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Laboratory Investigation of the Effect of Diesel Contamination on the Unfrozen Water Content Curve of a Frozen Soil

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Abstract

The results presented in this paper are part of a laboratory investigation of unfrozen water content changes due to diesel contamination using a Time Domain Reflectometry (TDR) cable tester carried out at the geotechnical laboratory of the Royal Military College of Canada.

Key Words diesel contaminated soils, frozen soils, unfrozen water content, TDR

Introduction

Frozen soils are complex systems by virtue of their multi-phase nature. This type of soil, as described by Tsytovich (1975)[1], consists of at least four-phases: solid mineral particles, ideally plastic ice inclusions (cementing ice and interlayer ice), water in the bound and liquid states, and finally gaseous components.

Through these components, water is present in its three phases simultaneously; solid, liquid and vapor. The properties of each component differ from those of the others. The study of such a system is complex because the components are bounded to one another and interact strongly.

When a soil is frozen, especially fine-grained soils, not all the water within the soil pores freezes, but only part of it. As he was studying the freezing point depression and the supercooling temperature of soil water, Bouyoucos (1916)[2] observed that significant amounts of unfrozen water coexist with ice in soil at temperatures below 0^{o}C. Up to 50% of the moisture in a soil may exist as a liquid at temperatures of -2^{o}C (Nersesova and Tsytovich, 1965[3]). As the temperature drops further, phase transitions of the water continue. Hoekstra (1969)[4] observed that mineralogical composition and the type of exchangeable ions caused minor variations on the thermodynamics equilibrium between unfrozen water and ice. The amount of water that freezes depends, primarily, on the magnitude of negative temperature that constitutes the main factor, on

the specific surface of the mineral particles, on the composition of absorbed cations, and on pressure (Tsytovich, 1975[1]; Andersland and Ladanyi, 1994[5]). Consequently, these parameters have direct influence on the water quantity that remains unfrozen.
The presence of unfrozen water in frozen soil is due to the opposing effects of attraction forces to the zone of strongly bound water and to water of variable phase composition. The freezing temperature of the pore water falls because a layer with more mobile molecules, a "warmer" layer that requires a lower freezing temperature, appears between them (Tsytovich, 1975[1]). The attraction forces result from capillarity and osmotic effects, and to a variety of adsorption effects associated with soil particle surfaces (Williams and Perfect, 1980[6]).

Time Domain Reflectometry

Principles

Time Domain Reflectometry (TDR) is a method that is based on electromagnetic waves propagation along transmission lines. This technique had its initial application in the detection of defaults appearing in telecommunication cables, before being extended to the study of dielectric properties of organic liquids (Fellner-Feldegg, 1969[7]) and soils (Davis and Chudobiak, 1975[8]; Davis, 1975[9]).

The TDR signal velocity propagation v is related to the relative dielectric permittivity ε of an assumed lossless soil by the following equation (Topp et al., 1980[10])

$$v = \frac{c}{\sqrt{\varepsilon}} \qquad (1)$$

c is the light propagation velocity in vacuum, $c = 3x10^8$ m/s.

The travel time Δt that is needed by the TDR signal to travel forth and back in a waveguide of length L, can be written:

$$\Delta t = \frac{2L}{c}\sqrt{\varepsilon} \qquad (2)$$

The last equation yields the direct dependency between the TDR signal travel time and the soil dielectric properties. This dependency is characterized by the soil permittivity ε.
A clean soil is composed of solid grains, water and air. The relative dielectric permittivities of these components are respectively: $\varepsilon_s = 4$, $\varepsilon_w = 65$, $\varepsilon_{air} = 1$. The large contrast between the dielectric permittivity of water and those of the other soil components is noticeable. Therefore, soil water content will have a strong influence on the soil dielectric permittivity value.

Mixing model

The mixing model, relating soil water content to soil dielectric permittivity, is a semi-empirical approach based on physical and geometrical considerations (Roth et al., 1990[11]). This model considers the contribution of concentration and permittivity of each component to the global dielectric permittivity of the soil. In the case of a clean unsaturated soil, only three phases exist: solid grains, water and air. The relative dielectric permittivity of such a soil is given by the mixing law:

$$\varepsilon = \left[\theta\, \varepsilon_w^{\beta} + (1-\phi)\, \varepsilon_s^{\beta} + (\phi-\theta)\, \varepsilon_{air}^{\beta} \right]^{\frac{1}{\beta}} \qquad (3)$$

θ and ϕ designate respectively, the volumetric water content and the soil porosity.
β is a factor related to soil grain geometry and their spatial distribution. For a soil assumed to be homogeneous and isotropic $\beta \approx 0.5$ (Alharthi and Lange, 1987[12]).
In case of soil contaminated by a non-miscible liquid such as diesel, a fourth phase is added to the soil composition. Equation (3) giving the dielectric permittivity is reformulated to take into account the contaminant phase. With ψ, the volumetric diesel concentration and by ε_{diesel} the relative dielectric permittivity ($\varepsilon_{diesel} = 2.88$), the soil dielectric permittivity ε is given by the modified mixing model proposed by Chenaf (2000)[13],

$$\varepsilon = \left[\theta\, \varepsilon_w^{\beta} + \psi\, \varepsilon_{diesel}^{\beta} + (1-\phi)\, \varepsilon_s^{\beta} + (\phi-\theta-\psi)\, \varepsilon_{air}^{\beta} \right]^{\frac{1}{\beta}} \qquad (4)$$

