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Physical properties of peat and palsa formation

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Abstract

This work considers the physical properties of peat and their effects on the formation of palsas under cold environmental conditions. Peat samples were taken in winter from the surface of a palsa in Finnish Lapland and from its frozen core and the material characteristics were determined. The thermal conductivity of the peat samples, measured with a thermal needle probe, varied between 0.23 and 0.28 W/mK with natural water content and between 0.43 and 0.67 W/mK in frozen peat. The thermal conductivity of saturated peat samples ranged from 0.41 to 0.50 W/mK and after freezing from 1.48 to 1.49 W/mK. Unfrozen water content in frozen palsa sample was measured by the TDR method. Water in the studied peat freezes at temperatures of 0 to −0.8 °C, which is considerably a higher temperature range than in high frost-susceptible soils like silts. The frost susceptibility of the peat was measured in the laboratory with a frost heave test, but no frost heave was observed, which means that these peat forming palsas have no potential to form segregated ice lenses. The formation of a palsa is based on the thermal properties of peat.

Keywords: Peat; Palsa; Thermal conductivity; Frost susceptibility

1. Introduction

Palsas, peat mounds with a permanently frozen peat and mineral soil core, are typical phenomena in the circumpolar zone of discontinuous permafrost (Lundqvist, 1969; Seppälä, 1972, 1988). They can be up to 150 m in diameter and can reach a height of 12 m (Lagarec, 1982). One of their characteristics is having steep slopes, rising above the mire surface, which leads to the accumulation of a large amount of snow around them (Seppälä, 1990). The summits of palsas are free of snow even in the middle of winter, however, because the wind carries it off and deposits it on the slopes and elsewhere on the flat mire surface (Seppälä, 1990, 1994). Permafrost is found on palsa mires only in the palsas themselves, its formation being based on the physical properties of peat. Dry peat is a good insulator, but wet peat conducts heat better (Seppälä, 1986, 1988) and frozen peat better still. It has been shown in an earlier study (Brown, 1966: 21) that the thermal conductivity of dry peat is equivalent to that of snow, about 0.00017 g cal s^{-1} sq cm °C cm, whereas that of unsaturated peat is about 0.0007, that of saturated peat about 0.0011 and that of frozen saturated peat it can approach 0.0056, comparable to that of ice. Brown did not say anything about the characteristics of the peat studied, however. These figures mean that the cold can

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Table 1
Peat samples

Sample	Depth of sampling (m)	Size of sample (mm)	Shape of sample
I	Surface 0–0.09	300×220×90	Irregular block
II	Surface 0–0.10	300×150×100	Irregular block
III	0.75–0.85	55×95	Cylinder
IV	0.85–1.05	55×130	Cylinder

penetrate deep into the peat layers and heat can easily flow from deeper wet peat layers in winter, whereas the dry peat on the palsa surface insulates the frozen core and prevents thawing during the short summer. Without a covering peat layer the permafrost would disappear in palsa regions, where the mean annual air temperature is close to −2 °C.

Peat can absorb a great deal of water, and capillary water can move through it easily. This is a second characteristic of peat, which supports the growth of palsas. Freezing takes place from above, and the downward flux of cold freezes the peat and sucks water from below to the freezing front. This has been expected to form segregated frozen peat layers with thin ice lenses. The water content in the core of a palsa ranges from 80 to 90% in weight. The fact that mounds 7 m in height rise up from a mire with a peat layer 2 m thick cannot be explained only by the volumetric expansion of freezing water, however, for a palsa will suck a considerable amount of extra water into its freezing core from the surrounding wet mire during its formation.

The main purpose of this work was to measure the physical properties of the peat that forms palsas in Finnish Lapland. Samples of natural frozen peat were taken from a palsa in winter, kept frozen and measured at different temperatures in the laboratory. They were then thawed and dried, and subsequently saturated and frozen again under controlled conditions in the laboratory.

2. Material and methods

The peat samples were collected frozen in winter from a palsa mire called Vaisjeäggi in Utsjoki, northern Finland (69°49′N, 27°10′E). The surface samples were cut with an axe and the subsurface samples below the active layer with a drill which takes cores of diameter 55 mm. The sampling depths ranged from 0 cm to 105 cm (Table 1). The samples were stored in plastic bags and kept frozen at −20 °C. For measurements in the laboratory we chose four samples (Table 1).

