DETERMINATION OF THE UNFROZEN WATER CONTENT OF SALINE PERMAFROST USING TIME-DOMAIN REFLECTOMETRY (TDR)

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Abstract

Time-Domain Reflectometry (TDR) was used to carry out measurement of the unfrozen water content on two soils at three salinities over the temperature range -1° to -12°C. It was observed that as the amount of unfrozen water content increased at high salinity (i.e. 30 ppt) the location of the open circuit response on the TDR trace was obscured due to signal attenuation. A comparison was established between the predicted unfrozen water content using the NaCl phase diagram and the measured values for the clean sand (sol A). An evaluation of the unfrozen water content for the silty sand (soil B) using data from Hutchinson (1989) based on a method proposed by Banin and Anderson (1974) and modified by Patterson and Smith (1983) did not correlate well with the experimental measurement on the low plastic soil. In conclusion, the use of short parallel transmission lines to evaluate the unfrozen water content with TDR is a simple and reliable technique to determine the unfrozen water content.

Résumé

La technique TDR (time-domain-reflectometry) a été utilisée pour mesurer la teneur en eau non gelée dans deux types de sols gelés à trois salinités différentes dans l'intervalle de température de -1°C à -12°C. Une atténuation du signal, causant une imprécision de la détermination du circuit ouvert sur la trace du TDR, est observée lorsque la quantité d'eau non gelée augmente due à une haute salinité. Les résultats expérimentaux pour le sable uniforme (sol A) ont été comparés à la teneur en eau non gelée prédite par le diagramme de phase du NaCl. Une évaluation de la teneur en eau non gelée pour le sable silteux (sol B) établie à partir de données présentées par Hutchinson (1989) basée sur une méthode de Banin et Anderson (1974) et modifiée par Patterson et Smith (1983) ne correspond pas favorablement aux résultats expérimentaux pour ce sol de faible plasticité. En conclusion, l'utilisation de lignes de transmission parallèlles courtes avec la technique du TDR permet une évaluation simple et fiable de la teneur en eau non gelée dans les sols gelés salins.

Introduction

As part of an extensive research program on the mechanical behaviour of frozen saline soils, the unfrozen water content was evaluated, since the amount of unfrozen water has a controlling influence on the strength and deformation behaviour. Different measuring methods were investigated, and the use of the time-domain-reflectometry (TDR) method was selected because of its simplicity. Other methods such as adiabatic calorimetry, dilatometry, nuclear magnetic resonance (NMR) require expensive equipment and trained personnel. In order to investigate the influence of salinity and soil composition, two soils, at three salinities (5, 10, 30 ppt) were tested between -1° and -12°C.

Background

The TDR technique, originally used as a tool to detect faults along transmission lines, has become an effective method for determining the water content in soils. The first investigation using the TDR was carried out by Davis and Annan (1977). The technique measures the "apparent" dielectric constant, K_a, and was shown to be independent of frequency in the TDR range (10^6 to 10^9 Hz).

Electromagnetic theory shows that in non-magnetic low loss material, the propagation velocity is given by;

$$V = \frac{C}{K_a}\ 0.5 \qquad (1)$$

where V : propagation velocity (m/sec)
C : free-space electromagnetic wave velocity = 3×10^8 m/sec

As stated by Patterson and Smith (1981), the TDR measures the propagation velocity and the reflection voltage of the transverse electromagnetic wave. The TDR unit provides a small pulse (step voltage) which travels unchanged along the transmission line until it comes in contact with a dielectric discontinuity (impedance mismatch) which causes a partial

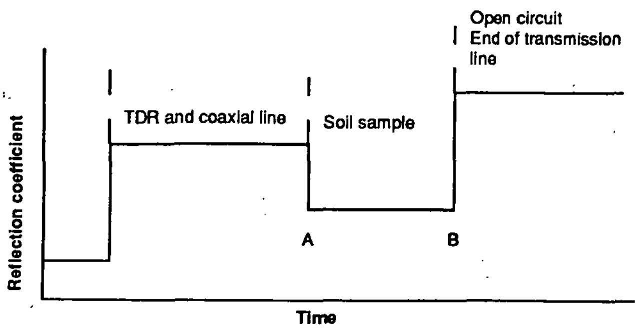

Figure 1. Typical TDR trace (modified from Topp et al. (1980)).