The factor of the air permittivity in equation 4 is in fact the air-filled porosity. As soon as the freezing starts, the number of phases involved is increased from four to five. An additional term that denotes the presence of ice will appear in the formulation of the mixing law.
During freezing, a variation of water content occurs since part of the water is subject to a phase transition from water to ice. In addition, as ice density is lower than water density, the volume occupied by ice is larger and a decrease of air-filled porosity occurs during freezing. The air-filled porosity is not constant as the freezing process goes on and it would be more appropriate to use the term "instant porosity". The modified mixing law for this new situation is written as follows,

$$\varepsilon = \left[\theta'\, \varepsilon_w^{\beta} + \gamma\, \varepsilon_{ice}^{\beta} + \psi\, \varepsilon_{diesel}^{\beta} + (1-\phi)\, \varepsilon_s^{\beta} + \phi'\, \varepsilon_{air}^{\beta} \right]^{\frac{1}{\beta}} \qquad (5)$$

It can be noticed in the new writing of the mixing law that terms associated to diesel and to soil solid grains remain unchanged as freezing does not affect their volume fractions. Conversely, the unfrozen water content and the air porosity are affected by ice crystal growth. The new (unfrozen) water content and air porosity are respectively designated by θ' and ϕ' in equation (5), while the concentration of the generated ice is designated by γ.

Assuming that the soil sample will not be subject to volume variation during the freezing (ie. The soil porosity remains unchanged) the new air porosity can be deduced. It is given by the following equation,

$$\phi' = \phi - (\theta' + \gamma + \psi) \quad (6)$$

The ice concentration γ is determined from the mass conservation law applied for water before and after freezing starts. The expression of the volumetric ice content in the freezing soil is given by,

$$\gamma = \frac{\rho_w}{\rho_{ice}} \left(\theta - \theta'\right) \quad (7)$$

The combination of equations (5), (6) and (7) allows the determination of unfrozen water content θ' existing in an unsaturated contaminated freezing soil from measurements of its dielectric permittivity ε, which is performed by TDR method.

Materials and methods

Soil column preparation

The tested samples were prepared with soil identified as "poorly graded sand", according to the unified soil classification system ASTM D 2487[14]. This soil is designated by the name "Unity 2000" in reference to the Unity area, in the vicinity of the city of Kingston in Ontario (Canada), from where it was extracted. The grain size curve of the Unity 2000 soil is plotted on Figure 1.
Since the objective of the study is to analyze the influence of diesel and its concentration on the quantity of water that remains liquid during freezing of the soil, several samples at different water and diesel contents were prepared. The exact proportions of water and diesel in the tested samples are shown on Table 1. It can be observed that two series of samples were tested corresponding to two different water contents of about 15% and 20%. The values that are indicated on Table 1 for this parameter were measured just before proceeding with the diesel contamination of the soil. They represent the ratio of mass of added water over dry soil. The diesel concentration, shown on the same table, is the mass of diesel added to contaminate the moistened soil, over the total mass of liquid (water + diesel) present in the soil.
Soils are prepared following the well-known protocol of preparation of moistened soils. The appropriate amount of water is added to achieve the desired water content after which the sample is stored for twenty four hours in sealed plastic bags to insure uniform moisture distribution. The contamination operation is performed by adding a pre-established diesel quantity to reach the planned contamination level. The diesel is thoroughly mixed with the moistened soil to achieve a homogeneous state of contamination. At each step of the sample preparation, control and measurement of water and liquid contents were performed by gravimetric method.

Diesel was chosen to contaminate the soil samples to be tested because it is a common fuel used in northern regions of Canada and is a major contaminant in those areas. Table 2 summarizes the relevant properties the diesel used.
To be tested, the soils were filled in cylindrical columns. These have two functions: holding soils in similar regular shapes and insulating them thermally. They are made of Plexiglas material and designed with sufficiently large dimensions in order to avoid edge effects. Holes were drilled on opposite sides of the walls at the top, middle, and bottom levels, allowing insertion of TDR probes and thermistors for unfrozen water content and temperature measurements in those sections during the tests. The walls of the columns are wrapped with thermal insulator material (styrofoam) that minimizes thermal exchange with the external medium.

The TDR probes are made of two parallel cylindrical rods with planar extremities (rod length = 45mm, rod diameter = 3mm, rod spacing = 19.5mm).

