Laboratory studies of near surface temperature and moisture conditions of permafrost soils

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ABSTRACT
This paper presents a laboratory freeze-thaw study of permafrost soils from the Mackenzie valley, Northwest Territories, Canada. Two laboratory models consisting of soil columns of 40 cm in height and 15 cm diameter were built. The models were constructed and put in a walk-in freezer to simulate repeated freeze-thaw cycles. A total of 11 freeze-thaw cycles were tested. Extreme air temperatures were applied to one model during the last cycles of the experiment to simulate extreme weather conditions. Significant increase of moisture content was observed above the cryofront which is consistent with field observations. A moisture deficit zone was also observed within the active layer. In this study, it was found that the extremely high ice content zone near the permafrost table can be altered under extreme air temperature conditions. The zone of enhanced moisture moved down with the extreme warm air temperature. However, the normal peak ice-rich zone may re-establish after repeated freeze-thaw cycles under normal climate conditions.

RÉSUMÉ
Cet article résulte d'une étude expérimentale concernant le gel-dégel du pergélisol provenant de la vallée du Mackenzie, Territoires du Nord-Ouest, Canada. Deux appareils contenant des colonnes de sol d'une hauteur de 40 cm et d'un diamètre de 15 cm ont été construits. Ces modèles ont été fabriqués et placés dans un congélateur afin de simuler les cycles répétés de gel-dégel. Un total d'onze cycles gel-dégel ont été simulés. Un échantillon fut soumis à des températures extrêmes pendant les derniers cycles de l'expérience afin de simuler des conditions climatiques extrêmes. Une accumulation significative de la teneur en eau fut notée au-dessus de l'isotherme 0℃, ce qui est consistant avec des observations sur le terrain. Une zone ayant un déficit en humidité fut également observée dans la couche active. Cette étude, démontre que la zone riche en glace près du pergélisol peut être altérée sous des conditions extrêmes de température. La zone riche en glace fut déplacée vers le bas lors de températures extrêmes. Cependant, cette zone peut être rétablie à la suite de cycles gel-dégel répétés sous des conditions climatiques normales.

1 INTRODUCTION

In permafrost, the active layer and near surface permafrost are conditioned by repeated freeze-thaw cycles. Weather fluctuation induces variation in ground thaw depth which results in an intermediate layer that remains frozen for two or more years, but does thaw occasionally. This layer is currently still classified as permafrost by traditional definition (Everdingen 2002). However, researchers have been using the term *transient layer* to distinguish this layer from the active layer and the "long-term" permafrost (Shur 1988; Shur et al. 2005; Bockheim and Hinkel 2005; Wang et al. 2005; French 2007; Wang and Lesage 2007; Wang and Saad 2007; Nelson et al. 2008; Wang et al. 2008). Typical ice distribution profiles in permafrost terrain indicate excessive ice content increase in the vicinity of near surface permafrost (Pollard and French 1980; Harris 1988; Wang et al. 2008). Thawing of the ice-rich zone may translate into significant reduction of shear strength and therefore slope stability and other geotechnical problems. Despite its engineering importance, little is known about the transient layer. Thus, there is an urgent need to study this near surface permafrost layer and its behaviour.

A laboratory study has been carried out with a focus on thermal behaviour and moisture migration of fine-grained permafrost samples subject to repeated freeze-thaw cycles. Extreme air temperatures were applied to one soil sample in an attempt to simulate the formation of the transient layer. Temperature results are presented and evaluated in comparison to a finite element model. Finally, the moisture condition changes are assessed and compared with field observations.

2 TRANSIENT LAYER AND MOISTURE CONDITIONS NEAR THE PERMAFROST TABLE

The transient layer is the result of annual maximum thaw depth variations. The temperature within this zone may rise to above 0ºC in a return period of two years or longer. Its return time scale can range from sub-decadal to multi-century which causes its characteristics to differ from both active layer and permafrost soils (Shur et al. 2005). No criterion has been established thus far as to delineate the boundaries of the transient layer. Several methods have been used in an attempt to define the transient layer boundaries, for example, Shur et al. (2005) used a theoretical approach and Bockheim and Hinkel (2005) based their findings on several criteria such as cryogenic structures (i.e. ice enrichment), sample location and soil properties. The use of any method or establishment of any criterion to delineate the extent of the transient layer may largely dependent on the purpose of the study. For example, the sub-decadal and multi-century thawing probabilities may serve short-term and long-term engineering purposes respectively.