reflection and a partial transmission of the signal. The travel time (tt) of the reflected wave along the transmission line can be evaluated from the signal trace, distance AB in figure 1, and consequently the propagation velocity can be calculated knowing the length of the transmission lines (1) using;

$$V = \frac{1}{(t\,t)} \qquad (2)$$

Combining equations (3) and (4), the apparent dielectric constant can be expressed as;

$$K_a = \left(\frac{C(tt)^2}{21} \right) \qquad (3)$$

The concept of using the dielectric constant to evaluate the moisture content of soils arose from the fact that the dielectric constant of soil grains (K'_{soil} = 2 to 4) is much lower than the dielectric constant of free water (K'_{water} = 80 at 20°C). Moreover, it has been established (Davis and Annan (1977), Hoekstra and Delaney (1974)) that the dielectric constant is weakly dependent on soil type, density, temperature or pore water salinity, but is strongly dependent on the liquid water content.

Topp *et al.* (1980) established a relationship between the apparent dielectric constant (K_a) and the volumetric water content (Θ_v) of soils.

$$K_a = 3.03 + 9.30\Theta_v + 146.0\Theta_v^2 - 76.7\Theta_v^3 \qquad (4)$$

They proved that except for very fine-grained or organic soils, this relationship holds over a wide range of soil types and textures and is independent of temperature and salinity. Smith and Tice (1988) explained that for high specific surface area materials (very fine-grained soils), the value of the apparent dielectric constant decreases because of the large amount of absorbed water which has a dielectric constant lower than 80. However, the authors observed that saline pore fluids increased signal attenuation since a saline pore fluid has a higher electrical conductivity than non-saline pore fluid.

Since ice and soil grains have similar dielectric constant (K_{ice} = 3.2 and K_{soil} = 2 to 4), Patterson and Smith (1981) extended the use of TDR to the evaluation of the volumetric unfrozen water content in frozen soils. These authors used a combined TDR-dilatometry method on ice-water mixtures and frozen soils to verify the validity of (equation 4) for frozen soils. Good agreement was obtained between the two techniques. Moreover, the authors showed good correlations between the TDR results and previously published unfrozen water content data using other measuring techniques. In general, it is considered that the evaluation of the unfrozen water content using the TDR technique is precise within ±2.5 % in Θ_v (volumetric unfrozen water content).

Patterson and Smith (1983 and 1985) extended the application of the TDR technique for unfrozen water content determination to saline frozen soils. They observed that the main difficulty with the method was an increase in signal losses for highly saline soils (salinity > 5 ppt) caused by the increase in pore water electrical conductivity. The high signal attenuation makes it difficult to determine the open circuit response from the TDR trace, and consequently the evaluation of the travel time becomes less accurate. A compromise between long transmission lines which increase the precision of the travel time and short transmission lines which improve the definition of the open circuit response had to be made to solve this problem. When using appropriate line length, Patterson and Smith (1983, 1985) obtained good agreement between the volumetric unfrozen water content measured using TDR and measured using other methods. Smith and Tice (1988) also compared favourably the results when measured using the NMR and TDR.

Topp *et al.* (1980) observed variation between the predicted and experimental values at low or high water content. As stated by Patterson and Smith (1983), at low water content, the TDR method tends to overestimate the unfrozen water content, because air which has a dielectric constant of 1 replaces ice.

Two configurations of the transmission lines can be used: an unbalanced coaxial line or a balanced parallel transmission line. The coaxial configuration constrains the magnetic field to within the sample. However, this configuration is only applicable for laboratory testing. The parallel configuration is more versatile (laboratory and field) even if the extent of the magnetic field is unknown. The parallel configuration requires the use of a transformer called a "balun" to establish the connection between the coaxial line hooked to the TDR unit and the parallel lines within the sample. The choice of the "balun" should be made carefully in order to match as close as possible the impedance of the coaxial line to that of the sample to avoid additional signal attenuation.