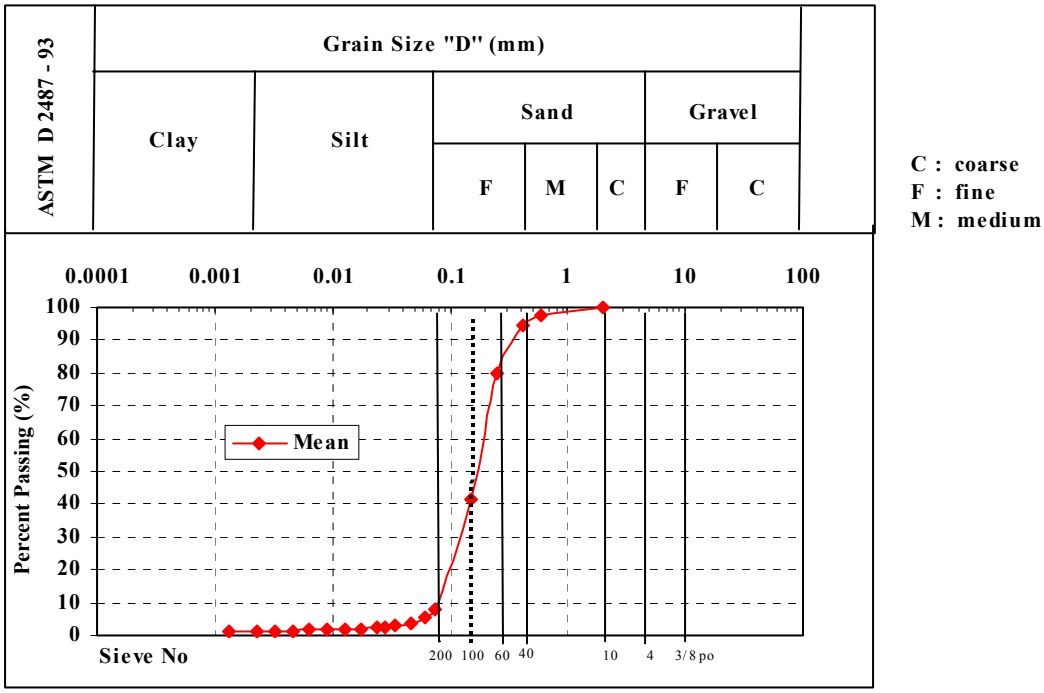


Figure 1: Grain size analysis, Unity soil 2000

Table 1. Composition of tested samples

Poorly graded sand (*) (Unity 2000 soil)		
Samples Serial #	Water Content (%)	Diesel concentration (%)
1-1	14.74	0
1-2	14.94	2.09
1-3	14.64	7.37
1-4	14.72	12.62
1-5	15.09	17.67
1-6	14.80	25.98
2-1	19.39	0
2-2	19.71	2.17
2-3	18.96	7.41
2-4	19.36	12.63

Table 2. Diesel properties

Designation (*)	Diesel Fuel Arctic, 3.6-M90 Type A
Density	0.77
Freezing temperature	233.15 K (- 40 ^{o}C)
Relative dielectric permittivity	2.88
(*) According to the Canadian General Standards Board (CGSB)	

All columns are filled in four layers such that the top of each layer is level with the access holes. TDR probes and thermistors could be inserted at each step without disrupting soil compaction, and insuring good contact with the soil that surrounds them. When the top of the column is reached, the upper surface of the soil column is levelled, and then covered with plastic film. Care is taken to ensure that only the upper surface of the soil column is in thermal contact with the external environment. The soil column wrapping design imposes a downward vertical progression of the temperature gradient and hence of the freezing front. The soil column is then installed in a cold room, initially set at a stabilized constant temperature of -5^{o}C. The choice of the cold room temperature was selected because this temperature is clearly located below the freezing point of water and above the freezing point of diesel (Tables 2 and 3).

Table 3. Water and ice properties

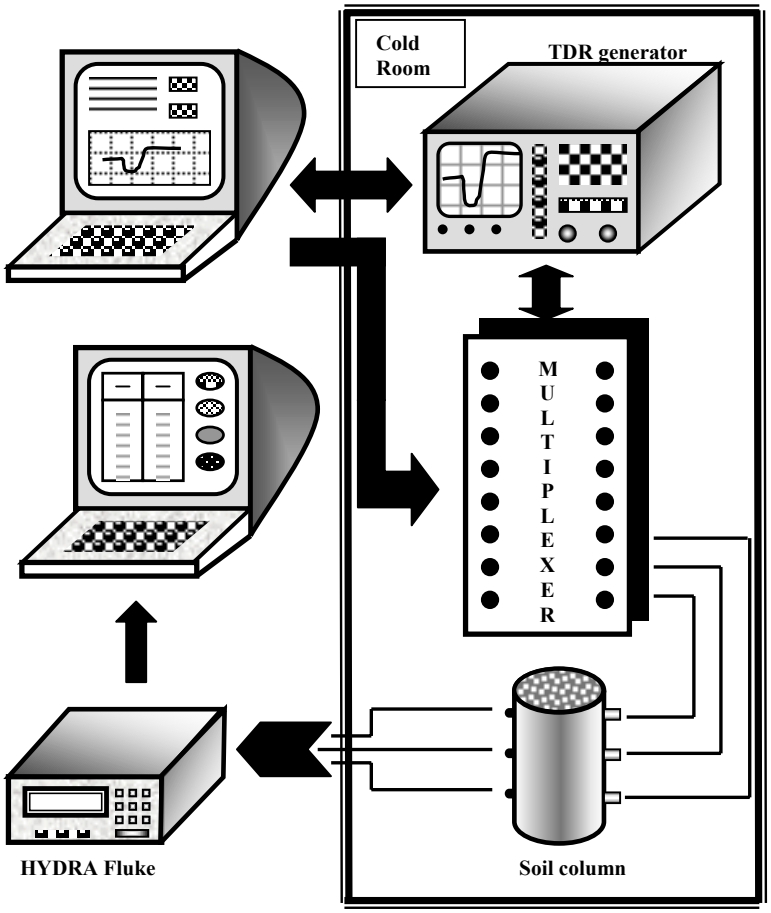
Density :	
unfrozen water , ρ_w	10^3 kg m^{-3}
ice , ρ_i	916.8 kg m^{-3}
Freezing temperature :	
pure water , T_0	273.15 K (0^{o} C)
Relative dielectric permittivity :	
unfrozen water , ε_w	65
ice, ε_i	6
Latent heat :	
water , L	$3.336 10^5$ J kg^{-1}

