ACID MINE DRAINAGE BEHAVIOUR IN LOW TEMPERATURE REGIMES- THERMAL PROPERTIES OF TAILINGS

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SECTION 1   INTRODUCTION

Acid mine drainage (AMD) mitigation strategies in cold regions should be able to take advantage of cold temperatures and permafrost conditions. The chemical reactions that cause AMD are slowed down at lower temperatures and frozen material has very low hydraulic conductivity. A review of the important physical and chemical processes that could affect AMD potential in permafrost environments is reviewed in MEND 1.61.2 (1996). This MEND report recognized that there is a lack of information available on the thermal properties of mine waste materials (waste rock and tailings). In order to provide some information that examines this issue, a laboratory research program was initiated at the University of Alberta and Norwest Mine Services Ltd. was contracted to manage the laboratory work, evaluate the data, and report on the results.

The main objective of this report is to present the results of laboratory research on the thermal properties of saturated mine tailings. The focus of the testing was for determining the thermal conductivity and unfrozen water content of saturated mine tailings samples. Additionally, the unfrozen hydraulic conductivity and the amount of unfrozen water provides an indication of the order of magnitude decrease in hydraulic conductivity that is realized after freezing. Estimates of frozen hydraulic conductivity are reviewed in this report.

The work presented here was carried out under the auspices of Environment Canada and the Department of Indian Affairs and Northern Development through a contract (# KA601-6-5182/001/XSB) with Public Works and Government Services Canada. Mr. Benoit Godin with Environment Canada in Whitehorse, Yukon was the Science Contracting Officer and the contract administrator was Mr. Tom Morrissey with Public Works and Government Services Canada in Vancouver, British Columbia.

SECTION 1 INTRODUCTION

Les stratégies visant à réduire le drainage minier acide (DMA) devraient être conçues en fonction des basses températures et la formation de pergélisol. À des températures plus basses, les réactions chimiques qui causent le DMA ralentissent et la conductivité du matériel congelé est peu élevée. Les processus physiques et chimiques qui pourraient influer sur le DMA dans un environnement pergélisolé ont été examinés dans le rapport NEDEM 1.61.2 (1996). Ce rapport a reconnu le manque d'information disponible relativement aux propriétés thermiques des déchets miniers (stériles et résidus). Dans le but de fournir de l'information détaillée sur la question, l'Université de l'Alberta a mis sur pied un programme de recherche en laboratoire et Northwest Mine Services a été retenu en vertu d'un contrat pour gérer les travaux effectués en laboratoire, évaluer les données et préparer un rapport des résultats.

Le principal objectif de ce rapport est de présenter les résultats des recherches effectuées en laboratoire sur les propriétés thermiques des résidus miniers saturés. La vérification était axée sur la détermination de la conductivité thermique et du contenu d'eau non congelée dans les échantillons de résidus miniers saturés. De plus, la conductivité hydraulique du matériel non congelé et la quantité d'eau non congelée indiquent une baisse de l'ordre de grandeur de la conductivité hydraulique du matériel suite à la congélation. Dans ce rapport, les estimations de la conductivité hydraulique du matériel congelé sont passées en revue.

Les travaux dont fait état le présent rapport ont été effectués sous les auspices d'Environnement Canada et le ministère des Affaires Indiennes et du Nord Canadien dans le cadre du contrat (# KA601-6-5182/001/XSB) passé avec Travaux publics et Services gouvernementaux Canada. M. Benoit Godin qui fait partie d'Environnement Canada à Whitehorse, au Yukon, a agit à titre d'agent de contrats scientifiques et M. Tom Morrissey, de Travaux publics et services gouvernementaux Canada à Vancouver, en Colombie-Britannique, à titre d'administrateur de contrat.

SECTION 2   SAMPLE CHARACTERIZATION

Tailings samples were obtained from the Wellgreen and Lupin mine sites. The Wellgreen mine site is located in the Yukon within the discontinuous permafrost zone and the Lupin mine is located in the Northwest Territories within the continuous permafrost zone. Tailings water samples were obtained from the Lupin site and the Anvil Range mine in the Yukon. Figure 1 shows the location of the three sites and the distribution of permafrost regions in northern Canada.

The Lupin mine extracts gold and silver from greywacke and mudstone host rocks. The tailings contains approximately 3 to 4% sulphur which is contained within pyrrhotite, pyrite and arsenopyrite sulphide minerals (NMEND #2, 1994). The Wellgreen mine, which is currently inactive, extracted nickel, platinum, palladium and copper from layered ultramafic intrusive rocks. The tailings are high in sulphur content (approximately 10%) which occurs in pyrrhotite minerals that constitutes a very large proportion of the ore mineralogy (NMEND #3, 1994). The Anvil Range Mine, which is also currently inactive, produced lead, zinc and silver from synsedimentary sulphide lenses located within phyllite host rocks. The tailings water shows elevated levels of zinc which originates from sphalerite in the ore body (NMEND #3, 1994).

2.1   TAILINGS SOLIDS PROPERTIES

The program involved testing four different tailings solids materials. Grain size curves for each material are shown in Figure 2 and Table 1 shows a summary of grain sizes.

The two samples from the Wellgreen site (designated slab and crumbs) were obtained from the tailings beach and represent a weathered silty sand material. The slab sample consists of large chunks of crusted tailings and the crumbs are gravel sized pieces that broke off from the slabs during sampling. These samples were retrieved by using a cement saw to cut a block out of the dried out tailings hardpan. Testing was carried out with reconstituted material and, as a result, the original structure of the material was lost during sample preparation. The terms "crumbs" and "slab" were retained for sample identification purposes.

The Lupin tailings sample is a sandy silt obtained directly from the tailings line (fresh tailings material). The high specific gravities obtained from both the Lupin and Wellgreen samples indicates that metallic minerals are present. The control sample consists of a silty sand comprised entirely of quartz.

TABLE 1 TAILINGS SOLIDS PHYSICAL PROPERTIES

TAILINGS SAMPLE DESCRIPTION		GRAIN SIZE			SPECIFIC GRAVITY
		% clay	% silt	% sand	
Wellgreen Tailings Beach Samples	Crumbs	2	20	78	3.13
	Slab	2	21	77	3.16
Lupin Tailings		5	65	30	3.17
Control Sample (silty sand)		0	17	83	2.72

Table 2 shows a summary of the X-ray diffractions analysis carried out to determine mineralogy. The main differences between the Wellgreen and Lupin tailings are that the Wellgreen samples have significant quantities of oxide products while the Lupin sample is much more quartz rich. The mineralogy differences in the Wellgreen crumb and slab samples appears to be due to different proportions of oxide and sulphide minerals. This indicates that the weathering products at the Wellgreen site are highly variable along the beach. The iron oxide minerals in the slab sample were probably acting as a cement in the undisturbed material. This could help to explain the tendency for this material to break out as slabs during the sampling process. Appendix A contains a more complete description of the x-ray diffraction test results.