Experimental procedure and equipment

Sample preparation

The first step in sample preparation was to mix and saturate the soil with a saline solution. Each dry soil, a uniform sand (soil A) and a silty sand (soil B) (figure 2) was mixed with a saline solution (5, 10, and 30 ppt) prepared

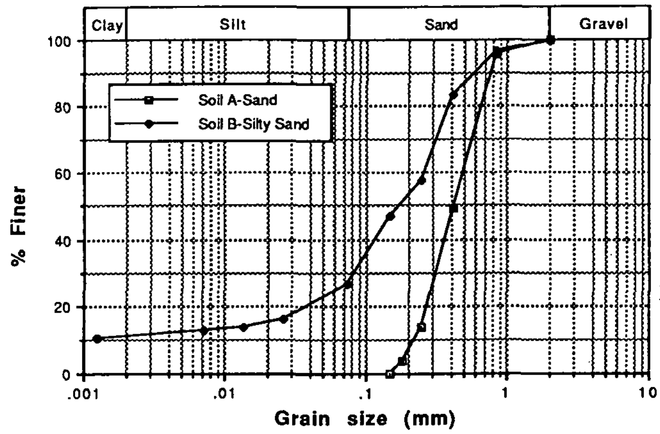

Figure 2. Grain size distribution.

using pure NaCl. The soil slurry was then poured into a split mould, and the parallel transmission lines were pushed into the slurry. The soil was then consolidated under a vertical stress of 80 kPa and finally frozen unidirectionally using a liquid nitrogen freezing system. The samples were then wrapped and stored in at -25°C until they were transported in dry ice to the NRC laboratories in Ottawa for testing.

TEST EQUIPMENT

The parallel lines were made of stainless steel (diameter 2 mm) to avoid corrosion and were 80 mm in length with a 20 mm spacing between the probes.

A Tektronix 1502 TDR unit connected to a Hewlett-Packard XY plotter was used through out the testing. The horizontal scale of the TDR represents the travel time and was calibrated using a coaxial air line of known length. The connection between the parallel transmission lines and the coaxial line was made through an Anzac TP-101 "balun" which has a primary impedance of 50 ohms and a secondary impedance of 50 ohms.

TEST PROCEDURE

First, to allow for a precise temperature measurement, a hole was drilled into the sample into which a thermocouple was placed and the hole was backfilled with distilled water. The samples were then placed in a Tenney environmental temperature controlled chamber maintained at -12°C for 24 hours to establish thermal equilibrium within the samples. The temperature of the chamber could be controlled to ± 0.1 °C.

The samples were tested through the temperature range -12° to -1 °C by warming up by steps of one degree. At each temperature, two sets of readings were taken at a four hour interval. Over the temperature range -7° to -1 °C, one set of readings was taken after the sample was inverted for six hours to avoid gravity migration of the unfrozen water and maintain a uniform soil moisture distribution within the sample.

After the test was completed, each sample was cut into slices which were stored in a humid room at 10°C, and later used to measure the total gravimetric water content and the pore fluid salinity. The moisture content were carried out using ASTM-D2216 and the salinity measurements by extracting a few drops of pore fluid from the thawed sample and using a refractometer (Endeco Refractometer, Type 102) to determine fluid salinity. This procedure is similar to the ASTM D4542-85 method.

Experimental results and discussion

Figure 3 shows a typical TDR trace with the location of point A (start of line) and B (end of line) for soil B-30 ppt at -10°C. It can be seen from the large "jump" in the trace before point A that the impedance match between the coaxial line and the parallel line was poor. This might have caused a decrease of the signal intensity before its entry into the soil. A different balun might have been a better choice for example an Anzac TP-103 (50-200 ohms transformer). The TDR determination of the volumetric unfrozen water content are presented in figures 4 and 5 for the sand (soil A) and the silty sand (soil B) respectively. The first observation is that the unfrozen water content is almost constant at temperatures below -6°C for all samples. For soil at a salinity of 10 ppt, no reading was possible at -1 °C due to equipment problem.

At -1 °C and a salinity of 30 ppt, the samples were thawed since the freezing point depression of a solution with such a salinity is -1.8°C. As should be expected, the unfrozen water content at any temperature increases significantly with an increase in salinity and increases slightly with a decrease in grain size. It should be kept in mind that the silty sand can not be considered a fine-grained soil as it contains less than 2 % clay size particles.