Instrumentation and experimental method

Once the columns are placed in the cold room, the experimental set-up is completed as shown in Figure 2. The TDR probes are connected to a multiplexer whose function is to switch the

excitation signal between the different columns and TDR probes from top to bottom in a continued sequential order. From the other side of the columns, thermistors are connected to the input module connections of HYDRA FLUKE. This apparatus is a multi-channel data acquisition unit measuring the thermistors' resistance, which is modulated by their temperature. For the temperature range of the experimental tests (-5°C and above), the used thermistors offer an accuracy of ± 0.1°C.

The experimental set-up is composed of two units: an excitation unit, and an acquisition and processing unit (Figure 2). The part in charge of excitation is mainly constituted by a TDR signal generator working as emitter and receiver, a multiplexer, and TDR probes. A computer controls entirely the excitation bloc. The acquisition and processing unit is composed of the quoted TDR generator, HYDRA FLUKE and two PCs. One PC is connected to both the TDR signal generator and the multiplexer. This computer works both as acquisition and processing element. The second computer is connected to HYDRA FLUKE and collects the thermistors' resistance measured continuously for the three sections of the soil columns. The design of the experimental



device offers the advantage of being entirely automated.

Fig. 2. Experimental set-up

The excitation TDR signal is an electromagnetic step impulse characterized by a few tenths of a Volt in amplitude, and a very short rise time. The excitation signal is transmitted to the TDR probes by coaxial cables via the multiplexer.
The reflected TDR signals take the inverse pathway of the excitation signal. They are transmitted from the TDR probe to the multiplexer system. This one sends the reflected signals to the TDR generator; and finally, the experimental data is transferred to the computer for saving, and for processing later. Equation (2) and equation (5) allow the calculation of the associated unfrozen water content. This quantity is measured continuously at the three sections (top, middle and bottom) of the soil column during the test at regular time intervals. The relative shortness of the measurements frequency allowed plotting of accurate data of unfrozen water content curves according to time and to temperature during the test.
The temperatures are calculated from the resistance data measured with the thermistors. These measurements executed by the HYDRA FLUKE and processed by the data acquisition program are performed in sequential order with an adjustable frequency. For the test serials that were carried out, the frequency was fixed to one reading per 60 seconds. This frequency allows, during the test, the accurate monitoring of the evolution of the temperature in the three sections of the soil columns as the freezing front progresses from top to bottom.

Results and discussion

Unfrozen water content curves

Figures 3 to 7 show the relative unfrozen water content curves according to temperature, at top, middle and bottom sections obtained for samples with 15% initial water content. The relative unfrozen water content designates the measured unfrozen water content over the initial soil water content. This latter is indicated by θ_0 on the corresponding figure. The relative unfrozen water content evolution for the clean sample (0% diesel) is plotted on Figure 3. Figures 4 to 7 show the evolution of the same parameter for the samples contaminated at 7%, 12%, 17% and 26% of diesel concentration, respectively.
As first glance, it can be mentioned the similarity in the shape of the relative unfrozen water content curves for all the samples, either clean or contaminated, as the temperature decreases (Figures 3 to 7). This similarity is observed at the three sections of the soil column as well. The curves are globally composed by two sections; vertical and horizontal. Indeed, the relative unfrozen water content curve begins by a dramatic decrease. The relative values of unfrozen water content fell from around 100% to nearly 40%. The decrease takes place in a very narrow temperature interval located between 0^oC and -0.4^oC. From this temperature on, the unfrozen water content seems to rapidly stabilize and fluctuates between the values of 20% and 40% for the considered samples prepared at 15% of water content.
From this curves, it can be said that most of the soil water freezes during the time corresponding to the vertical section. The freezing process i.e. the phase transition seems to be nearly completed in the horizontal branch. It can be noticed that the relative unfrozen water content remains constant as the temperature continues to decrease. Nersesova and Tsytovich (1965)[3] made similar observations and characterized the unfrozen water curves in three parts associated to three temperature ranges of water phase transitions in frozen soils. The length of the vertical branch of a given soil column is proportional to its freezing time, which defined here as the time