TABLE 2   TAILINGS SOLIDS MINERALOGY SUMMARY

MINERAL TYPE	Mineralogy (wt %)		
	Wellgreen		Lupin
	Crumb	Slab	
Quartz	10%	trace%	36%
Calcite/Aragonite	11.5%	9%	2%
Iron Oxide Minerals		51%	
Iron Sulphide Minerals	48%	40%	45%
Iron Chlorite			17%
Cuprite	19%	trace	
Sulphur	11.5%		

Table 3 shows results of acid base accounting tests on the tailings samples. The test results show that the Wellgreen tailings are acidic and have a very high affinity for continued acid generation based on a negative net neutralization potential (NNP). The test results for the Lupin tailings shows a neutral material with a moderate affinity for generating acid. Appendix B contains the laboratory test results for acid based accounting which were carried out following the Sobek method.

TABLE 3   ACID BASE ACCOUNTING TEST RESULT SUMMARY

TAILINGS SAMPLE DESCRIPTION		PASTE pH	% SULPHUR			ACID BASE ACCOUNTING (modified method)			
			SULPHATE	SULPHIDE	TOTAL	MPA	NP	NNP	NP/AP
Wellgreen Tailings Beach Samples	Crumbs	2.9	1.32	12.53	14.35	449	- 11	- 459	- .02
	Slab	3.2	1.25	12.70	14.5	452	- 8	- 450	- .02
Lupin Tailings Sand		7.4	0.04	2.76	2.82	88	9	79	.10

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2.2   PORE FLUID PROPERTIES

Four different pore fluids were used for testing. Two different samples (designated A and B) were obtained from the Anvil Range tailings pond. The Lupin pore fluid was obtained directly from the tailings discharge. Distilled water was used as a pore fluid with the control sample sand.

Table 4 shows the results of pH and conductivity testing for the 3 different tailings water samples (two samples from Anvil Range and one from Lupin) and the distilled water used for the test program. None of the porewater samples indicate acid conditions. The electrical conductivity (EC) for each sample has been used to estimate the total dissolved solids (TDS) using the relationship:

$$TDS \text{ (in mg/l)} = 640 \times EC \text{ (in dS/m)}$$

TABLE 4   PORE FLUID PROPERTIES

SAMPLE	pH	ELECTRICAL CONDUCTIVITY (dS/m)	CALCULATED TOTAL DISSOLVED SOLIDS (mg/L)
ANVIL A	7.9	2.6	1664
ANVIL B	7.7	0.62	397
LUPIN	9.8	2.8	1792
DISTILLED	7.0	1.4	896

The as-received chemical analysis for 30 different metal ions was carried out for each pore fluid sample as shown in Table 5. The analysis shows that calcium, magnesium, sodium, iron, and potassium are the dominant metals present in the tailings. Copper, arsenic, and zinc are the major heavy metals. The certificates of analysis are contained in Appendix B.

TABLE 5   PORE FLUID CHEMICAL ANALYSIS SUMMARY
(AS RECEIVED)

SAMPLE	CONCENTRATION OF MAJOR METALS (μg/L)											
	As	Ca	Cu	Fe	K	Mg	Mn	Na	Ni	Pb	Sr	Zn
ANVIL A	<1	>50000	<0.1	1250	12750	>50000	9850	50000	240	<2	3150	4230
ANVIL B	14	>50000	<0.1	1000	19250	20200	977	26800	61	330	129	4770
LUPIN	10100	>50000	5180	23100	35000	655	303	>50000	652	<2	656	21300
DISTILLED WATER	1	<50	254	<10	<50	8.5	0.70	100	2.8	14	0.45	56.0

2.3   SATURATED TAILINGS SAMPLES

Six different saturated tailings/pore water samples were prepared for thermal properties testing (unfrozen water content and thermal conductivity) as follows:

- Wellgreen Crumbs A (Wellgreen Crumbs with Anvil A porewater)
- Wellgreen Slab A (Wellgreen Slab with Anvil A porewater)
- Wellgreen Crumbs B (Wellgreen Crumbs with Anvil B porewater)
- Wellgreen Slab B (Wellgreen Slab with Anvil B porewater)
- Lupin (Lupin tailings with Lupin porewater)
- Control (quartz sand with distilled porewater)

The Wellgreen tailings material is a weathered tailings undergoing active oxidation. The four different samples prepared from these tailings provide an indication of the range in thermal properties that might be expected for different kinds of weathered tailings materials. The size consist of the Wellgreen material is similar to the control sample.

The Lupin sample provides thermal properties information for a fresh unoxidized material that has potential to generate acid. The Lupin tailings also represent a finer grained material (sandy silt).

In addition to the as-received water chemistry summarized in Table 5, additional chemical analysis was carried out on tailings samples immediately after mixing with process water, at 1 hour, and at 2 hours after mixing (Appendix C). The analysis shows that significant differences in pore water chemistry were realized

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in short periods of time, especially for the Wellgreen samples. Using the electrical conductivity as a measure of the increase in total dissolved solids, increases ranging between 500 and 2,000 mg/L were realized over a 2 hour period for the Wellgreen samples. The Wellgreen samples contained secondary minerals formed due to evaporation on the tailings beach. The large increases in total dissolved solids for these samples reflects the solution of these minerals. An evaluation of the change in water chemistry after mixing has not been undertaken here.
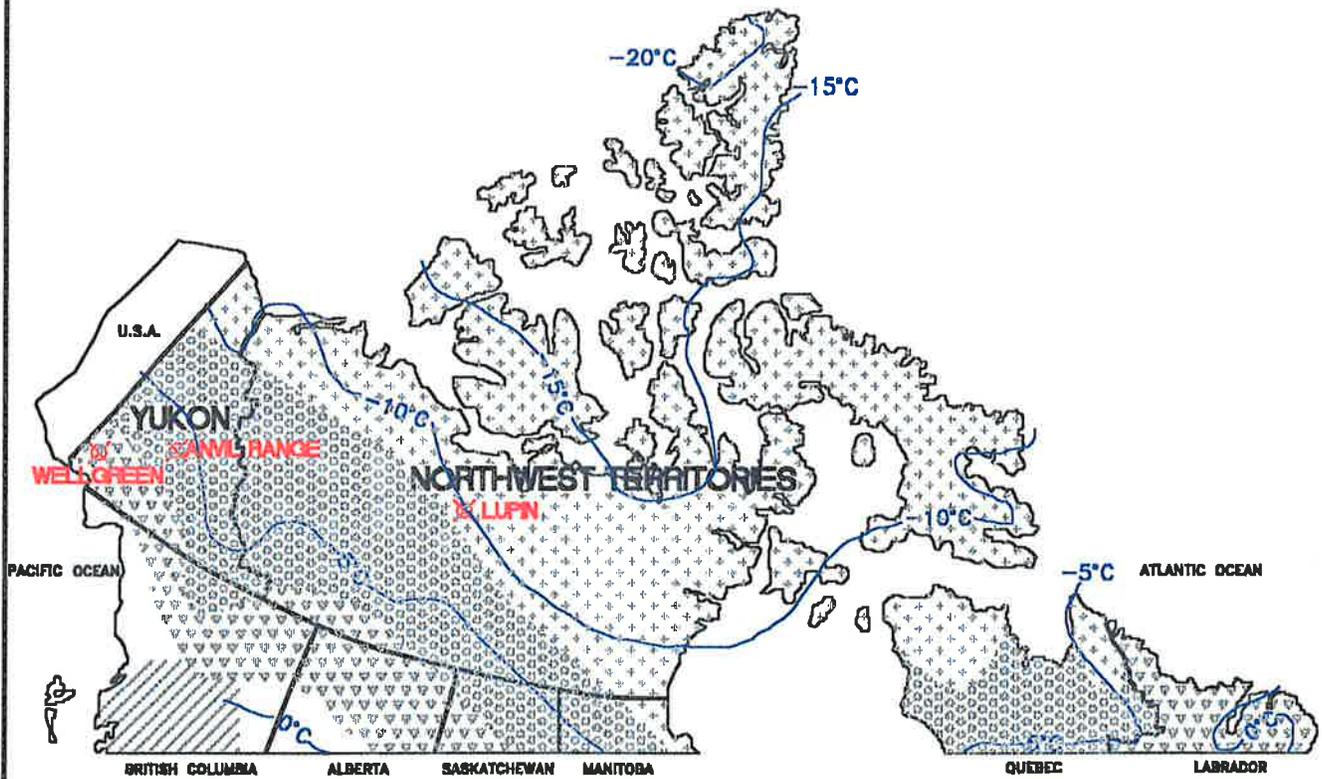
LEGEND