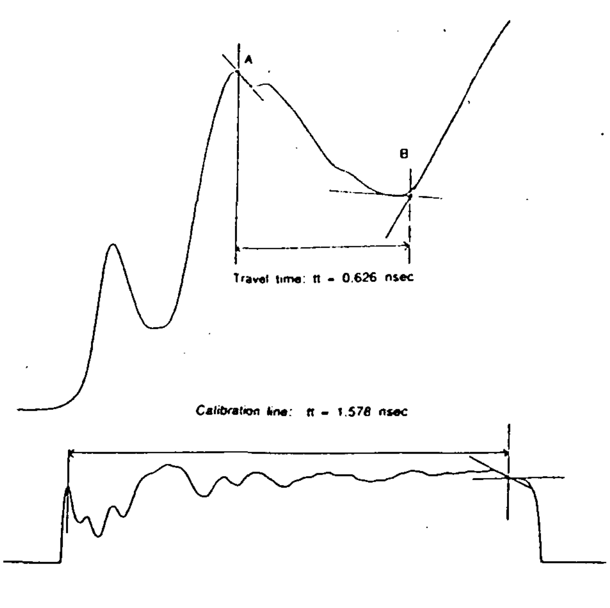

Figure 3. Experimental TDR trace for soil B 30ppt at -10 °C.

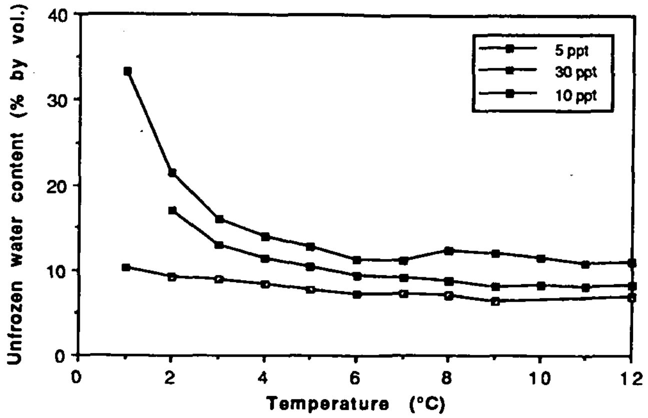

Figure 4. Volumetric unfrozen water content for soil A (sand).

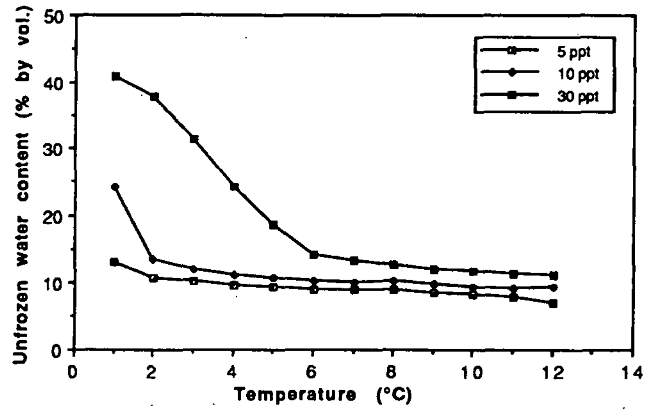

Figure 5.Volumetric unfrozen water content for soil B (silty sand).

Table 1 summarizes the total moisture content, salinity, and dry densities of the test samples. The average gravimetric moisture content for the sand (soil A) is 17.6% with a dry density of 1.71 Mg/m^3 and for the silty sand (soil B) it is 16.5% with a dry density of 1.78 Mg/m^3. Soil B is nonplastic. The values of unfrozen water content at -1°C from the TDR for the samples with a salinity of 30 ppt give Θ_{vu} of 33.4% for soil A and Θ_{vu} of 40.9% for soil B. Which corresponds respectively to gravimetric moisture contents of 19.5% and 23.0%. These values are slightly higher than the total moisture content determined by the gravimetric method. This could be explained by an uneven water distribution in the TDR samples due to gravitational water migration as the amount of unfrozen water increases with an increase in temperature. Moreover, as stated before, the determination of the end point (point B) on the TDR trace becomes more difficult as the salinity and unfrozen water content increases.

