Measuring the Water Retention Curve of Snow

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ABSTRACT: The water retention curve (*WRC*), which shows the relationship between the volumetric water content and matric potential, is a fundamental part of the characterisation 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 snow cover. In this study, we measured the *WRC* of granular snow (550 kg m^{-3}) of various grain sizes in gravity drainage column experiments. Our experiments revealed many similarities between the *WRC* of snow and that of sand. Consequently, to analyze the *WRC* of snow, we applied the van Genuchten model (VG model), which is a standard model in soil analysis, to the *WRC* of snow. Two parameters in the VG model that determine the form of the *WRC* have a strong relationship with sample grain size. Our results suggest that the *WRC* of snow can be described as a function of grain size using the VG model.

KEYWORDS: water retention curve, water transportation, van Genuchten model.

1 INTRODUCTION

It is essential that water movement through snow cover be described accurately to improve the forecasting of wet snow avalanches. To model water movement through snow cover, it is necessary to formulate the unsaturated hydraulic conductivity (*UHC*) of snow as a function of snow characteristics, such as snow type, density, and grain size. Since it is difficult to measure the *UHC* of snow, only a few attempts have ever been made, and only for restricted snow samples (Sugie and Naruse, 2000; Yamaguchi and Sato, 2007). Based on a few experimental results, Yamaguchi and Sato (2007) suggested that the *UHC* of snow depends on grain size. Due to a lack of theoretical structure in their argument, further consideration is warranted.

The water retention curve (*WRC*) shows the relationship between the volumetric water content and matric potential and is a fundamental part of the characterisation of hydraulic properties. It is easier to measure the *WRC* than the *UHC*; consequently, the *WRC* of snow has been measured experimentally (*e.g.,* Colbeck, 1974, 1975; Wankiewicz, 1979). However, there is little agreement on how the *WRC* of snow depends on snow characteristics.

Pedology models used to estimate the *UHC* of soils are based on *WRC* measurements (*e.g.*, Mualem, 1976). If the hydraulic properties of snow behave in a similar fashion to those of soil, we could modify such models to the analysis of the hydraulic properties of snow. Moreover, *UHS* can be modelled as a function of snow characteristics when factors dependent on the *WRC* are clarified. In this study, we measured the *WRC* of snow of the same type and density with different grain size and evaluated the dependence of the *WRC* on grain size.

2 METHOD

2.1. Sample

We used granular snow kept in a cold room at –20 °C for one year. The snow was sorted into three size fractions (1.0mm, 1.5mm, 2.0mm) using fine meshed sieves. Then, at least, 1,000 individual grains were photographed through a microscope, and the area of each was determined using ImajiJ software developed by US National Institutes of Health. The diameter of each grain was defined as the diameter of the circle with same area.

Snow of each grain size was packed into a sample column (described below) and tamped to a bulk dry density as 550 kg m^{-3}. The three different grain sizes were 1.1mm, 1.5mm, and 2.1mm and were labelled G_S, G_M ,and G_L, respectively (Table 1). At least six experiments were performed for each grain size, and the standard deviations of the density for each are also given.

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Table 1. Sample information.
The value is given as the mean ± the standard deviation.

Sample	Diameter (mm)	Dry density (kg m^{-3})
G_S	1.1±0.3	549±3
G_M	1.5±0.4	548±4
G_L	2.1±0.4	545±5

2.2. Determining the *WRC*

The *WRC* of snow was measured inside a cold room (0 ±0.1 °C) using a method based on the principle of gravity drainage column experiments, summarized in Figure 1.

The column consisted of several acrylic rings (20mm high and 50mm in diameter) taped together securely so that water could exit the column only form the bottom. The column holding the sample was placed in an empty insulated box. Then, water with ice at 0 °C was added to the insulated box until the packed snow sample in the column was submerged. The water was allowed to seep into the packed snow until saturation was reached (30 minutes) (Fig 1a). Finally, the water was removed from the insulated box using a pump until a defined water table elevation was reached. Then, the column was left until a steady state was reached under 0 °C condition (Fig. 1b).