needed for the free water to be wholly frozen. Once all the free water is frozen, the temperature begins to decrease and the bounded water begins to freeze. However, it can be noticed that beyond the curved part corresponding to the freezing point temperature, the unfrozen water content does not decrease significantly. This is in part due to the fact that the bounded water content is very small compared to the free water content. In addition, attraction forces acting between soil grains and the surrounding water layer prevent the crystallization from taking place. As a result, the unfrozen water content decreases very slowly or remains nearly constant.

Diesel and initial water contents influence

Figures 3 to 7 show that once the free water is frozen, i.e. the part corresponding to the horizontal branch of the curves, the plot corresponding to the top section of the soil column is below that one corresponding to the bottom section. This means that there remains more water in the liquid phase in the bottom section of the column than in the top one. This can be observed for all tested columns at 15% of water content, either clean (Figure 3) or contaminated (Figures 4 to 7).

The influence of diesel on relative unfrozen water content is shown for samples moistened at 15% for top, middle and bottom sections on Figures 8.a, 8.b and 8.c respectively. Even if the curves corresponding to different samples are not superimposed, they remain tightly close to each other.

After examination of these figures, it cannot be said that the effect of diesel on relative unfrozen water content was clearly highlighted. However, it can be observed that there tends to remain more unfrozen water in contaminated columns than in clean ones. Especially, in Figures 8.b and 8.c corresponding respectively to middle and bottom sections of the tested columns.

As indicated on Table 1, two other serials were tested. The first one is a set of one clean and two diesel contaminated samples, moistened at 20% initial water content. The relative unfrozen water content curves are plotted on Figures 9, 10 and 11 for samples with contamination rates of 0 %, 7% and 12% respectively.

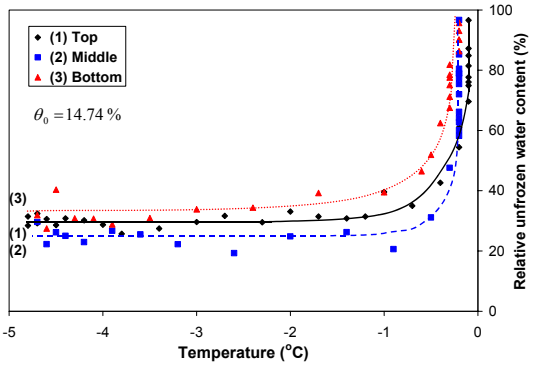


Fig. 3. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 15% water and 0% diesel

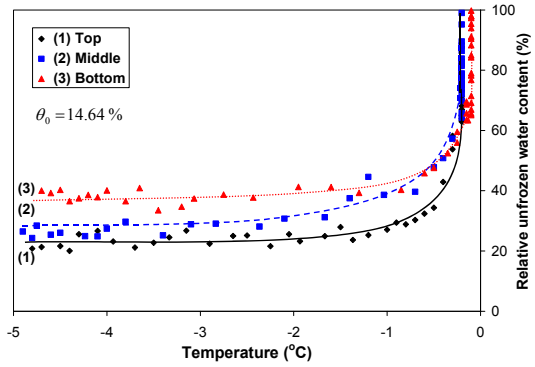


Fig. 4. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 15% water and 7% diesel

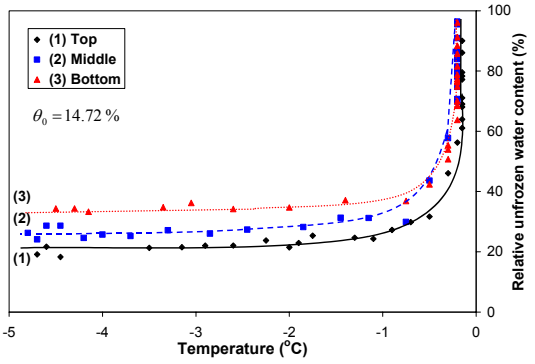


Fig. 5. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 15% water and 12% diesel

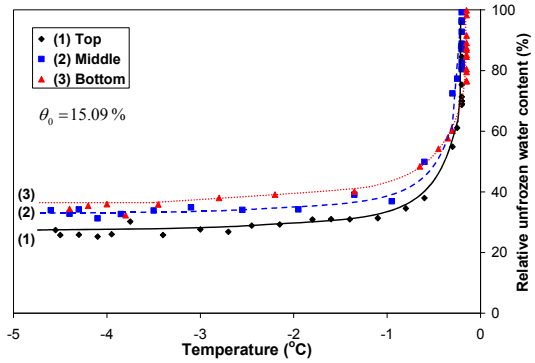


Fig. 6. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 15% water and 17% diesel