▦	CONTINUOUS PERMAFROST ZONE
▦	DISCONTINUOUS PERMAFROST (WIDESPREAD)
▽	DISCONTINUOUS PERMAFROST (SCATTERED)
⧄	ALPINE PERMAFROST

——— MEAN ANNUAL AIR TEMPERATURE ISOTHERMS

✖ STUDY SITES

Environment Canada   Environnement Canada

FIGURE 1

NORTHERN PERMAFROST REGIONS OF CANADA

(modified from MEND 1.61.2, 1996)

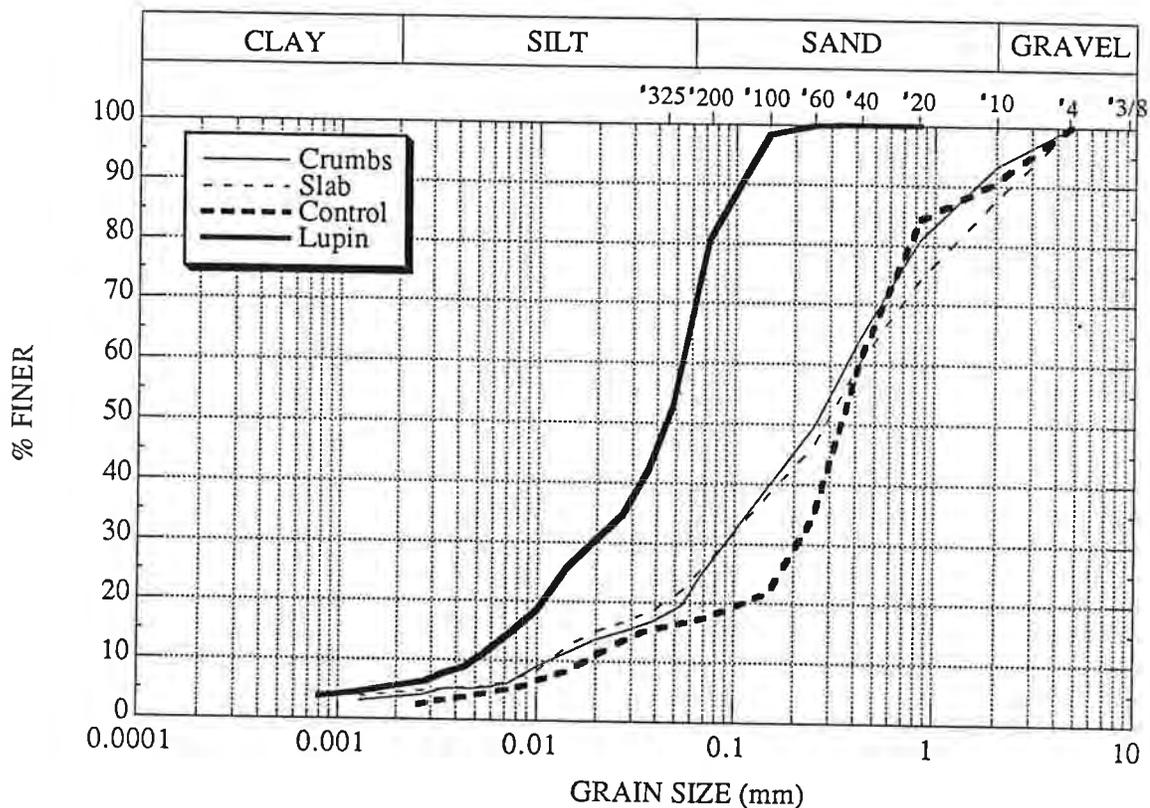| DRAWN BY: ABM	FIGURE 1	SCALE	NorWest
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Grain Size Distribution

FIGURE 2   Grain Size Distributions of Sample Materials

SECTION 3   UNFROZEN WATER CONTENT

Saturated frozen soils are composed of soil solids, ice, and unfrozen water. The amount of unfrozen water that is present at temperatures below 0°C in a frozen soil is dependent on several factors including temperature, applied pressure, specific surface area, and pore fluid chemistry. In fine grained soils, unfrozen water is closely associated with the soil particles themselves due to adsorption forces. Pore fluid solutes can cause a depressed freezing point, which results in unfrozen water occurring in coarse grained soils. In sandy soils at temperatures below the depressed freezing point unfrozen water is present until the eutectic temperature of the solute is attained. The eutectic point is the temperature at which simultaneous crystallization of solvent (freezing) and solute (precipitation) takes place. Further information related to the manner in which unfrozen water is associated with soil particles is contained in MEND 1.61.2 (1996) and Farouki (1986).

Measurement of unfrozen water content in soils can be carried out with nuclear magnetic resonance (NMR) or time domain reflectometry (TDR) techniques. Time domain reflectometry measures the travel time of a megahertz pulse through the soil, from which an apparent dielectric constant is obtained. Topp et al (1980) determined an empirical relationship between apparent dielectric constant and volumetric water content that is nearly independent of soil type, density, temperature, and salinity. The dielectric constant of ice and soil solids is similar and therefore there is a unique empirical relationship between the apparent dielectric constant measured by TDR methods and unfrozen water content. By comparing the relationship between unfrozen water content measured directly by NMR techniques and apparent dielectric constant from TDR, Smith and Tice (1988) have calibrated a relationship between apparent dielectric constant (Ka) and volumetric unfrozen water content (θ_u) as follows:

$$\theta_u = (-1.458 \times 10^{-1}) + (3.868 \times 10^{-2})\,Ka - (8.502 \times 10^{-4})\,Ka^2 + (9.920 \times 10^{-6})\,Ka^3$$

Volumetric unfrozen water content is the ratio of the volume of unfrozen water to the total volume, normally expressed as a percentage. Smith and Tice (1988) used 17 different soil types ranging from clay to gravel for their calibration and determined a standard error of estimate of 1.55% in volumetric unfrozen water content. Their measurements indicate that the polynomial curve fit presented above can be used to predict unfrozen water content over a wide range of soil types. This relationship has been used in this study to reduce the data obtained from TDR testing. Appendix C contains a description of the test methods and a sketch of the test apparatus.