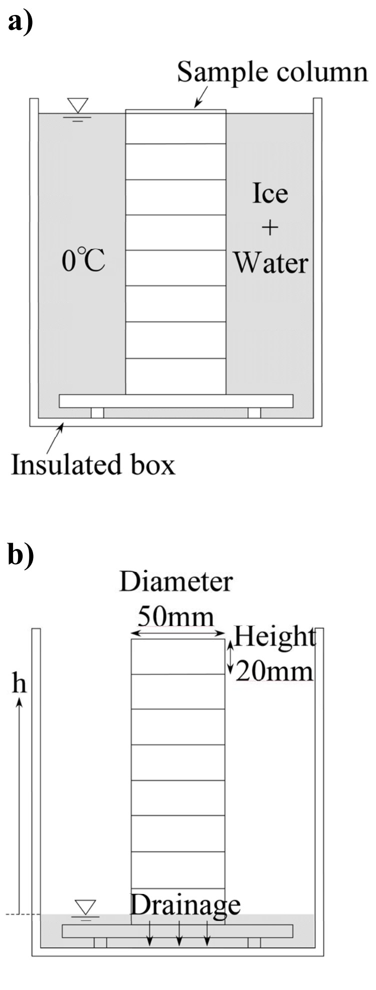

Fig.1 System used to measure the water retention curve of snow.

The pressure of the water located at height *h* above the water table equals the pressure of the free water surface. Therefore, water located at height *h* has a negative pressure, namely the matric potential (ψ). Here, suction is assigned the opposite sign of ψ, and the value of the suction of the water at height *h* is considered to be *h* (mH_2O). In this study, the height from the water table to the position at the middle of each acrylic ring is defined as the average suction for each acrylic ring.

The weight water content of each acrylic ring was measured using a portable calorimeter (Kawashima et al., 1998). Each weight water content was transformed into a volumetric water content (θ_v) using the dry density of the sample, measured before the experiment.

3 RESULTS

Figure 2 shows how the volumetric water content (θ_v) changed throughout the experiment for each grain size. In each graph, we plotted the combined results of at least six experiments. For each experiment, we used fresh snow samples and changed the water table elevation. Figure 2d) shows a plot of the changing volumetric water content of sand for comparison (Watanabe and Flury, 2008).

The results of snow experiments were similar to sand; both had three obvious phases, although the position/timing of these phase varied for different grain sizes.

The first phase (Phase I) appears when the value of *h* is smaller than the critical value of *h*. In this phase, θ_v is independent of *h*, *i.e.*, θ_v is constant (the sample column remains saturated) although the value of *h* changes. We regarded the critical value of *h* as the point at which air enters the sample (h_{air}). The value of h_{air} varies for each snow sample, while the value of constant θ_v is similar for each snow sample.

The second phase (Phase II) appears in the zone of intermediate values of *h*. During this phase, θ_v changes dramatically with *h*. A comparison of sand and snow during this phase indicates that the θ_v of snow is more sensitive than that of sand to change in of *h*, *i.e.*, Phase II of snow is narrower and has a steeper gradient than that of sand.

The third phase (Phase III) appears in the zone of the relatively high value of h. In this phase, θ_v settles out to a particular value (θ_v^r) with increased h. In this study, we regarded the value of θ_v^r as the residual water content. The value of θ_v^r was similar for each snow sample.

4 DISCUSSION

As shown in Fig.2, the *WRC* of snow was similar to that of sand. We attempted to apply the theory developed for use in pedology and soil studies to determine the *WRC* of snow. We adopted the van Genuchten model (van Genuchten, 1980), which is a standard model used to describe the characteristics of the *WRC*.

The van Genuchten model (VG model) is as follows:

$$S_e = \frac{\theta_v - \theta_v^{\ r}}{\theta_v^{\ s} - \theta_r} = \left(1 + |\alpha h|^n\right)^{-\frac{n-1}{n}}, \qquad (1)$$

here, S_e is effective saturation; α and n are parameters used to define the formula for the curve; θ_v^r and θ_v^s in eq. (1) are the residual and saturated water contents, respectively. θ_v^r and θ_v^s were taken as common for all three samples and their experimental values ware 0.02 and 0.36, respectively. Parameters α and n were determined by applying the VG model to the experimental results using the program RETC (van Genuchten et al., 1994).

All of the experimental results for snow show good agreement with the curve fitted using the VG model (Fig. 3). The coefficient of determination (R^2) for the regression of the experimental measurements versus fitted values exceeded 0.98 for each grain size. From these results, we considered the VG model a valid method for describing the characteristics of the *WRC* of snow.

We also examined the relationship between grain size and parameters α and n of the VG model. α (>0) is related to the scale of h_{air}, while n (>1) influences the gradient of θ_v vs. h ($d\theta_v$ $/dh$) (Phase II), although $d\theta_v/dh$ is also depends on α, as shown in eq. (1).