In many arctic field investigations, an ice-enriched zone has been identified and described as being either within the transient layer (Shur 1988; Shur et al. 2005, Bockheim and Hinkel 2005; French 2007; Nelson et al. 2008) or at the base of the active layer (top of permafrost) (Mackay 1971, 1983; Pollard and French 1980; Cheng 1983; Kokelj and Burn 2003, 2005). This ice-rich layer has a great impact on the thermal stability of the underlying permafrost, on certain periglacial processes and on the formation of cryostructures. It stabilizes the subjacent permafrost and serves as a thermal barrier between the active layer above and the underlying permafrost. Shur et al. (2005) believe that the probability of thaw deeper within the transient layer is decreased due to ice enrichment within this zone. Its latent heat properties protect the underlying permafrost from thaw during most warm periods. Furthermore, the extent of latent heat required to thaw this ice-rich layer inhibits rapid thaw and tends to govern the active layer thickness (Nelson et al. 1998, 2008). This layer therefore plays a critical role in active layer and near surface permafrost response to climate changes and surface disturbances (Shur 1988).

The moisture condition of the transient layer is key in determining thawed soil strength. Shear strength of thawed ice-rich soils is significantly lower in comparison to soils having low ice content (Wang et al. 2005). Slope failure can be initiated if the driving force exceeds resistance. During summers with deep thaw, progressive displacements have been observed at the active layer base where fine-grained soils are ice-rich (Lewkowicz and Clarke 1998; Harris and Lewkowicz 1993, 2000). Retrogressive thaw flow may begin when ice-rich permafrost is exposed to the atmosphere from localized failures (Wang et al. 2009).

A study by Kokelj and Burn (2003) established a relationship between tree leaning and near surface ground ice in the Mackenzie Delta. The leaning of trees was more prominent in areas where an ice-rich zone was present. Kokelj et al. (2007) examined how ice content changes near ground surface affect the active layer thermal regime and surface morphology in Inuvik, NWT. They concluded that ice enrichment near ground surface is the principal mechanism driving hummock form modification. Thermokarst development is yet another process believed to be influenced by the thermal regime of the transient layer (Shur 1988). The thickness and characteristics of this layer determine the likelihood and extent of thermokarst progression in fine-grained ice-enriched soils.

All of the aforementioned studies indicate the effects of the formation of an ice-rich zone found in near surface permafrost. These studies highlight the need to better understand near surface permafrost behaviour under extreme climate conditions – the purpose of the present study.

3 LABORATORY TESTS

This section describes laboratory model setup and test procedures.

3.1 Laboratory Apparatus

Two identical laboratory apparatuses were set up to model soil pore water pressure and temperature changes under repeated freeze-thaw cycles. The model assembly is as shown in Figure 1. Each apparatus consisted of a 40 cm height and 15 cm diameter column of remoulded soil sample. The soil column was contained in a 6 mm thick PVC cylinder. The cylinder was contained in a plastic barrel (inner barrel) that was placed in another barrel (outer barrel) for lateral insulation. The PVC cylinder was secured on a metal base as illustrated in Figure 1. The metal base held the soil sample and provided high thermal conductivity between the soil sample and the ambient environment outside the system.

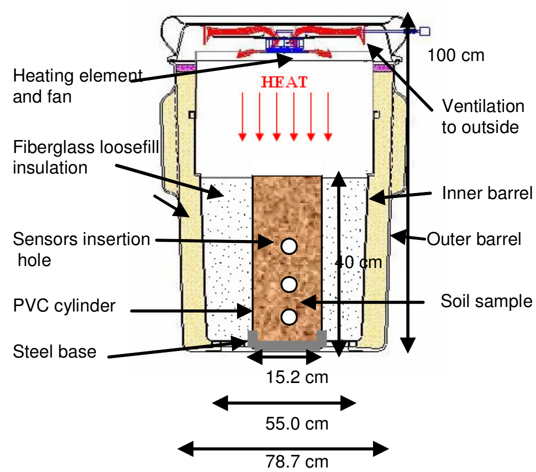


Figure 1. Sketch of the laboratory model

Both model assemblies were placed in a walk-in freezer. The base of the soil column was exposed to the freezer room temperature and the top of the sample was exposed to an encapsulated heating chamber. Both the freezer and the heating chamber temperatures are adjustable.