Figure 3 shows the data obtained from the testing plotted as volumetric unfrozen water content versus temperature. Table 6 shows a tabulation of unfrozen water contents at various temperatures interpolated from the data in Figure 4. The table indicates the following points:

- The Control sample does not have any unfrozen water at temperatures below 0°C. This is to be expected for a sand (negligible absorption properties) with distilled pore water (no freezing point depression) and helps to confirm the validity of the testing procedures and the empirical relationship between unfrozen water and apparent dielectric constant discussed above.
- At temperatures in the range of -1°C, unfrozen water contents in the range of 7 to 10% are measured. The highest value of 10% for the Wellgreen A samples corresponds to the highest conductivity pore fluid.
- At temperatures between about -5°C and -15°C the unfrozen water contents for all the tailings materials is about 5%.

TABLE 6   SUMMARY OF UNFROZEN WATER CONTENT-
TEST RESULTS

	% VOLUMETRIC UNFROZEN WATER CONTENT				
	@ > 0°C	@-1°C	@-5°C	@-10°C	@-15°C
WELLGREEN SLAB A	48%	10%	6.2%	5.5%	5.0%
WELLGREEN SLAB B	48%	7.0%	5.2%	4.8%	4.2%
WELLGREEN CRUMBS A	48%	10%	5.0%	4.0%	4.0%
WELLGREEN CRUMBS B	48%	9.0%	6.3%	4.8%	4.2%
LUPIN	51%	7.0%	5.2%	4.8%	4.2%
CONTROL	51%	0%	0%	0%	0%

A comparison of the unfrozen water content values with similar grain size naturally occurring non-plastic soils at different sodium chloride salinities (Hivon and Sego, 1995) is shown in Figure 4. Hivon and Sego measured unfrozen water contents for sand and silty sands with pore fluids at 0, 10, and 30 parts per thousand (ppt) salinity. Seawater has a salinity of about 30 ppt.

Figure 4a compares the results of Soil C, (fines content of 50%) with the Lupin tailings (fines content of 70%). The unfrozen water contents for Soil C at zero ppt salinity compare very favourably with the Lupin values. This indicates that the fines (-200 Mesh) within the Lupin sample contributes to the unfrozen water content, as opposed to the porewater which had an as received salinity estimated at less than 2 ppt.

Figure 4b compares the results of Soil B (fines content of 20%) with the Wellgreen samples (fines content of 22 %). The unfrozen water content for the Wellgreen tailings is higher than Soil B at 0 ppt indicating that the porewater chemistry may be contributing to the unfrozen water content. The change in

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unfrozen water content at sub-zero temperatures is much less for the Wellgreen sample than for Soil B @ 10 ppt. It is conceivable that the Wellgreen samples may reach salinity values approaching 15 ppt after several hours and this would be consistent with the comparison of the test results shown in Figure 4b.

Figure 5 shows the results of testing for unfrozen water content at - 80° C. The data indicates unfrozen water contents approaching 2% at this very low temperature.

Unfrozen Volumetric Water Content versus Temperature for Wellgreen and Lupin Tailings

Unfrozen Volumetric Water Content versus Temperature for Wellgreen Tailings and Control Samples
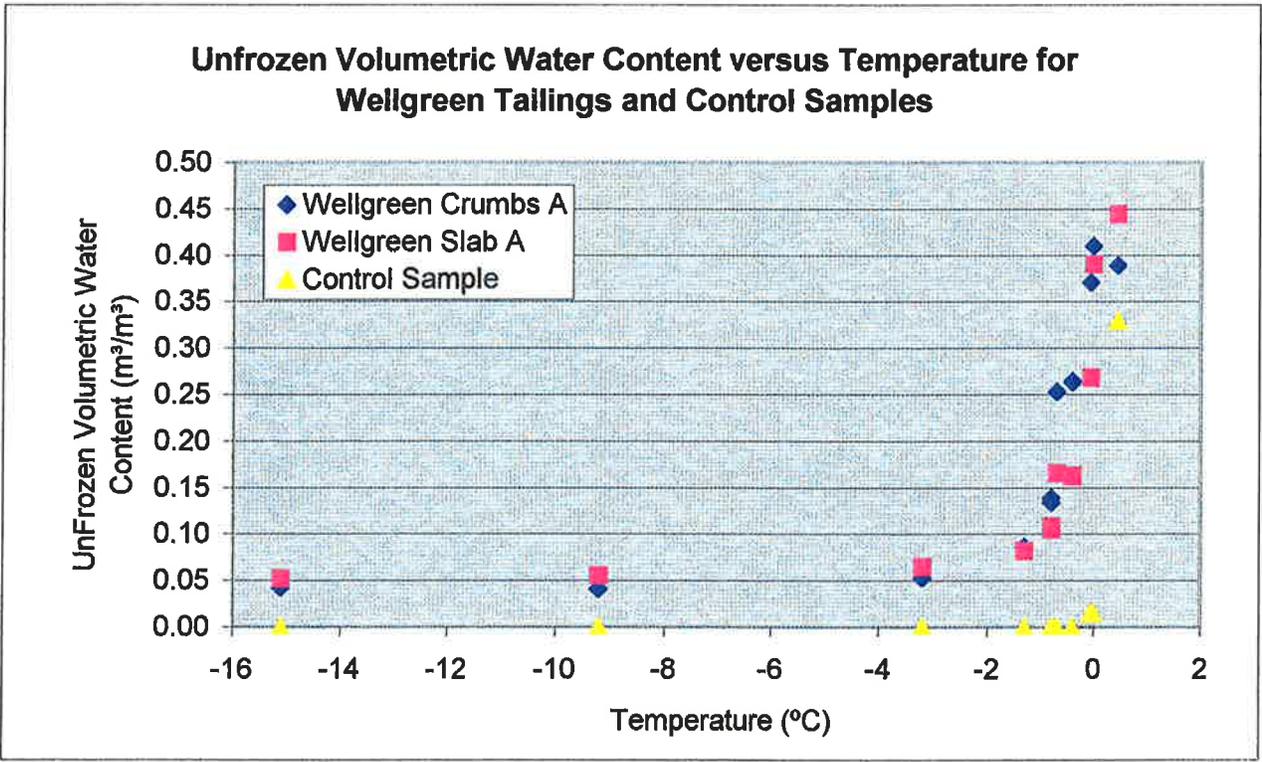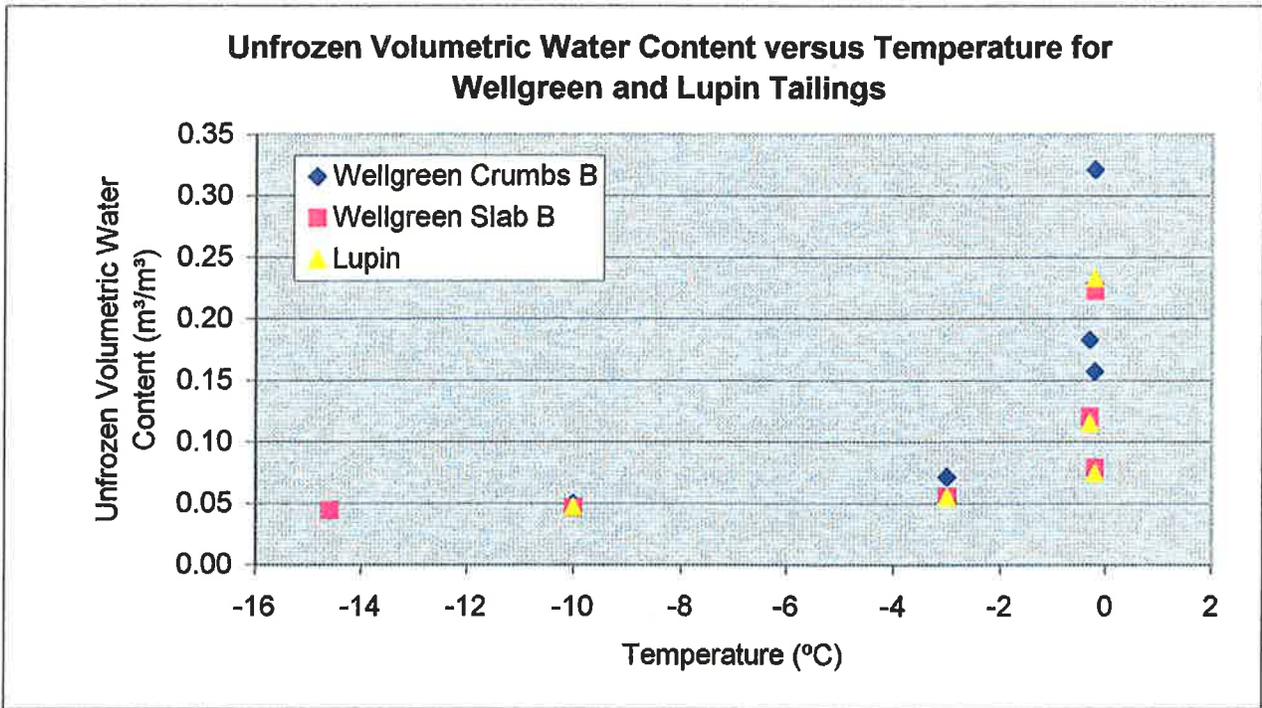
FIGURE 3   Unfrozen Water Content versus Temperature for
Tailings Samples