Figure 3 shows that h_{air} decreases with increasing grain size. Therefore, α shows a strong dependence on grain size and increases dramatically with grain size. By contract, during Phase II, $d\theta_v/dh$ becomes steeper when grain size is increased. As a result, n also shows a strong dependence on grain size. The value of n increases with increase of grain size.

These results suggest that the *WRC* of snow

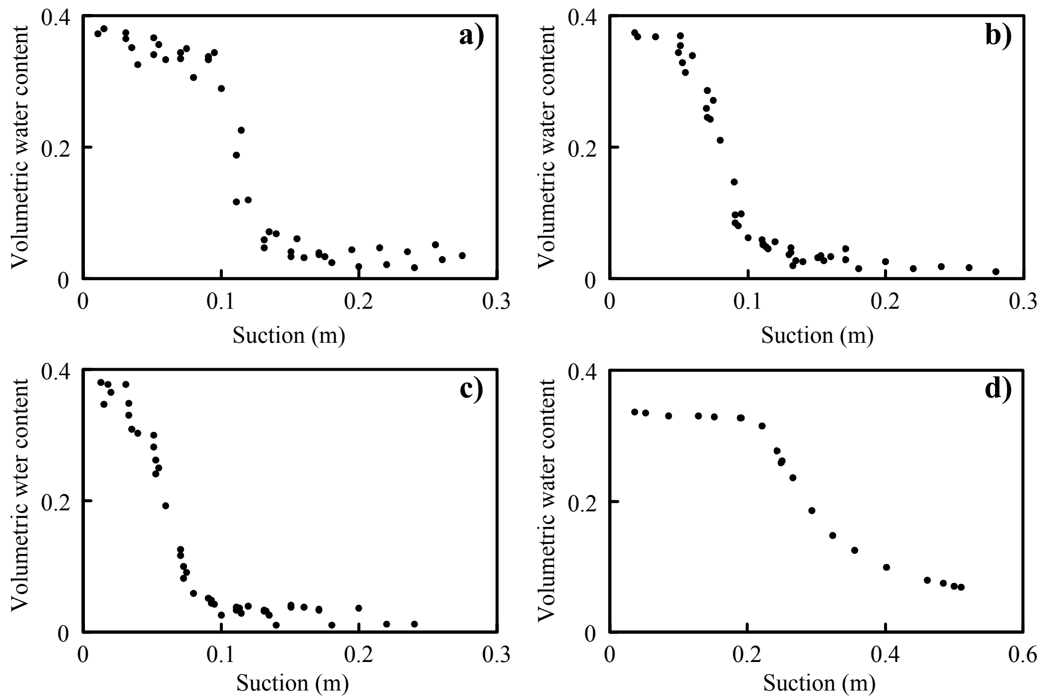

Fig. 2 Experimentally determined water retention curve for each sample.
a) Samples G_s (d=1.1mm), b) G_m (d=1.5mm), and c) G_L (d=2.1mm),
d) A sand sample (d=0.4mm) taken from Watanabe and Flury (2008)
* Note: The x-axis scale different for the snow samples and sand.

may be determined by incorporating a grain size effect into VG model.

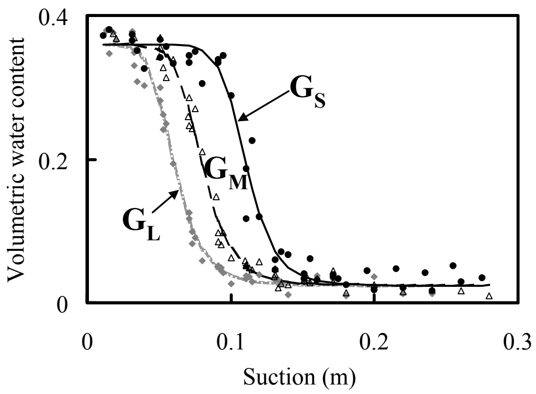

Fig. 3 Experimental results and water retention curves using the VG model for each sample.

5. CONCLUSIONS

Cold room experiments were carried out to obtain the characteristics of water retention curve (*WRC*) of granular snow controlling its density and grain size. Since the obtained curves were similar in form to that of sand, we applied the van Genuchten (VG) model to analyze the *WRC* of snow. This gave the following results.

1. The *WRC* of snow determined by the VG model show a good correlation with the experimental results.
2. The parameters α and n in the VG model show a strong dependence on sample grain size: α increases and n decreases as sample grain size increases.
3. The *WRC* of snow can be described as a function of grain size using the VG model.
4. The unsaturated hydraulic conductivity can be determined from the *WRC* using theoretical models in soil analysis (Mualen, 1976).

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