Each soil column was equipped with a total of four K-type thermocouples and three PDCR-81 miniature pore pressure transducers inserted at 5, 15, 25 and 32 cm depth from the top surface. The thermocouples and pore-pressure transducers were inserted at the same depths. The sensors were connected to a data acquisition system (DT500 dataTaker), with an overall system accuracy of ±1.5ºC.

3.2 Testing Procedure

The freeze-thaw tests were conducted on two samples (S1 and S2) of remoulded silty clay from the Mackenzie valley, Northwest Territories, Canada. Both samples were prepared to represent typical near surface permafrost moisture conditions encountered in this region. As reported by Wang et al. (2008), the field soil moisture contents vary from 20% in the active layer to more than 100% into the permafrost. An average moisture content of 50% was established to represent the typical moisture condition around the permafrost table. Both samples were tested simultaneously for eleven freeze-thaw cycles (174 days). Identical freeze-thaw temperatures were repeated for the first eight cycles for both samples. While the same freeze-thaw condition was repeated for another three cycles for sample S2, variations were applied to sample S1 for Cycles 9 and 11 to simulate two extreme temperature conditions at the top.

The interior wall of the PVC cylinder and the steel base were coated with lithium grease to minimize friction during heaving and consolidation of the soil sample. The sensors were calibrated and installed through the predrilled holes on the PVC cylinder. The soil sample was then carefully placed into the cylinders and effort was made to minimize potential air trapping in the samples. Freezing of the soil columns from both the top and the bottom was initiated after the models were assembled. Freezing at the top of the sample was achieved by keeping the heating chamber open to the freezer environment with the heating element turned off. After the soil temperature reached the target freezing temperature, the heating chamber was closed and heating was initiated at the top while the bottom of the column was maintained at the freezer room temperature. It is recognized that, ideally, other climatic factors, e.g., precipitation, runoff, evaporation, and wind etc., should be simulated. However, simplification is necessary to isolate the temperature effect. It should be noted that the duration of the laboratory modelling was compressed to carry out many cycles of repeated freezing and thawing within a reasonable time frame. For this reason, water was added at the top of the columns every day of the thawing cycle. The amount of water added was just enough to compensate for moisture losses and to avoid soil desiccation that may create direct water flow paths.

Table 1 lists the upper and lower boundary conditions applied on both soil columns to simulate winter and summer conditions. Colder bottom boundary temperature (-7ºC in summer) was used in Cycle 1 as a trial cycle for which thawing reached only the sensors at 5 cm depth. It was also an accuracy check of the freezer temperature control to make sure that the lower portion of the samples were not operating near the melting point at any time. Adjustments were made in subsequent cycles to maintain the bottom boundary temperature at -5ºC in summer and -10ºC in winter, which is within the proximity of the average ground temperature in permafrost in the Mackenzie valley (Taylor and Judge 1974; Smith and Burgess 2000; Andersland and Ladanyi 2004; Wang and Saad 2007). The heating chambers were maintained at a temperature of 25ºC for the repeated thawing cycles, which is within the proximity of normal summer high temperatures in the Mackenzie valley region. The temperatures of 20ºC and 30ºC were used for sample S1 during later cycles to simulate extreme weather variations from normal conditions.

Table 1. Boundary temperatures for S1 and S2

Cycle	Season Simulated	Lower Boundary (ºC)	Upper Boundary (ºC)	
			S1	S2
1	*Winter*	-10	-10	-10
	Summer	-7	25	18
2 to 8	*Winter*	-10	-10	-10
	Summer	-5	25	25
9	*Winter*	-10	-10	-10
	Summer	-5	20	25
10	*Winter*	-10	-10	-10
	Summer	-5	25	25
11	*Winter*	-10	-10	-10
	Summer	-5	30	25

