes (low uniformity) and a lower correlation coefficient for experimental measurements vs the fitted values of the VG model. Figure 3a and b show the relationships between the parameters α and n of the VG model and ρ/d (DN = 20). Both α and n depend strongly on the value of ρ/d : α increases quickly as ρ/d decreases, whereas n increases with ρ/d . The VG model parameters have the following relationships to ρ/d with high correlation coefficients, R :

$$\alpha = 4.4 \times 10^6 \left(\frac{\rho}{d}\right)^{-0.98} \quad (R = 0.98) \quad (6)$$

$$n = 1 + 2.7 \times 10^{-3} \left(\frac{\rho}{d}\right)^{0.61} \quad (R = 0.93). \quad (7)$$

Having shown the good relationship between the parameters

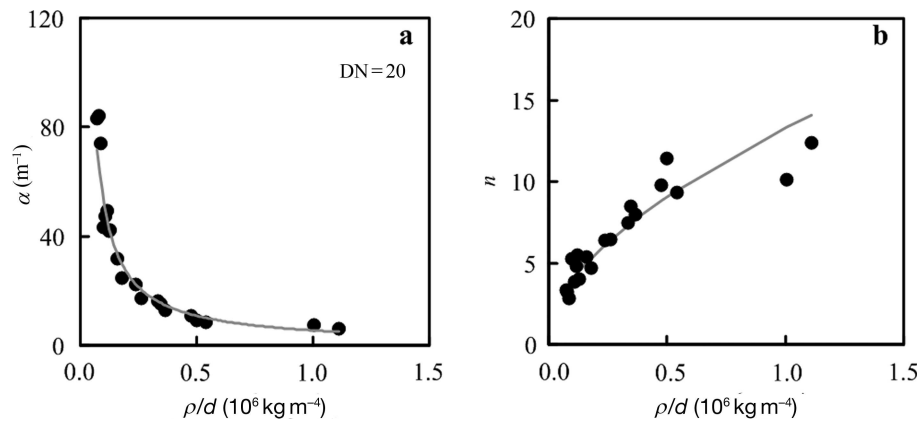


Fig. 3. Dependence of the parameters in the VG model on ρ/d for the S-samples. (a) α in the VG model. (b) n in the VG model. DN is plotted data number.

of the VG model and ρ/d , we consider the physical meaning of ρ/d . Assuming that the snow sample is composed of ice crystals with grain size d , ρ is described as

$$\rho = \frac{\left[N \times \frac{4}{3} \pi \left(\frac{d}{2} \right)^3 \rho_i \right]}{V_0}. \quad (8)$$

Here V_0 is the sample unit volume, N is the total number of ice crystals in the unit volume and ρ_i is the density of ice. Introducing ρ/d into Eqn (8) gives

$$\frac{\rho}{d} = \frac{\left[N \times \frac{4}{3} \pi \left(\frac{d}{2} \right)^3 \rho_i \right] / V_0}{d} \propto \frac{N \times 4\pi \left(\frac{d}{2} \right)^2}{V_0}. \quad (9)$$

The right-hand side term in Eqn (9) is the total area of all ice crystal surfaces in the unit volume, i.e. the total surface area of all tubes (pores) in the unit volume. Therefore, ρ/d is nearly equivalent to the specific surface area of a unit volume of snow (SSA_v). Because the specific surface area is thought to be an important physical property of snow (e.g. Arakawa and others, 2009), we investigated the use of another definition of specific surface area to describe the parameters α and n of the VG model; namely, we applied the total surface area per unit weight (SSA_w) and made estimates using measured d and ρ_i ($SSA_w = 6/(d\rho_i)$). The relationship between the parameters (α and n) and SSA_w showed functions similar to those of Eqns (6) and (7), but their correlation coefficients, R , were lower than those of ρ/d ($R=0.94$ for α and $R=0.89$ for n). Moreover, SSA_w is considered to have the greatest influence over d but not over ρ , which also controls the form of the WRC of snow (Fig. 2a). Based on these results, we considered that ρ/d , which is related to SSA_v , is better than SSA_w when describing the parameters in the VG model. We thus used ρ/d in ensuing analyses of samples of different densities.

Next, we examined the relationships between the parameters for the WRC of natural snow having a non-uniform grain size and ρ/d . Figure 4a and b present the relationships of the parameters α and n of the VG model for natural snow and ρ/d with the regression curves described using Eqns (6) and (7). Figure 4a shows a relationship similar to that of the S-samples between α and ρ/d , i.e. α increases as ρ/d decreases. A function similar to that of Eqn (6) (power function of ρ/d) was applied to describe α for all data for the N-samples (DN=41). A high correlation between α and the power function of ρ/d was obtained ($R=0.72$), although its coefficient and multiplier were different from those of Eqn (6). Analysis of each grain type showed that the melt