The surface samples were composed of nutrient-poor sedge (*Carex*) peat of pH 3.4 and had a water content of 79% of the total mass by weight. The peat was somewhat humified, corresponding to grade 5 on the von Post scale. The samples did not contain any mineral material, and their ash content was only 2.0% of dry weight.

2.1. Thermal conductivity measured by the thermal needle probe method

Thermal conductivity was measured with a thermal needle probe at constant temperatures. The instrumentation consisted of a constant current source, a precision

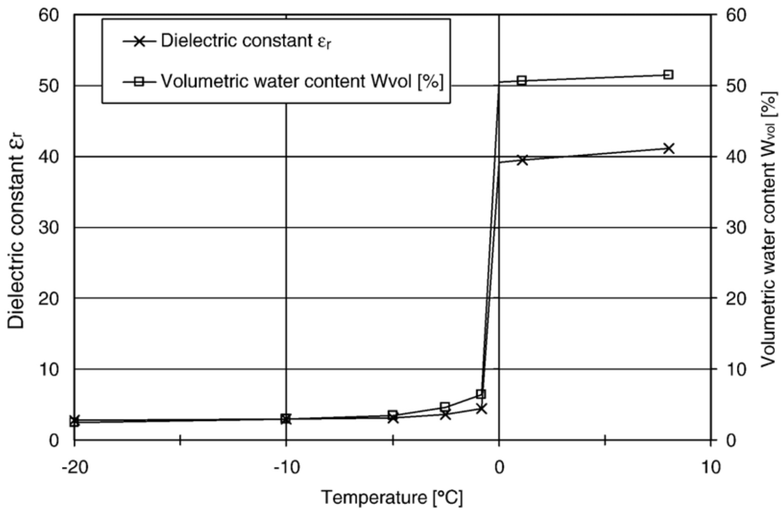

Fig. 1. Dielectric constant and volumetric water content of the peat samples from the palsa surface as a function of temperature.

Table 2
Results of measurements of thermal conductivity in the peat samples (Fig. 2)

Sample	w_{vol} (unfrozen) [%]	T [°C]	K_{frozen} [W/mK]	$K_{unfrozen}$ [W/mK]
Surface layer I	44	−12	0.67	
Surface layer I	44	20		0.28
Surface layer I	65	−12	1.48	
Surface layer I	65	20		0.41
Surface layer II	56	−12	0.43	
Surface layer II	56	20		0.23
Surface layer II	65	−12	1.49	
Surface layer II	65	20		0.50
Surface layer I	52	−10	0.65	
Surface layer I	52	−5	0.69	
Surface layer I	52	0.5		0.29
Surface layer I	52	8		0.29
Surface layer I	52	20		0.26
Surface layer II	40	−10	0.46	
Surface layer II	40	−5	0.41	
Surface layer II	40	0.5		0.20
Surface layer II	40	8		0.23
Surface layer II	40	20		0.24
Depth 75–85 cm III	68	−5	1.05	
Depth 75–85 cm III	68	0.5		0.52
Depth 75–85 cm III	68	8		0.48
Depth 75–85 cm III	68	20		0.49
Depth 85–105 cm IV	78	−10	1.26	
Depth 85–105 cm IV	78	−5	1.23	
Depth 85–105 cm IV	78	0.5		0.48
Depth 85–105 cm IV	78	8		0.52
Depth 85–105 cm IV	78	20		0.52

thermometer, a computer for data recording and processing and probes ranging from 55 to 95 mm in length and from 3 to 4 mm in diameter. The element inside the probe was heated at a power varying from 0.103 to 0.163 W so that the temperature increase within 25 min was about 1.5–2.0 °C. Data were stored at intervals of five seconds, and measurements were performed under computer control. All probes were calibrated in water and in the dry homogenous loose sand, whose thermal conductivity values are known. To prevent convection 1 g Agar jelly powder was mixed carefully with 1 l water at temperature +20 °C. The thermal conductivity of water (0.567 W/mK) was used in the calibration. Another calibration value was 0.223 W/mK which is the thermal conductivity of dry sand measured by calibrated heat flow plate. The determination of thermal conductivity by means of a thermal needle probe is based on the temperature increase at the mid-point of the probe, which is plotted against the logarithm of time to form a straight line. The slope of this line is then taken to define the thermal conductivity, in accordance with Eq. (1):