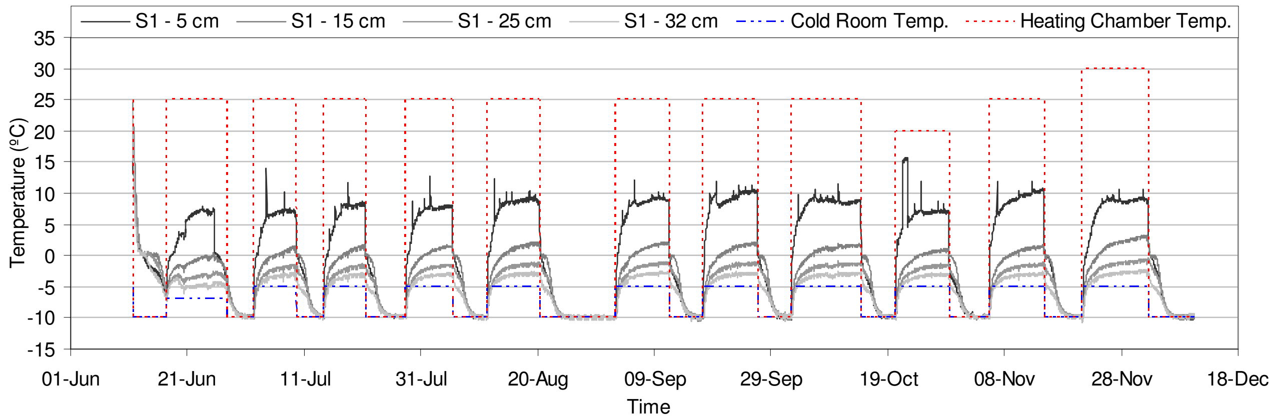
4 RESULTS AND DISCUSSION

This section presents soil temperature and moisture condition changes observed from the tests. Discussions of measured pore water pressures are beyond the scope of this paper and are therefore not included.

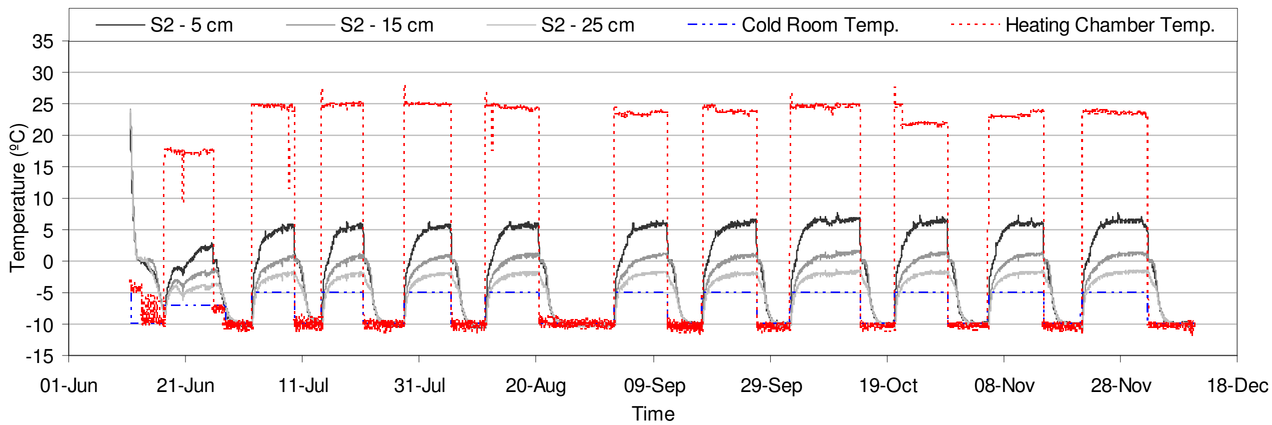
4.1 Temperatures

Figure 2 plots the temperature history data recorded in the laboratory during the entire test. Both charts depict the temperatures measured for each thermistor location. Data for the sensor located at the 32 cm depth in sample S2 are not shown due to sensor malfunction. Temperatures were recorded in the heating chamber of samples S1 and S2 by means of a thermometer and a thermistor, respectively which are also shown in Figure 2. In Figure 2b, it can be observed that some cycles recorded a chamber temperature below 25ºC. This is likely caused by shifting of the sensor or obstruction of air flow around the sensor.

Temperature jumps were recorded at the sensor location of 5 cm depth during the thawing cycles (Figure 2). These jumps can be attributed to the addition of water to the soil surface.