The measured salinities are close to the nominal salinities except for soil B at 5 ppt. The post-TDR salinity determination gives an average value of 8.6 ppt. It was noticed just before performing the salinity tests that the samples had dried during storage (2 days), causing a decrease in moisture content and consequently an increase in the measured pore water salinity. The moisture content samples were not stored for as long a period of time explaining why no significant difference in moisture content is observed between these specimens and the ones at 10 or 30 ppt.

Table 1. Physical properties of samples tested.

Soil Type	*Nominal Salinity (ppt)*	*Sample Location*	*M.C. (%)*	*Measured Salinity (ppt)*	*Dry Density (Mg/m^3)*
A	5	top	17.8	5.2	
(sand)		middle	18.5	--	---
		bottom	19.7	4.6	
A	10	top	16.5	9.8	
(sand)		middle	17.9	--	1.68
		bottom	17.2	12.0	
A	30	top	17.2	28.1	
(sand)		middle	17.4	--	1.74
		bottom	16.4	27.7	
B	5	top	15.6	9.9	
(silty sand)		middle	15.7	6.6	1.76
		bottom	16.3	8.7	
B	10	top	15.4	12.8	
(silty sand)		middle	15.8	12.3	1.80
		bottom	16.2	12.5	
B	30	top	17.0	32.7	
(silty sand)		middle	18.3	29.3	1.76
		bottom	18.1	31.0	

Comparison of TDR results with NaCl phase diagram

Figure 6 presents a comparison between the measured unfrozen water content by TDR for soil A and the predicted unfrozen water content using the phase diagram of NaCl. This prediction was done only for soil A (clean sand) since fine-grained particle would affect the phase composition. The prediction was made by using the following rule on the phase diagram in the temperature range of -1 °C to -12 °C and assuming a gravimetric moisture content of 17.5 % and a dry density of 1.71 Mg/m³.

$$W_u = \frac{X}{X_{eq}} \text{ and } \Theta_u = \frac{\rho_d}{\rho_w} W_u \qquad (5)$$

W_u	:	unfrozen water content
X	:	initial concentration of saline solution
X_{eq}	:	concentration of saline solution at equilibrium for a given temperature
Θ_u	:	volumetric unfrozen water content.
ρ_d	:	soil dry density
ρ_w	:	water density

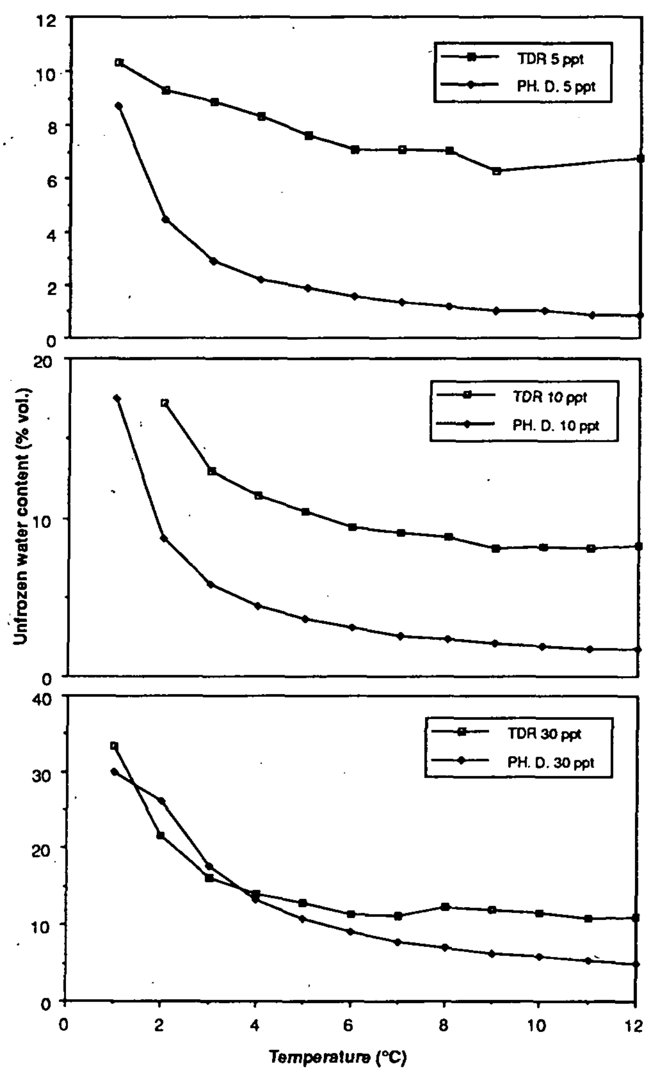

Figure 6. Comparison of phase composition curves using TDR and NaCl phase diagram for soil A.