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A) Volumetric Unfrozen Water Content versus Temperature for Soil C and Lupin Tailings

Legend:
- - - ■ - - Soil C @ 0ppt (Hivon & Sego, 1995)
- - - ◆ - - Soil C @ 10ppt (Hivon & Sego, 1995)
- - - ▲ - - Soil C @ 30ppt (Hivon & Sego, 1995)
—✕— Lupin Tailings

B) Volumetric Unfrozen Water Content versus Temperature for Soil B and Wellgreen Tailings

Legend:
- - - ● - - Soil B @ 0ppt (Hivon & Sego, 1995)
- - - ▲ - - Soil B @ 10ppt (Hivon & Sego, 1995)
- - - ■ - - Soil B @ 30ppt (Hivon & Sego, 1995)
—✕— Wellgreen Tailings

FIGURE 4   Comparison of Unfrozen Water Content Values with Data from Hivon & Sego (1995)

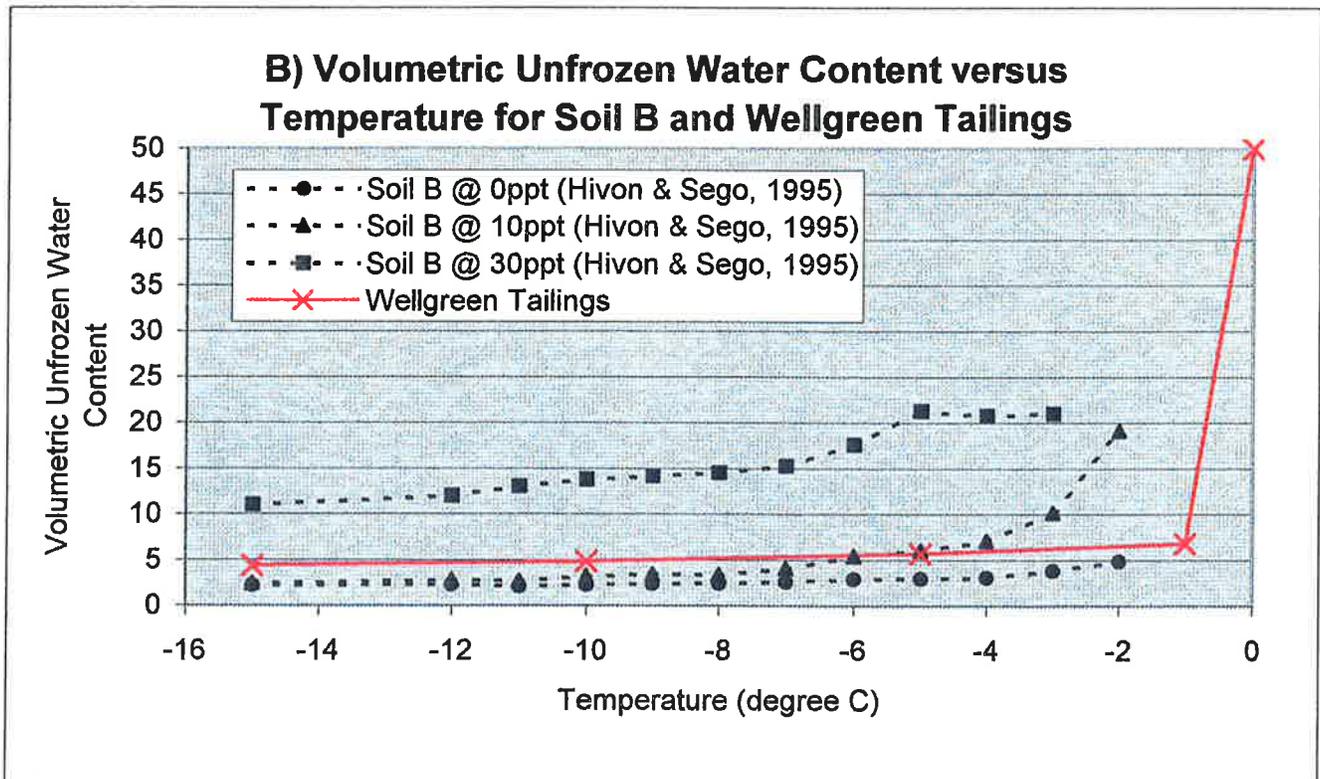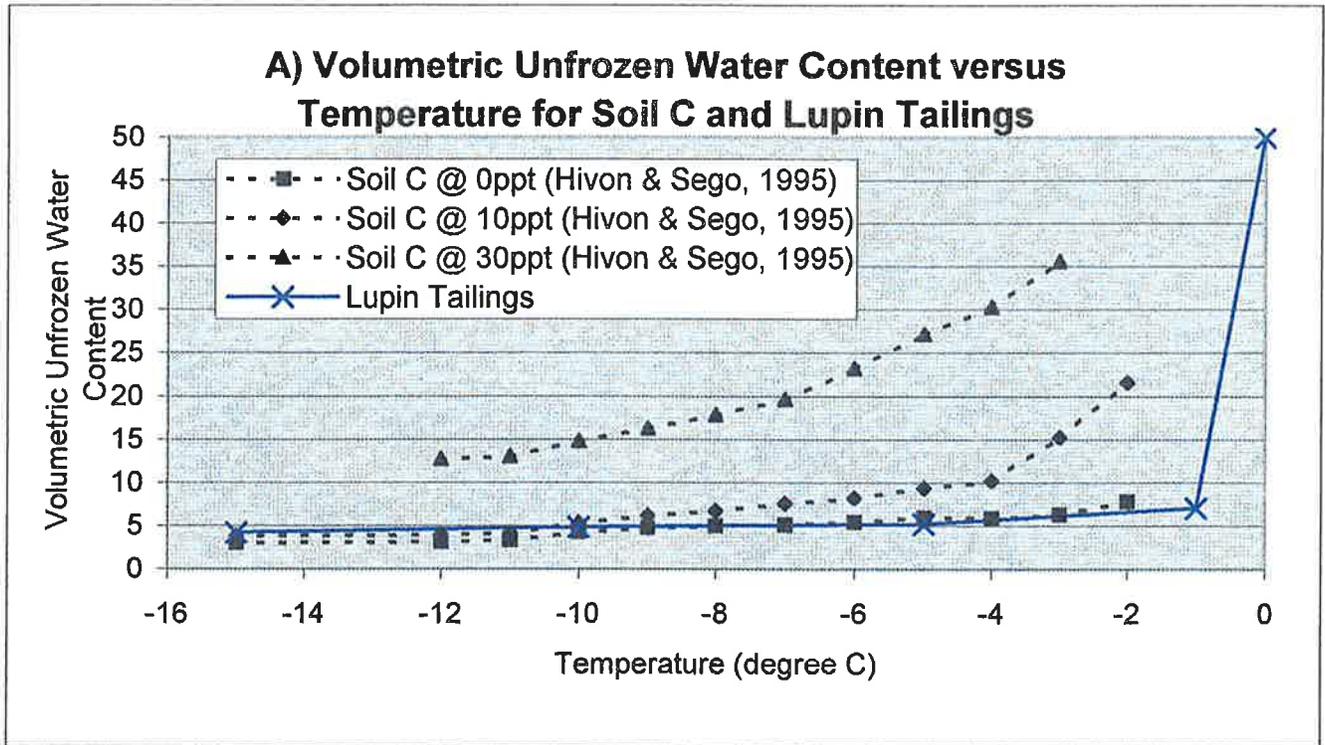**Unfrozen Volumetric Water Content versus Temperature for Wellgreen B and Lupin Tailings (very low temperature behavior)**
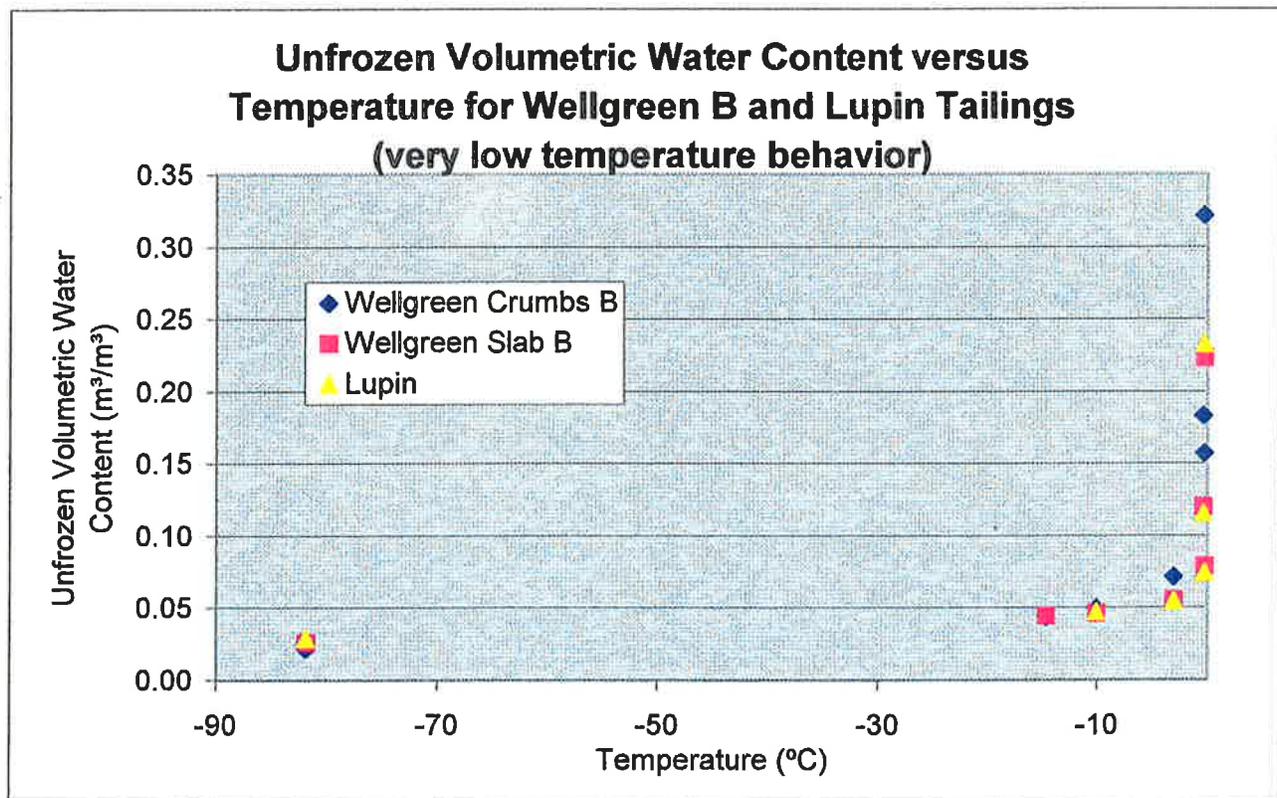
FIGURE 5   Unfrozen Water Content at Very Low Temperatures

SECTION 4   THERMAL CONDUCTIVITY TEST RESULTS

Heat transfer though soils occurs mostly by conduction. Direct measurement of thermal conductivity in soils can be measured with steady state or transient methods. A transient method was used for the tests in this report as described in Appendix D. Farouki (1986) provides a comprehensive review on the measurement of thermal conductivity in soils, including a comparison of different measuring and estimation methods.