(a) Sample S1



(b) Sample S2

Figure 2. Temperature history for (a) Sample S1 and (b) Sample S2

The maximum temperature profiles with respect to sample depth are compared in Figure 3. This chart shows the temperature distribution when equilibrium conditions were reached during the thawing cycles. By comparing the 25℃ air temperature case on the chart, it is apparent that soil temperatures are higher in S1 than in S2 especially for the sensor at the 5 cm depth. At this depth, the temperature sensor shifted up by approximately 1.5 cm during testing. This difference is accounted for in the thermal profiles (Figure 3). Based on linear interpolations between two adjacent sensors at depths 15 and 25 cm, the maximum cryofront depths in S1 were 18.7 cm, 20.5 cm and 23.0 cm for air temperatures of 20℃, 25℃ and 30℃, respectively; whereas in S2, it was 19.2 cm for a thawing cycle of 25℃. The cryofront reached a greater depth during extreme thawing conditions (cycle of 30℃ air temperature) compared to that of the 25℃ thawing cycle. More precisely, the experimental results indicate that the cryofront moved down by 12% from its normal depth for an air temperature increase of 5ºC. It moved up by 9% for an air temperature decrease of 5℃. If the normal cryofront depth is used as a reference, the 12% deepening of cryofront due to the extreme air temperature is in general agreement with the active layer variation of 3 to 28% reported by Shur et al. (2005).

It should be noted that the cryofront depths discussed above were interpolated linearly from two adjacent sensors of 10 cm apart. If extrapolations are used as discussed in Riseborough (2008), the cryofront depths would be slightly higher. However, the difference should be within the range of accuracy of the system.

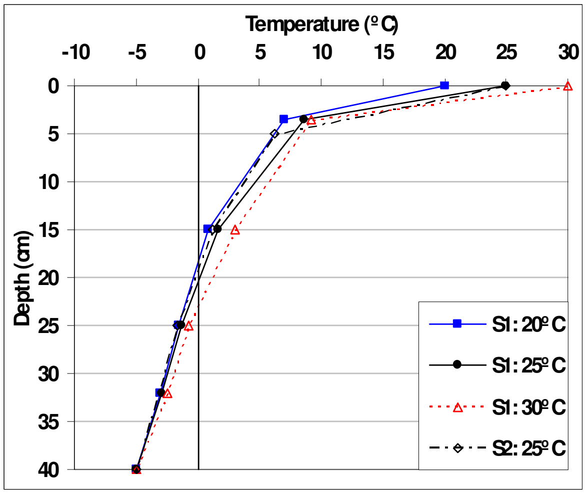


Figure 3. Experimental results of maximum soil temperatures (average of all thawing cycles)

4.2 Numerical Model

A finite element model (FEM) was used to verify the effectiveness of the insulation used in the laboratory models. Commercial software (Temp/W, developed by GeoSlope International Ltd. 2007) was used for the analysis. The model was set up to simulate the freeze-thaw conditions applied to the specimens during the physical experiment. A radially symmetric model was setup to simulate the soil column used in the physical test. Two soil material layers were assumed: (1) The upper active layer to a depth of 20 cm; and (2) Permafrost from 20 cm to 40 cm depth. Table 1 lists the top and bottom boundary conditions applied to the model. The soil properties were assumed based on the literature (Penner 1970; Penner et al. 1975; Goodrich 1982; Riseborough and Smith 1993; Riseborough 2002; Andersland and Ladanyi 2004; Overduin et al. 2006; Wang et al. 2007) and are summarized in Table 2. The analysis was carried out for two scenarios: no lateral insulation and fully insulated laterally. The models were solved for a total of 174 days using the same freeze-thaw cycles as applied on the physical model.