For salinities of 5 and 10 ppt, the prediction using the phase diagram significantly underestimates the unfrozen water content. However, the shape of the curves are quite similar. This under estimation as compared to TDR values of the unfrozen water content can be explained by the fact that the prediction using the phase diagram assumes a pure NaCl solution and no interaction between the soil grains and the pore fluid. At these very low unfrozen water contents, it is possible that a small amount of clay size particles in the soil interacts with the solution to cause a slight increase of unfrozen water content. For the salinity of 30 ppt, good agreement is observed between the predicted and measured unfrozen water content. For that salinity, the amount of unfrozen water content is larger, and small errors are not as significant. This result gives some confidence in using the TDR method to evaluate unfrozen water content.

Comparison of TDR results with Banin and Anderson's (1974) method

Patterson and Smith (1983) simplified, for the special case of NaCl, a method originally developed by Banin and Anderson (1974) to predict the freezing point (T_n) of a saline soil, when the unfrozen water content (Θ_i) at its natural salinity is known. It is given by:

$$T_n = T_i + \frac{S_o \Delta}{\Theta_i / \Theta_o} \qquad (6)$$

where	T_n	:	new freezing temperature at which R_i will occur
	T_i	:	Freezing temperature at natural salinity
	Θ_i	:	volumetric unfrozen water content at temperature T_i for the soil its natural salinity
	Θ_o	:	volumetric moisture content of thawed sample
	S_0	:	salinity
	Δ	=	-5.867 x 10-2 °C/(gNaCl/l)

Hutchinson (1989) used the method of Tice *et al.* (1976) to determine the unfrozen water content of the silty sand (soil B) based on its liquid limit at a salinity of 0 ppt for the temperatures of -1 °C and -2 °C. Values of gravimetric unfrozen water content of 2.92 % and 1.99 % were calculated for -1 °C and -2 °C respectively and then plotted on a log-log graph to extrapolate the values of unfrozen water content over the range of -3 ° to -15 °C. Using these values, the authors determined the volumetric unfrozen water content (assuming a dry density of 1.78 Mg/m³) and then calculated the new freezing temperature for salinities of 5, 10, 30 ppt (assuming a total gravimetric moisture content of 16.5 %). Figure 7 shows the four curves. For a salinity of 30 ppt, a polynomial curve was fitted to the data in order to establish values of unfrozen water content between -1 ° and -15 °C.

Figure 8 presents the comparison between the measured and predicted unfrozen water content data for the temperature range -1 ° to -15 °C. The results do not match. The values of the unfrozen water content evaluated using the formula proposed by Patterson and Smith (1983) are

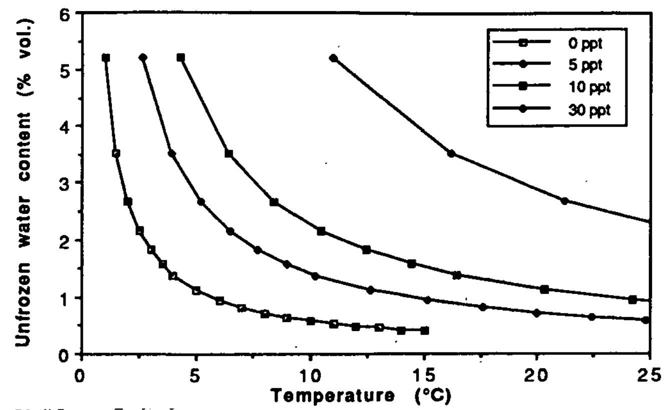

Figure 7. Phase composition curve for soil B at different salinities.