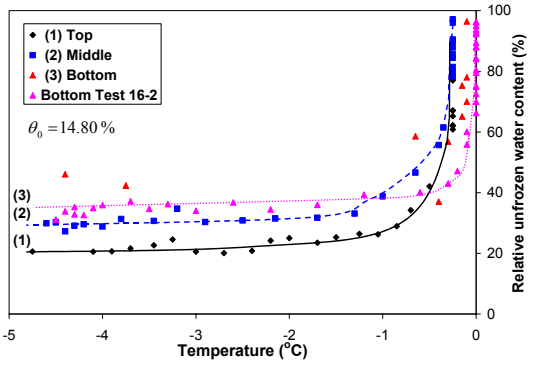


Fig. 7. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 15% water and 26% diesel

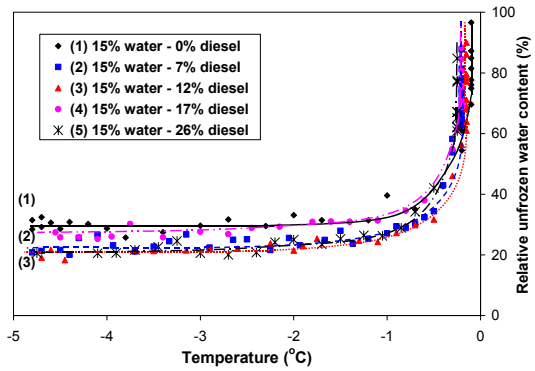


Fig. 8.a. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 15% water (top section)

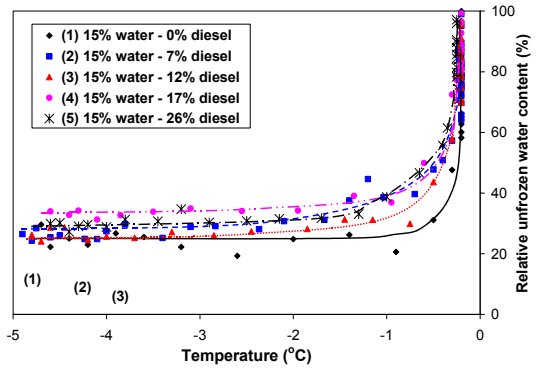


Fig. 8.b. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 15% water (middle section)

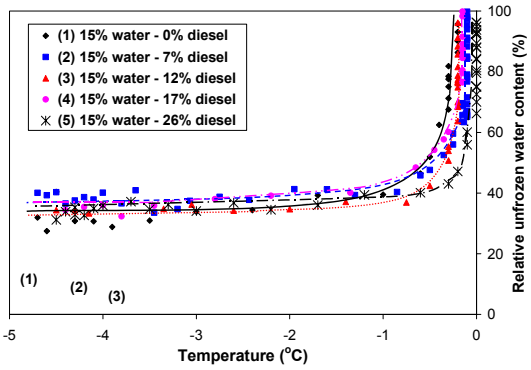


Fig. 8.c. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 15% water (bottom section)

Figures 9 to 11 exhibit features similar to those noticed for the soil columns at 15% initial water content (Figures 3 to 7). This indicates that the two-branch pattern that was observed on the unfrozen water content curves is primarily related to freezing soil behavior. Again, for this serial of samples, relative unfrozen water content at the end of the freezing phase is larger in the bottom section than in the top section of the column.

Figures 12.a, 12.b and 12.c present the relative unfrozen water content curves of clean and contaminated samples moistened at 20% of initial water content. They are grouped by the top, middle and bottom sections, respectively. As pointed out previously, diesel seems not to have a strong influence on the evolution of unfrozen water content with temperature during the freezing phase. The same observations made for the first serial of samples (15% water, Figures 8.a to 8.c) hold true for this serial.

The influence of the initial water content is highlighted in Figures 13.a, 13.b and 13.c on which are plotted the relative unfrozen water content in respectively the top, middle, and bottom sections for the clean samples tested (i.e. 0% diesel and initial water content of 15%, 20% and 23%).

The three figures exhibit similar patterns for the relative unfrozen water content. The curves begin by the vertical branches, which are nearly superimposed for the examined initial water contents at the three sections of the columns. That could mean that the initial water content, in the examined range, does not have a strong influence on the freezing point temperature. The tightening ends as the curves change concavity to take a nearly horizontal trend and is held until the end of the free water phase transition. After that, a clear separation appears between the curves corresponding to different initial water contents. Indeed, a clear separation is observed between the experimental points corresponding to samples moistened at 15% and those moistened at 20% and 23% of initial water content.

The horizontal branches of the relative unfrozen water content curves are lowered with an increase in the initial water content. This observation applies to the top, middle and bottom sections. This means that a higher initial water content in the soil sample results in a lower relative unfrozen water content at the end of the freezing process.