Table 2. Input soil properties for FEM analysis

Properties	State	Material	
		Active layer	Permafrost
Volumetric heat capacity (kJ/m3/°C)	Frozen	1950	2050
	Unfrozen	2350	2450
Unfrozen volumetric water content (m^3/m^3)	Frozen	0.051	0.066
	Unfrozen	0.44	0.57
Thermal conductivity (kJ/hr/m/°C)	Frozen	6.9	9.9
	Unfrozen	4.4	5.6

Figure 4 plots the maximum temperature profiles from both the laboratory and the numerical models. According to this figure, the measured temperatures are generally within the temperature range computed from the insulated and uninsulated cases. The comparison indicates that there could be some heat losses at the lateral boundary at the upper level of the physical model. The lower temperature readings from the upper two sensors in sample S2 (at depths 5 cm and 15 cm) were further exaggerated by a lateral shift of the sensors towards the cylinder wall that was noticed during inspection after the test. However, the temperature profiles from both the numerical and physical models agreed well at and below the cryofront level. It should be noted that the numerical model results are much dependent on the input parameters. This numerical modelling exercise was intended only to check for sensitivity to lateral boundary conditions.

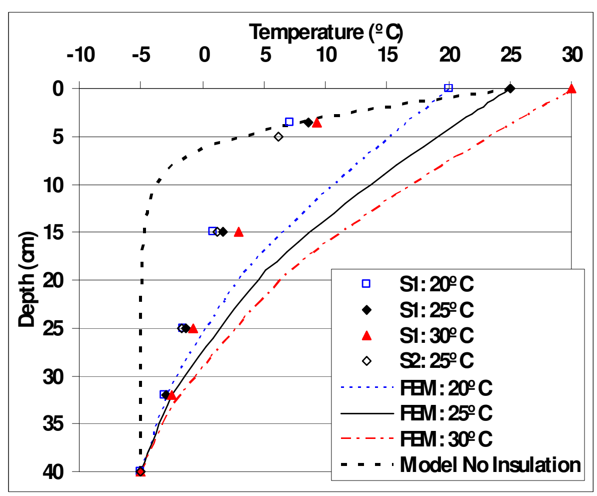


Figure 4. Comparison of maximum temperature profiles from physical and numerical (FEM) models

4.3 Moisture Distribution

Gravimetric moisture contents of soil samples taken initially and after the laboratory test are shown in

Figure 5. It is evident that moisture redistribution has occurred in both samples during the eleven cycles of testing. Both specimens show similar profiles with five distinct moisture zones, from top to bottom: (1) the upper zone of the active layer showing increased moisture content; (2) the lower zone of the active layer with decreased moisture content; (3) a layer of moisture surge above the cryofront; (4) a slightly decreased moisture zone in "permafrost"; and (5) a slightly increased moisture zone at the bottom boundary of the model.

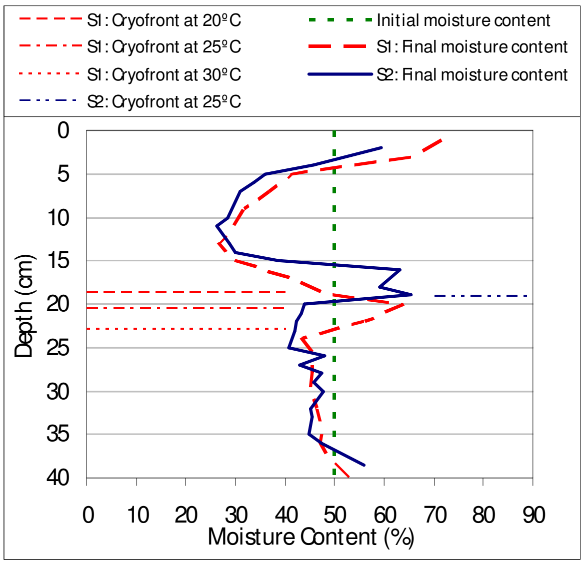


Figure 5. Soil moisture profiles measured after the test

The high water content near the top surface is due to the addition of water during each thawing cycle. The slight moisture increase at the bottom boundary is due to attraction of moisture to the freezing front where freezing was maintained for the duration of the test. The slightly lower moisture content in Zone 4 (below the cryofront) was most likely caused by moisture migration to the freezing fronts above and below this layer. The moisture in this layer had probably reached or was close to its equilibrium condition after repeated freeze-thaw cycles. This is believed so because dramatic moisture adjustment would have occurred otherwise as evidenced in the active layer and the ice-enrichment zone discussed below.