$$\lambda = \frac{q}{4\pi(T_2 - T_1)}(\mathrm{Int}_2 - \mathrm{Int}_1), \quad (1)$$

where

λ is thermal conductivity (W/mK)
q heating power per unit length of the probe (W/m)
T temperature (°C)
t time (s).

3. Volumetric water content measured with a time domain reflectometer

The dielectric constant was measured with a time domain reflectometer (Tektronix 1502B Tektronix Inc., Beaverton, Oreg.), in which a pulse generator sends a high rise time electromagnetic pulse along a coaxial cable and measures the voltage reflected back as a function of travel time. At the end of the balanced line are two parallel stainless steel rods, and it is the soil between these rods that forms the medium in which the pulse travels. The method measures in effect the time taken for a voltage pulse to travel the length of the rods. This length varied in the range 73–98 mm, the diameter of each rod was 2 mm and the spacing c/c 15–20 mm. The apparent dielectric constant can be calculated according to Eq. (2):

$$\varepsilon_r = \left(\frac{L}{l \times v_p}\right)^2, \quad (2)$$

where

ε_r is apparent dielectric constant
L travel time of the pulse
l length of the rods
v_p velocity of propagation.

Several TDR calibration equations have been published to measure volumetric water content of granular soils (e.g Topp et al., 1980; Ledieu et al., 1986; Malicki et al., 1996). These equations are not very suitable for

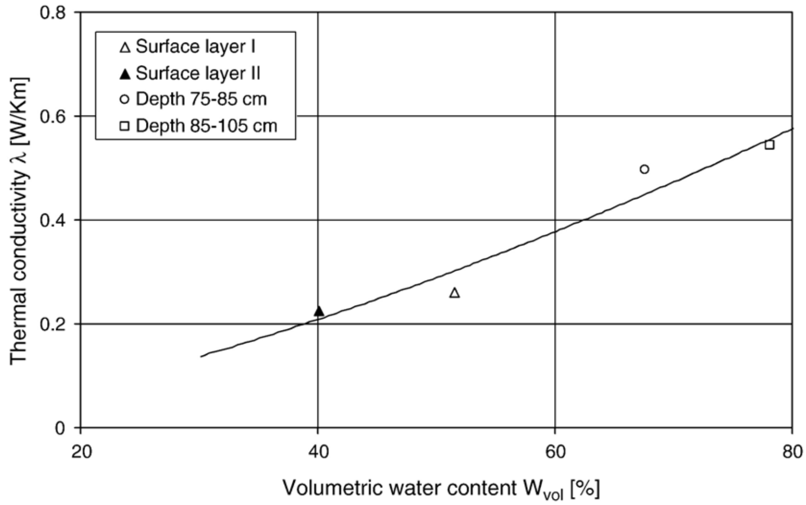

Fig. 2. Thermal conductivity and volumetric water content of peat samples from different depths in the palsa.

peat soils, because the texture and the structure of peat differ from that of granular soils. Several authors (e.g., Myllys and Simojoki, 1996; Shibchurn et al., 2005) have presented specific calibration equations for peat soils. Because the properties of peat vary according to the degree of the humification and the composition of plants, new calibration equation between dielectric constant and volumetric water content was developed. The following third order polynomial function was obtained for volumetric water content:

$$w_{\mathrm{vol}} = 9.6 + 1.96 \cdot \varepsilon_r - 0.02 \cdot \varepsilon_r^2 + 1.24 \cdot 10^{-4} \cdot \varepsilon_r^3 \quad (3)$$

In the calibration curve number of separate points were 655 and correlation coefficient r=0,969.