forms had a high correlation coefficient ($R=0.82$ with DN=29), whereas the rounded grains had a low correlation coefficient ($R=0.48$ with DN=12). Therefore, the high correlation between α for all data of N-samples and ρ/d reflects the good relationship between the melt-form α values and ρ/d . In Figure 4b, the relationship between n and ρ/d differs for each grain type. For the melt forms, n shows a dependence on ρ/d that is similar to that of the S-samples (n increases as ρ/d increases) and has a high correlation coefficient ($R=0.61$) when a function similar to that of Eqn (7) (1 + power function of ρ/d) was applied in describing its relationship with ρ/d . On the other hand, n values for rounded grains appear to be independent of ρ/d and no correlation between n and ρ/d was observed ($R=0.04$). These results suggest that the WRC of the melt forms in the snow-cover model can be modelled using d and ρ based on functions similar to those of Eqns (6) and (7), whereas we need to introduce another formula and/or a new parameter to describe the WRC of the rounded grains.

We examined why the relationship between the two parameters and ρ/d depended on grain type. As shown in Table 1, the ranges of bulk dry density variation of melt forms and rounded grains in the N-samples are almost the same ($300\text{--}600 \text{ kg m}^{-3}$), whereas the grain sizes, d , of rounded grains are obviously smaller than those of the melt forms (d of rounded grains: $0.5\text{--}1.0 \text{ mm}$; d of melt forms: $1.0\text{--}4.0 \text{ mm}$). Therefore, non-uniform grain size probably has a more important influence on pore-size uniformity for rounded grains than for melt forms because rounded grains have a small d . A decrease in pore-size uniformity should affect the values of α and n via the change in distribution of capillary tube diameter related to the shape of WRC (see Section 3.1). In fact, despite their non-uniform grain size, the melt forms of the N-samples show a dependence of α and n on ρ/d that is similar to that of the S-samples, which have a uniform grain size (Table 1). Another reason may be the effect of grain shape. The melt forms tended to be very round and sphere-like, whereas the rounded grains were of various shapes (e.g. elliptical). These differences may affect the parameterization results because we considered each grain to be a sphere. Moreover, there were many connections among grains, and cluster structures were locally present in the N-samples. These complicated structures could cause a mismatch between the real representative size of structures and mean grain diameter as determined by measurement of individual grains.

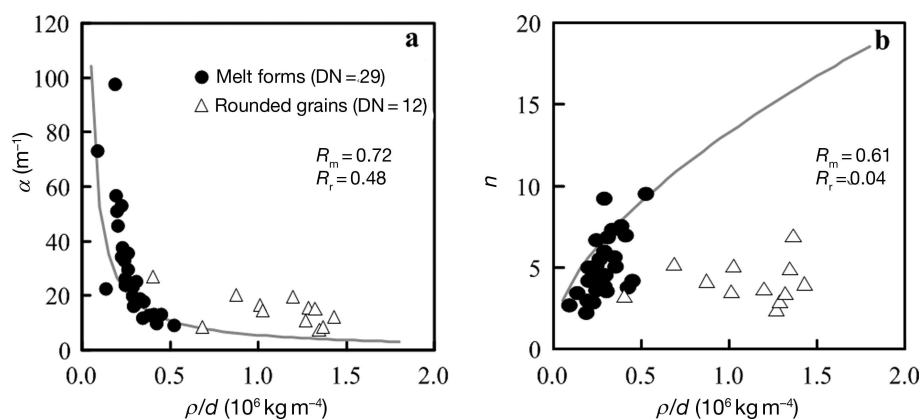


Fig. 4. Dependence of the parameters in the VG model on ρ/d for the N-samples. (a) α in the VG model. (b) n in the VG model. Black circles: results for melt forms. White triangles: rounded grains. Grey lines; regression curves calculated using Eqns (6) and (7). DN is plotted data number. R_m is correlation coefficient of melt forms. R_r is correlation coefficient of rounded grains.

4. CONCLUSIONS

The dependence of WRCs on characteristics of snow (grain size, bulk dry density and grain type) was examined using various snow samples. The analyses using the VG model gave the following results:

1. The distribution of pore size depended strongly on the sample grain size, d , and bulk dry density, ρ . The position of the peak pore size decreased when d became smaller (ρ became larger), and the concentration ratio of pore size increased when d became smaller (ρ became larger).
2. The WRC of melt forms can be described as a function of ρ/d , whereas rounded non-uniform grains did not show a good relation with ρ/d . Therefore, we should consider not only d and ρ but also grain type when modelling the WRC of snow.

In this study, using simple ideas based on soil physics, we have shown the possibility of modelling the WRC of snow using its characteristics, but we have not yet established a model. To introduce the influence of grain type in the model, it is necessary to translate grain type into physical parameters. It may be useful to introduce the idea of 'sphericity', which is used in numerical snow-cover models (Brun and others, 1989, 1992; Lehning and others, 2002a). The eventual establishment of a final model describing realistic water movement through snow cover and illustrating the dependence of hydraulic properties such as WRC and K on snow characteristics will require future experiments that incorporate the true porosity structure of real snow.

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