Typical thermal conductivity values for different soil constituents are shown in Table 7. Ice has a thermal conductivity about four times that of water and therefore frozen soils display higher conductivity. Seawater has a thermal conductivity only a few percent less than pure water (Farouki, 1986). Quartz has an appreciable higher thermal conductivity than most other commonly occurring soil minerals. The thermal conductivity of mineral solids decreases with increasing temperature, however the change in the thermal conductivity of mineral solids is less than 10% for temperatures ranging between - 10°C and + 20°C. It is common practice to consider thermal conductivity as a single parameter for either frozen or unfrozen conditions.

TABLE 7   TYPICAL THERMAL CONDUCTIVITY VALUES FOR SOIL CONSTITUENTS (AT 20°C)

SOIL CONSTITUENT	THERMAL CONDUCTIVITY (W/mK)	
WATER		0.57
ICE		2.2
QUARTZ		7.7
OTHER COMMON ROCK FORMING MINERALS	Feldspar	1.6 - 2.9
	Pyroxene	4.4
	Amphibolite	3.5

Figure 6 shows the results of the thermal conductivity testing. An interpretation of the data is shown on these figures as a "best fit" frozen and unfrozen thermal conductivity. All of the tailings exhibit a peak between the frozen and unfrozen values. This peak is not apparent for the control sample. The peak could be due to the onset of solute crystallization at the freezing temperature of the solution. Table 8 shows a summary of the estimated frozen and unfrozen thermal conductivity values derived from Figure 6. The Wellgreen samples all exhibit similar values with a frozen thermal conductivity that appears anomalously low (lower than ice). The other values are within the range expected for natural soil materials.