4. Determination of frost susceptibility of peat

The frost susceptibility of a soil can be most reliably measured under laboratory conditions by means of the frost heave test, the equipment for which consists of a frost heave cell, a temperature and displacement transducer, a freezing unit and a load frame. The specimens were frozen by circulating a glycol mixture at their freezing end under thermostatic control, while the unfrozen ends were maintained at a constant temperature (−3 °C) by circulating a coolant (+1.5 °C) in a closed tube in a compartment below the specimen. A water input was connected to the lower end. The temperature and displacement readings were measured by means of a computer at 1 min intervals throughout the test.

Palsa peat samples of diameter 100 mm and from 78 to 86 mm in height were used in the frost heave tests. The frozen samples were shaped to fit into the frost cell and were allowed to thaw before the measurements began. During the measurements the temperature of the upper surface of the sample was kept at −3 °C and the bottom surface at +1.5 °C. The temperatures of the samples themselves were measured to an accuracy of 0.1 °C with temperature probes inserted in their sides. The accuracy of the frost heave measurements was 0.001 mm when conducted with a movement sensor on the upper surface of the sample.

The following parameters were selected to indicate frost susceptibility: total frost heave (4 days), rate of frost heave, frost heave ratio and segregation potential. Freezing was considered to begin at the point where the measurements indicated a vertical transition in the specimen. The segregation potential was determined at the boundary between the transient and stationary stages (Konrad, 1987).

5. Experimental measurements

The thermal conductivity of the palsa peat samples was measured, together with the unfrozen water content of the frozen samples. Measurements were started at temperatures of −5 °C and −10 °C, respectively. Volumetric water content and dielectric constant were measured at temperatures of −20 °C, −10 °C, −5 °C,

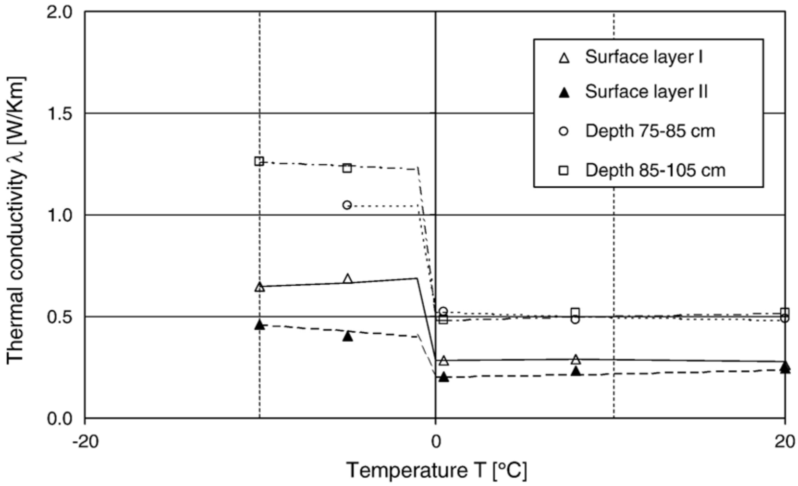

Fig. 3. Thermal conductivity in the peat samples in relation to temperature.

−3 °C and −1 °C, after which the samples were thawed and their thermal conductivity and volumetric water content at this stage were measured at temperatures of +0.5 °C to +20.0 °C. After that the samples were dried at room temperature and their thermal conductivity measured stepwise as a function of water content.

6. Results

6.1. Amount of unfrozen water in frozen peat

When the temperature of the frozen palsa peat sample rose from −20 °C to −2.5 °C the dielectric constant and the change in volumetric unfrozen water content calculated from its function were relatively small, increasing by only 2% of the volume of the sample. The ice melted mainly at temperatures of −0.8 to 0 °C, when the liquid water content rose to 50.4% (Fig. 1). When the temperature rose further, from 0 °C to +1.1 °C, all the ice melted.