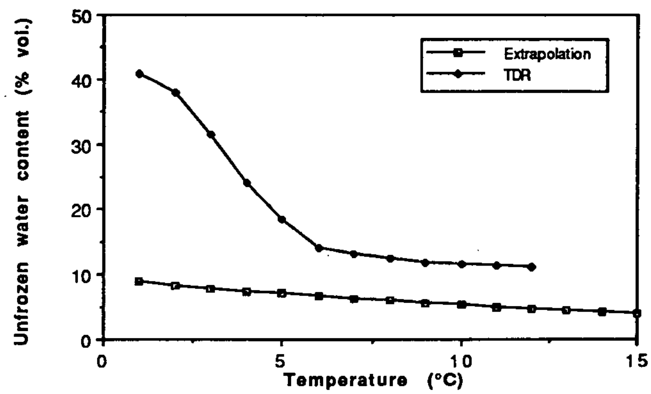

Figure 8. Extrapolation of the phase composition for soil B at 30 ppt salinity.

significantly lower than measured using the TDR. In the authors' opinion, this discrepancy is due to the nature of the soil tested. As mentioned by Hutchinson (1989), since the material was not plastic (low clay content), the evaluation of the liquid limit at 25 blows and 100 blows required by the method [Tice *et al.* (1976)] was very approximate. The authors believe that for low plasticity soils which have low unfrozen water content in the non-saline state, this method of evaluation is not appropriate.

Conclusion

The use of TDR for the evaluation of the unfrozen water content in saline frozen sands and silty sands is effective, simple and reliable as shown by the correlation between the phase diagram prediction and the TDR measurement for soil A at a salinity of 30 ppt and as shown by Smith and Tice (1988) by the comparison of NMR and TDR results. The measurements confirmed that an increase in salinity and a decrease in grain size cause an increase in unfrozen water content at a given temperature. Difficulties occur at warm temperatures (> -3 °C) and high salinities because of the increased signal attenuation. However, suitable choice of transmission line length (in this case 80 mm) can offset the experimental difficulty.

Further research on finer grained materials is required to establish if the method proposed by Banin and Anderson (1974) and modified by Patterson and Smith (1983) is applicable for plastic soils. Additional research in the use of TDR with parallel transmission line configuration in the field could lead to the development of a fast and easy tool to investigate in-situ unfrozen water content.

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References

BANIN, A. AND ANDERSON, D.M., 1974. Effects of salt concentration changes during freezing on the unfrozen water content of porous materials. Water Resources Research, 10 (1), pp. 124-128.

DAVID. J.L. AND ANNAN, A.P., 1977. Electromagnetic detection of soil moisture: Progress Report 1. Canadian Journal of Remote Sensing, 3 (1), pp. 76-86.

HOEKSTRA, P. AND DELANEY, A., 1974. Dielectric properties of soils at UHF and microwave frequencies. Journal of Geophysical Research, 79, pp. 1699-1708.

HUTCHINSON, D.J., 1989. Piles in frozen saline silty sand. Unpublished M.Sc. thesis, University of Alberta, 222p.

PATTERSON, D.E. AND SMITH, M.W., 1981. The measurement of unfrozen water content by time-domain reflectometry: results from laboratory tests. Canadian Geotechnical Journal, 18, pp. 131-144.

PATTERSON, D.E. AND SMITH, M.W., 1983. Measurement of unfrozen water content in saline permafrost using time-domain reflectometry. Proceedings: Fourth International Conference on Permafrost, Fairbanks, Alaska, National Academy of Sciences, Washington, D.C., 17-22 July, pp. 968-972.

PATTERSON, D.E. AND SMITH, M.W., 1985. Unfrozen water content in saline soils: results using time-domain reflectometry. Canadian Geotechnical Journal, 22, pp. 95-101.

SMITH, M.W. AND TICE, A.R. (1988). Measurement of the unfrozen water content of soils. Comparison of NMR and TDR methods. CRREL Report 88-18, 41 p.

TICE, A.R., ANDERSON, D.M. AND BANIN, A., 1976. The prediction of unfrozen water contents in frozen soils from liquid limit determinations. CRREL Report 76-8, 9p.

TOPP, G.C., DAVIS, J.L. AND ANNAN, A.P., 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resources Research, 16 (3), pp. 574-582.