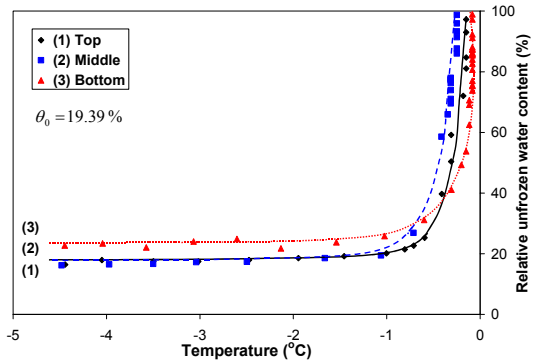


Fig. 9. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 20% water and 0% diesel

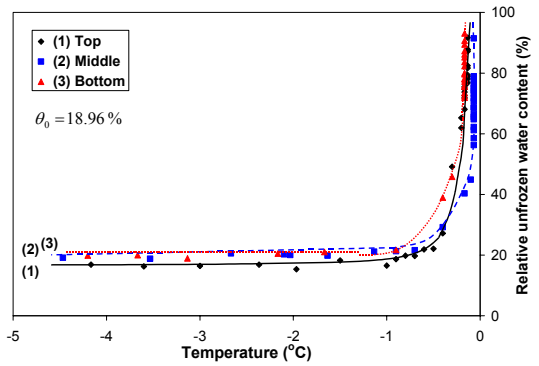


Fig. 10. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 20% water and 7% diesel

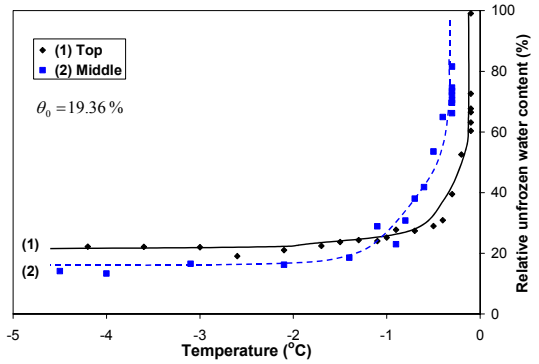


Fig. 11. Relative unfrozen water content as a function of temperature,
Unity 2000 soil at 20% water and 12% diesel

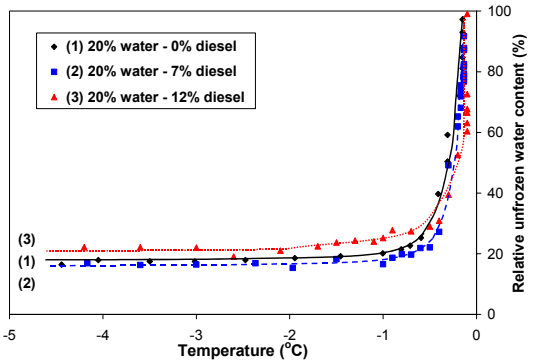


Fig. 12.a. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 20% water (top section)

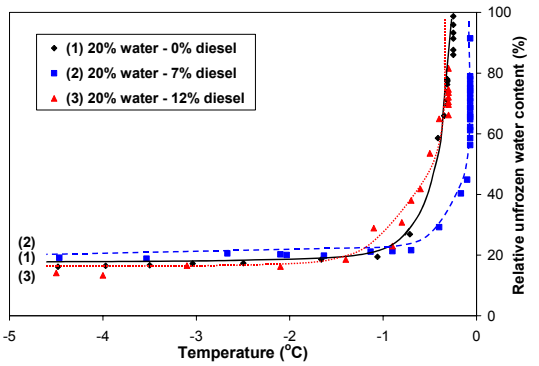


Fig. 12.b. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 20% water (middle section)

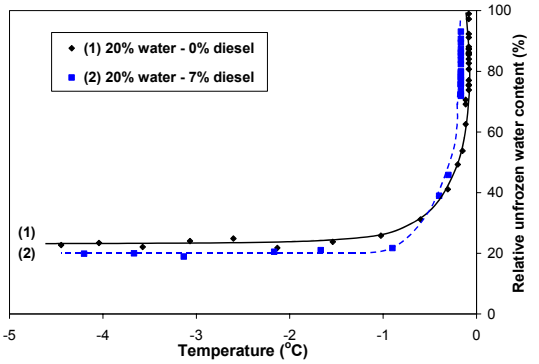


Fig. 12.c. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 20% water (bottom section)

It must be pointed out that the amount of unfrozen water at a constant temperature below 0°C is independent of the amount of ice, and therefore of total water content. In other words, when the thermodynamic equilibrium is reached at any given negative temperature, the amount of unfrozen water content is fixed for this temperature (Anderson and Morgenstern, 1973[15];

Courty and Kierlik, 2002[16]). This implies that if water is added or removed from an adiabatic system, some of the ice will either be formed or will melt in order to satisfy the ice-water equilibrium.
Consequently, as shown by Figures 13.a, 13.b and 13.c, the vertical branch is longer as the initial water content increases. This indicates that the higher the initial water content, the longer the freezing time will be. This is due to the fact that more ice is formed as the initial water content increases.