Unfrozen water plays an important role in frost action within peat that is in a frozen state, particularly in connection with secondary frost heave. It is generally acknowledged that the film of unfrozen water is the conduit through which liquid water is supplied to a growing ice lens, a viewpoint supported by a number of investigations (Hoekstra, 1966; Burt and Williams, 1976; Horiguchi and Miller, 1980). Ice lens formation is possible if the soil contains water with a large freezing temperature area, as an energy gradient causes water to flow to the growing ice. According to our measurements, peat does not contain much water which freezes

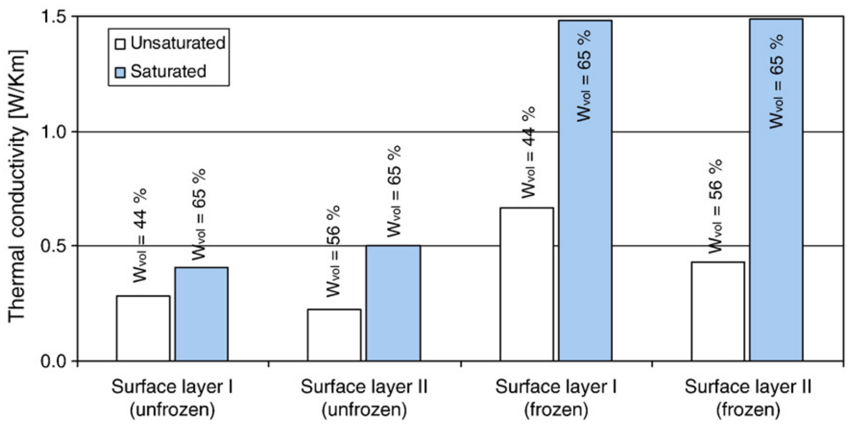

Fig. 4. Thermal conductivity of unfrozen and frozen surface peat of palsa with different water contents.

Fig. 5. X-ray photograph of the frozen core sample of the studied palsa. Sampling depth 87–100 cm. Frozen peat dark. Thin light sections are ice layers.

over a wide temperature scale, and thus it is probable that no ice lens formation is present as there would be according to the secondary frost heave theory.

6.2. Thermal conductivity of peat

The thermal conductivity of peat clearly depends on its water content and temperature (Table 2).

When the thermal conductivity and volumetric water content of the peat samples were measured before they were refrozen, the water content increased from 40 to 80% of the volume as the sampling depth increased to about 1 m. The increase in thermal conductivity was almost linear in relation to water content (Fig. 2).

The thermal conductivity of the frozen peat samples changed very little at temperatures of −10 °C to −5 °C, but differences were found between the samples collected from different depths in the palsa (Fig. 3). The surface sample had a thermal conductivity of 0.65 W/mK (at −10 °C), whereas that in the sample *IV* was 1.26 W/mK (Table 2). The thermal conductivity of the thawed peat samples was almost constant, and the differences between the samples are only minor.

Any change in the water content of the peat affected the thermal conductivity considerably, as it varied between 0.23 and 0.28 W/mK at a natural unfrozen water content, between 0.43 and 0.67 W/mK in frozen peat, from 0.41 to 0.50 W/mK when the peat samples were saturated with water and from 1.48 to 1.49 W/mK after refreezing (Fig. 4).

7. Frost susceptibility of peat

The frost heave test showed that the surface peat samples were non-susceptible to frost according to all the test parameters and that no formation of ice lenses was observed. Ice lens formation due to water intake within peat material is not probable. Favourable pressure conditions cause peat to behave like a frost-susceptible material, however, whereupon ice lenses form underneath the frozen layer of peat. The formation of ice lenses in the peat does not imply the segregation of ice as in frost-susceptible soil, but rather it is caused by conditional factors. In frost-susceptible soil ice lens formation takes place in the frozen fringe.

The structure of the permafrost in the palsa was also investigated by means of an X-ray examination of a frozen core sample taken one metre below the surface. No clear ice layers were found (Fig. 5). Only at one isolated point was a thin lens of ice observed, which was probably not formed due to frost formation but on account of the structure of the peat.

Although according to An and Allard (1995: 236) almost no segregation ice is formed in most peat types, particularly fibrous peat, during freezing, but we have found ice layers in palsas. This fact has been observed in many drillings into palsas. This is not normal ice segregation as can be observed in freezing silt, for example, but rather a perched saturated layer follows the thawing front as the active layer in a palsa thaws and some water migrates into the frozen layer and eventually into the permafrost underneath (*cf.* Mackay, 1983; Smith,1985), along the thermal gradient. This downward migration of water from the thawing active layer is physically similar to the upward migration of water to the freezing front (An and Allard, 1995: 236).