It is of great interest to note the moisture conditions of the second and third layers. Clearly, moisture has increased significantly in a layer of approximately 5 cm thick above the cryofront (Zone 3). Immediately above this high moisture zone, there is a significant drop of moisture despite water supplied at the surface during every thawing cycle. It was observed that the volume of moisture "deficit" in the active layer is greater than that of moisture "surplus" below. This is likely caused by an alternating two-sided movement of moisture in the active layer. In "summer" when thawing took place, the moisture in the active layer was attracted to the freezing front below, while in "winter", the unfrozen water in the active layer moved upward due to freezing at the top. These results are consistent with findings reported by others. Cheng (1983) and Mackay (1983) explained the ice accumulation near the permafrost table as a result of water migration during winter and summer in response to a thermal gradient between soil and air surfaces. Moisture is attracted to the cold front and accumulates at a certain depth which creates an ice-rich layer. Ice-enrichment is only present in permafrost terrain due to its two-sided freezing nature (Harris et al. 2008a, b; Kern-Luetschg and Harris 2008) which often leads to a moisture deficit in the active layer (Mackay 1983; Harris and Lewkowicz 2000).

As the two models are identical prior to the extreme temperature conditions of S1, it can be concluded that the "normal" 5 cm thick ice-rich zone above the cryofront under normal conditions in sample S1 was altered during the applied extreme temperature. The moisture surplus zone moved downwards by about 5 cm to the new deeper cryofront. This information is critical for understanding the transient layer. It should be noted that this new moisture surplus zone was created by only one cycle of extreme thaw. In addition, the moisture conditions in long-term permafrost may eventually reach equilibrium as demonstrated in Zone 4 described above. Some excess unfrozen water below the moisture surplus zone may eventually be drawn back to the normal surplus zone under repeated normal freeze-thaw cycles. Based on this information, it is expected that, if the cryofront is used as a reference line, the bottom of the moisture surplus zone should mark the top of the transient layer and the bottom of the transient layer may well extend to a depth similar to the thickness of the moisture surplus zone. However, this lower boundary is yet to be investigated for other air and ground conditions.

A recent Mackenzie valley field study conducted by Wang et al. (2008) established the moisture content profiles for 14 landslide sites. Fine-grained soil samples were extracted from the surface down to a depth well within the permafrost where soils have supposedly not undergone thawing in the recent history. It was concluded that water contents are lower in the active layer and increase with depth. A peak in water content at the active layer base and top of permafrost was noted at most sites. Two typical moisture profiles are shown in Figure 6. The shapes of the moisture charts reported by Wang et al. (2008) are very similar to those found in this study.

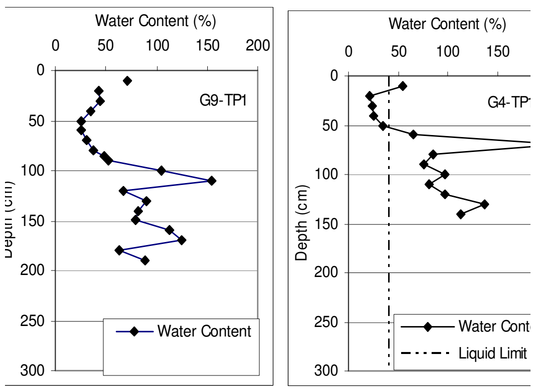


Figure 6. Typical soil moisture content profiles for two of the 14 sites from Mackenzie valley, Canada (Wang et al. 2008)

5 CONCLUSIONS

The thermal and moisture regimes of two fine-grained soil samples subjected to repeated freeze-thaw cycles were studied in the laboratory. The maximum and minimum thaw depths recorded provide an estimate of increase and decrease in active layer thickness for air temperature changes. Both permafrost samples tested in this study show evidence of moisture migration throughout the soil columns. An upper moisture deficit zone was created in the active layer, and a moisture surplus zone was created above the cryofront. The moisture content in the “long-term” permafrost zone established a near equilibrium condition. As a result of repeated freeze-thaw cycles, moisture accumulated above the cryofront, which resulted in a moisture surge. Extreme air temperature may degrade the ice-rich zone and move the moisture surplus zone down. However, the new moisture surplus zone could be only temporary. With repeated freeze-thaw cycles under normal climate conditions, this zone may eventually be re-established at its normal depth. The moisture changes observed in this study are comparable to those found from field investigations.

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