TABLE 8   THERMAL   CONDUCTIVITY   MEASUREMENT
          SUMMARY

SAMPLE	% POROSITY	THERMAL CONDUCTIVITY (W/mK)	
		FROZEN	UNFROZEN
WELLGREEN	48%	1.5	1.0
LUPIN	51%	2.7	1.7.
CONTROL	51%	4.5	3.0

The thermal conductivity of saturated naturally occurring soil can be estimated from empirical methods that relate the thermal conductivity of soil constituents to the porosity and degree of ice/water saturation. Farouki (1986) reports that estimates within about 25% of measured values can be obtained for saturated soils. Geometric mean equations by Johansen (1975) for unfrozen thermal conductivity (K_u) and frozen thermal conductivity (K_f) of saturated soils are as follows:

$$K_u = K_s^{(1-n)} 0.57^n$$
$$K_f = K_s^{(1-n)} 2.2^n 0.269^{\theta_u}$$

Where: K_s = thermal conductivity of soil solids
        n = porosity

θ_u = volumetric unfrozen water content

To determine the value of K_s for estimating the soil solids thermal conductivity, Johansen suggested the following geometric mean equation:

$$K_s = K_q{}^q K_o{}^{(1-q)}$$

Where: K_q = thermal conductivity of quartz
       = 7.7 w/m C°
       K_o = thermal conductivity of other minerals
       q = quartz content as a fraction of total solids content

For the thermal conductivity of other minerals, Johansen recommended 2.0 W/m c where the quartz content was greater than 20 % and 3.0 W/m C° for quartz contents less than 20 %.

Table 9 shows a comparison of measured thermal conductivity values versus those predicted using Johansen's method. The largest departure from the predicted values occurs for the Wellgreen samples which have notably lower measured values. This could be due to the weathering that could have affected the surfaces of the minerals, thus inhibiting thermal conductivity.

TABLE 9 COMPARISON OF MEASURED VERSUS PREDICTED THERMAL CONDUCTIVITY

SAMPLE		THERMAL CONDUCTIVITY (W/m° C)		
		MEASURED VALUES	PREDICTED VALUES (Johansen's method)	% DIFFERENCE
WELLGREEN TAILINGS	FROZEN $\theta_u = 5\%$	1.5	2.5	66
	UNFROZEN	1.0	1.4	40
LUPIN TAILINGS	FROZEN $\theta_u = 5\%$	2.7	2.5	7
	UNFROZEN	1.7	1.3	24
CONTROL	FROZEN $\theta_u = 0\%$	4.2	4.1	2
	UNFROZEN	3.0	2.0	33

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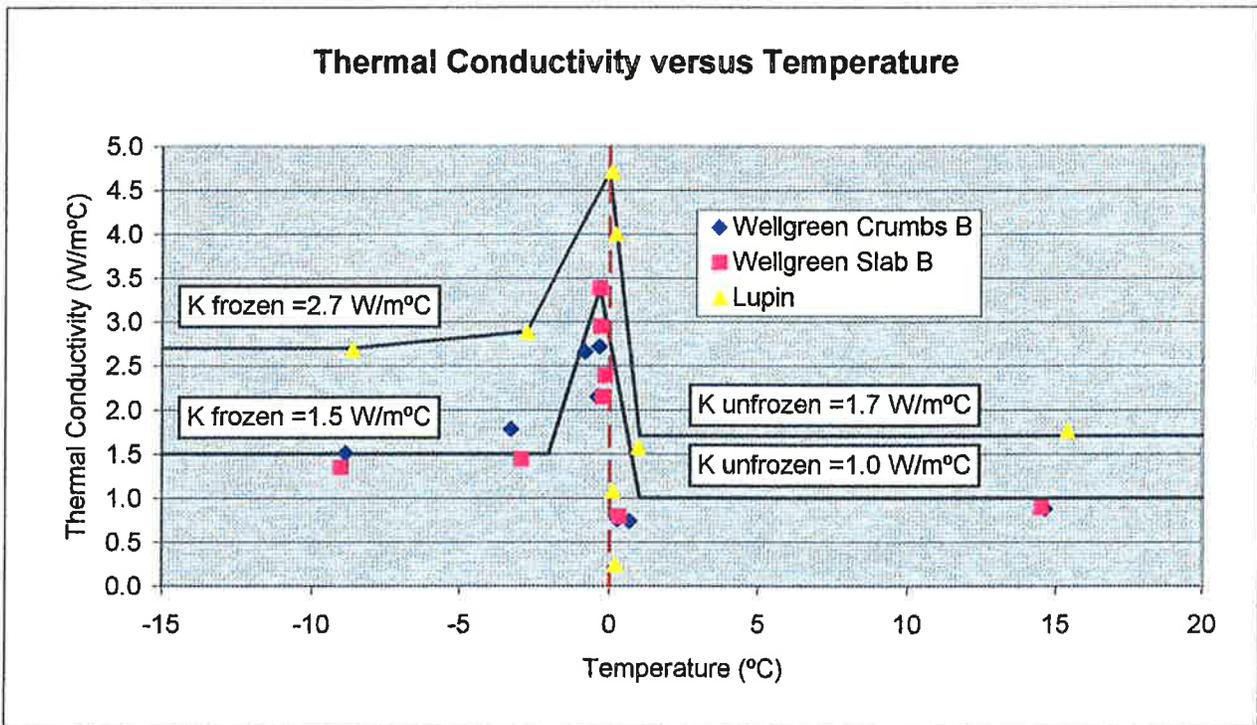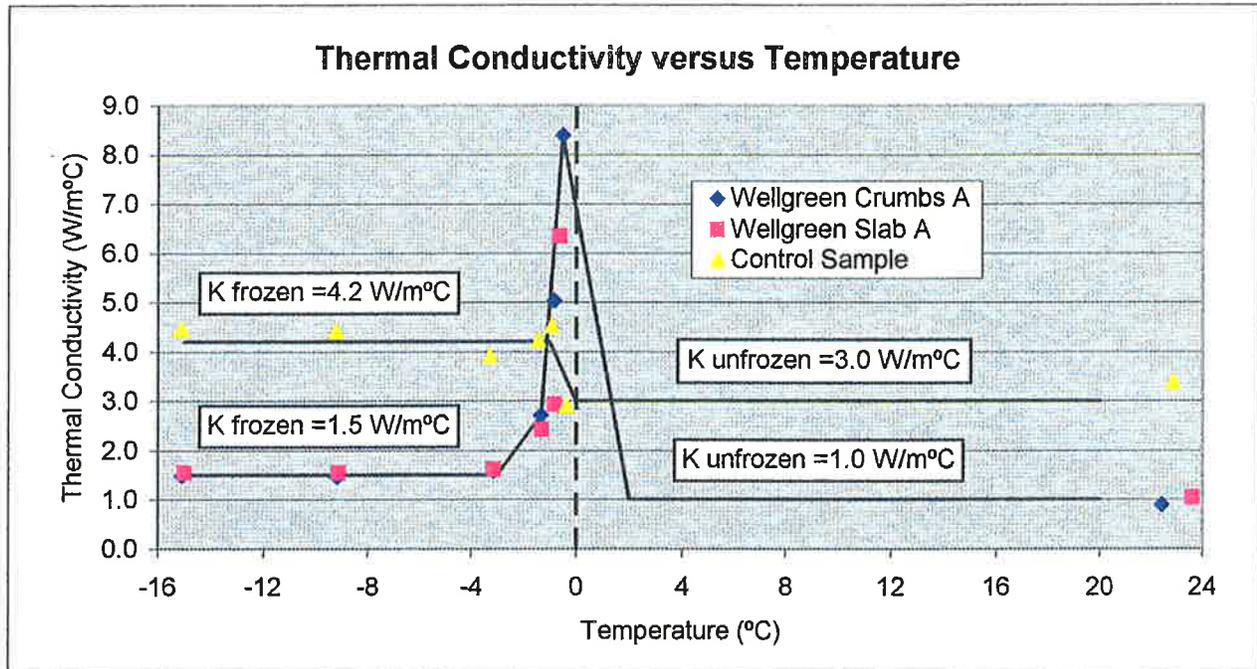Mine Services Ltd.