8. Conclusion

The thermal conductivity of peat is a fundamental factor for the freezing of a palsa. The thermal conductivity of the peat samples, measured with a thermal needle probe, varied between 0.23 and 0.28 W/mK in unfrozen peat and between 0.43 and 0.67 W/mK in frozen peat. The thermal conductivity of saturated peat samples ranged from 0.41 to 0.50 W/mK and after freezing from 1.48 to 1.49 W/mK. On the other hand, the change in temperature in palsa depends on the volumetric heat capacity, which increases as the water content increases.

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References

An, W., Allard, M., 1995. A mathematical approach to modelling palsa formation: insights on processes and growth conditions. Cold Regions Science and Technology 23, 231–244.

Brown, R.J.E., 1966. Influence of vegetation on permafrost. Proceedings Permafrost International Conference November 1963, Lafayette, Indiana. Publication, vol. 1287. National Academy of Science—National Research Council, Washington, D.C., pp. 20–25.

Burt, T.P., Williams, P.J., 1976. Hydraulic conductivity in frozen soils. Earth Surface Processes 1, 349–360.

Hoekstra, P., 1966. Moisture movement in soils under temperature gradients with the cold-side temperature below freezing. Water Resources Research 2, 241–250.

Horiguchi, K., Miller, R.D., 1980. Experimental studies with frozen soil in ice sandwich permeameter. Cold Regions Science and Technology 3, 177–183.

Konrad, J.-M., 1987. Procedure for determining the segregation potential of freezing soils. Geotechnical Testing Journal 14 (2), 51–58.

Lagarec, D., 1982. Cryogenic mounds as indicators of permafrost conditions, northern Québec. Proceedings Fourth Canadian Permafrost Conference, Calgary. National Research Council of Canada, Ottawa, pp. 43–48.

Ledieu, J., de Ridder, P., de Cleck, P., Dautrebande, S., 1986. A method of measuring soil moisture by time-domain reflectometry. Journal of Hydrology 88, 319–328.

Lundqvist, J., 1969. Earth and ice mounds: a terminological discussion. In: Péwé, T.L. (Ed.), The Periglacial Environment: Past and Present. McGill-Queen's University Press, Montreal, pp. 203–215.

Mackay, J.R., 1983. Pingo growth and subpingo water lenses, Western Arctic Canada. Proceedings 4th International Conference on Permafrost, Fairbanks, Alaska. National Academy Press, Washington, D.C., pp. 762–766.

Malicki, M.A., Plagge, R., Roth, C.H., 1996. Improving the calibration of dielectric TDR soil moisture determination taking into account the solid soil. European Journal of Soil Science 47, 357–366.

Myllys, M., Simojoki, A., 1996. Calibration of time domain reflectometry (TDR) for soil moisture measurements in cultivated peat soils. Suo 47 (1), 1–6.

Seppälä, M., 1972. The term 'palsa'. Zeitschrift für Geomorphologie 16, 463 N.F.

Seppälä, M., 1986. The origin of palsas. Geografiska Annaler. Series A 68, 141–147.

Seppälä, M., 1988. Palsas and related forms. In: Clark, M.J. (Ed.), Advances in periglacial geomorphology. John Wiley, Chichester, pp. 247–278.

Seppälä, M., 1990. Depth of snow and frost on a palsa mire, Finnish Lapland. Geografiska Annaler. Series A 72, 191–201.

Seppälä, M., 1994. Snow depth controls palsa growth. Permafrost and Periglacial Processes 5, 283–288.

Shibchurn, A., Van Geel, P., Kennedy, P., 2005. Impact of density on the hydraulic properties of peat and the time domain reflectometry (TDR) moisture calibration curve. Canadian Geotechnical Journal 42, 279–286.

Smith, M.W., 1985. Observations of soil freezing and frost heaving at Inuvik, Northwest Territories, Canada. Canadian Journal of Earth Sciences 22, 283–290.

Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resources Research 16, 574–582.