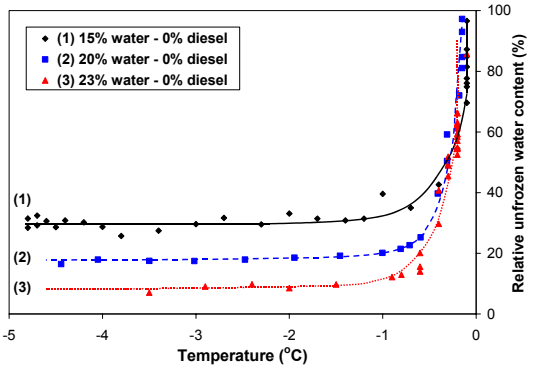


Fig. 13.a. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 0% diesel (top section)

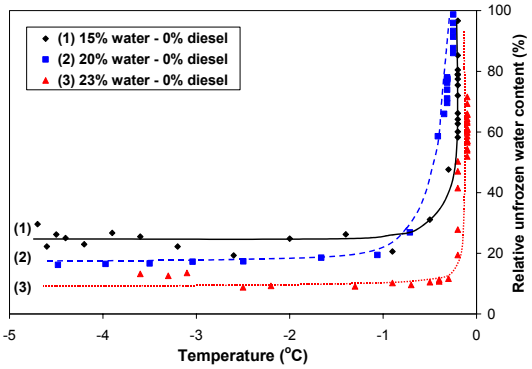


Fig. 13.b. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 0% diesel (middle section)

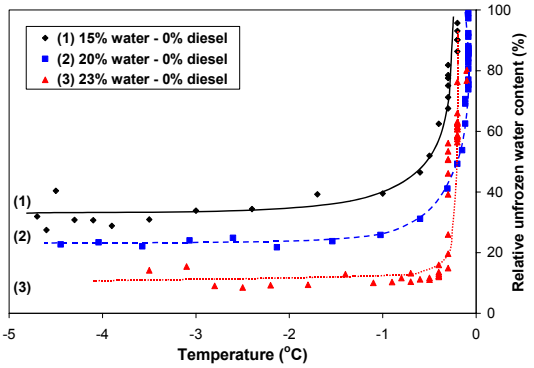


Fig. 13.c. Relative unfrozen water content as a function of temperature,
Unity 2000 soil – 0% diesel (bottom section)

Thermodynamics equilibrium can explain why the relative unfrozen water content in the bottom sections is larger than in the top ones. This was shown by the horizontal branches appearing in upward order from top to bottom in the relative unfrozen water content curves. This property was observed in nearly all cases of the tested serials (Figures 3 to 7; 9 to 11). Indeed, as soil is freezing, water migration from the bottom towards the freezing front occurs. This results in an increase of the water content (ice and liquid) in the top section of the columns. On the basis of what it was discussed previously, the amount of ice formed in the top section is larger than in the bottom. But the thermodynamic equilibrium at any given temperature imposes always that the same amount of water remains liquid, therefore the relative water content is lowered. The difference between top and bottom sections is likely due to the phenomenon of exclusion. This

consists in alien components being excluded from the water phase while ice crystals are growing. The frozen area is consequently virtually cleaned of any contaminant. In the case of a diesel contaminated soil column subjected to freezing from the top down, the exclusion phenomenon consists in excluding the diesel by pushing it to the bottom of the column while the freezing front progresses downward. Similar behaviour was observed on phenol and was highlighted in a study carried out by Tumeo and Davidson (1993)[17]. The exclusion phenomenon causes an accumulation of diesel at the bottom, thus increasing its concentration locally over the initial value. The conditions to meet the thermodynamic equilibrium are modified in that section compared to the top one. Thus, the amount of water that remains liquid is different between the top and bottom. The explanation is also valid for clean samples, as pore soil water is never pure. Mineral particles that are released by the solid grains of soil behave as solutes and are excluded in the same manner (Konrad and McCammon, 1990[18]). As specified by Nersesova and Tsytovich (1965)[3], the amount of liquid water in frozen soils is determined not only by the action of the field of force at the surfaces of the soil skeleton, but also by the content of water soluble compounds.

If the initial water content is increased the behavior remains similar to what was noted in the previous section. The difference is observed only for the water migration towards the freezing front. This property was observed and investigated by Xu et al. (1987)[19]. They stated that the driving force for water migration in frozen soils is the gradient of the soil-water potential. The influence of water content on water migration is a consequence of its influence on the soil-water potential.

Soil water, except for the gravitational water portion, is subjected to an action from the surface energy of the mineral particles, and an action from the capillary forces and adsorption forces. With a decrease in the degree of saturation, the capillary water is first removed, leaving the pellicular water. The forces to which water is subjected change from capillary forces to adsorption forces. As a result, the soil-water potential and hence water migration, always decrease with a decrease in water content.

Conclusions

A study of the effect of diesel contamination on the unfrozen water content curve of a silty soil is presented in this paper. This work is considered both novel and original, as there is no record of similar studies in the literature. It is shown in this paper that the average unfrozen water content increases from top to bottom because of the upward fluid migration in the sample as the freezing front propagates from the top section to the bottom section. In addition, diesel contamination seems to have less influence on the variation of the unfrozen water content at a given negative temperature, than the initial water content (water content before freezing) for the levels of contamination at which the soil samples were tested.

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