FIGURE 6 Thermal Conductivity versus Temperature for Tailings Samples

SECTION 5   HYDRAULIC CONDUCTIVITY

Intuitively, the hydraulic conductivity of a frozen material should be much less than the same material in an unfrozen state. Advective water transport at temperatures below $0°C$ is related to the amount and the distribution of unfrozen water. Horiguchi and Miller (1983), tested six materials including natural silts, clays, and zeolite. They found that hydraulic conductivity decreased sharply by three to four orders of magnitude (below 10^{-8}cm/s) as unfrozen water content fell to 50 - 70% of total water content when temperature reached -0.2 to -0.4 °C.

Direct measurement of hydraulic conductivity is difficult owing to problems associated with percolating water through a frozen specimen without altering the unfrozen water content of the sample. In addition the very low permeabilities for frozen material require large gradients for measurable flow volumes. Horiguchi and Miller (1983) discuss the two most commonly used methods for direct measurement and review test results obtained using a constant volume permeameter/dilatometer with "phase barriers" that exclude ice but transmit liquid water.

Direct measurement of frozen hydraulic conductivity was not carried out for this report. Instead, estimates of hydraulic conductivity are made using measured unfrozen hydraulic conductivity values and a semi-empirical approach for estimating frozen hydraulic conductivity.

5.1   UNFROZEN HYDRAULIC CONDUCTIVITY TEST RESULTS

Figure 7 shows the results of consolidation testing carried out to provide information on unfrozen saturated hydraulic conductivity at different void ratios. This is a standard test method used to measure the compressibility of soils (ASTM 0-2345). Hydraulic conductivity is calculated from the rate of volume change of the soil during one dimensional compression. Using this method it is possible to observe the manner in which permeability decreases as consolidation occurs. The figures show that the Wellgreen tailings (crumbs and slab) exhibit hydraulic conductivity values in the range of 10^{-3} to 10^{-4}cm/sec. The Lupin tailings show hydraulic conductivity values in the range of 10^{-4} to 10^{-5}cm/sec. The measured values for both sets of tailings are within the range expected for these materials

based on their grain sizes. Lower hydraulic conductivity for the Lupin tailings are due to higher silt content.

5.2   ESTIMATES OF FROZEN HYDRAULIC CONDUCTIVITY

Estimates of frozen hydraulic conductivity can be made from either purely empirical curve fitting methods or from semi-empirical approaches that are based on the physical similarity of unfrozen water and capillary water held in an unsaturated soil by surface tension. Both methods relate the rapid decline in hydraulic conductivity due to freezing to the fully saturated unfrozen value. In other words, there is a continuous functional relationship between the unfrozen hydraulic conductivity at $0°$ C and a much smaller value at very cold temperatures.

Black (1990) has reviewed the physical basis for the similarity between freeze/thaw and drying/wetting in soils. Black shows that data from ice free soil water retention experiments and analytical methods for evaluating unsaturated hydraulic conductivity can be used to describe hydraulic conductivity in frozen soil. Black's report has been included in Appendix E for reference.

Figure 8 shows soil retention data presented as matric suction versus volumetric water content for the Lupin Tailings sample. This is known as the soil water characteristic curve. The air entry value is the matric suction where air starts to enter the largest pores of the soil. The residual water content is the water content where a large suction charge is required to remove additional water.

An equation developed by Brooks and Corey (1966) can be used to estimate unsaturated hydraulic conductivity (k_u) from the saturated hydraulic conductivity (k_s) as follows:

$$k_u = k_s A^b$$
$$A = (\theta - \theta_R) / (n - \theta_R)$$
$$b = 3 + 2/\lambda$$

Where: θ = volumetric water content
θ_R = residual volumetric water content
n = porosity
λ = pore size distribution index

The Brooks and Corey equation requires the saturated hydraulic conductivity, the total residual volumetric water content and the pore size distribution index as input material parameters. Figure 9 shows predicted values of unsaturated hydraulic conductivity versus volumetric water content for the Lupin and Wellgreen tailings using the parameters for the Brooks and Corey equation shown in Table 10. The figure indicates the very rapid drop in hydraulic conductivity that is realized as the soil desaturates.

TABLE 10   SOIL PARAMETERS FOR ESTIMATING HYDRAULIC CONDUCTIVITY

SAMPLE	SATURATED HYDRAULIC CONDUCTIVITY (cm/s)	POROSITY %	RESIDUAL WATER CONTENT %	PORE SIZE DISTRIBUTION INDEX
WELLGREEN	10^{-3}	50	4	0.4
LUPIN	10^{-4}	50	6	0.4

A similar drop in hydraulic conductivity could be expected as a soil freezes and advective transport is limited to the water that is in an unfrozen state. Assuming that the relationship shown in Figure 9 provides a rough estimate for unfrozen hydraulic conductivity, the mine tailings used for testing in this study could be considered virtually impermeable at an unfrozen water content below about 10%. This is the maximum unfrozen water content that was measured in this study and corresponds to a temperature of about -1 °C.
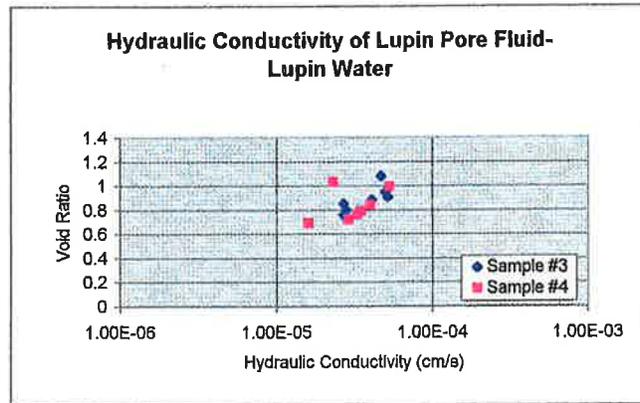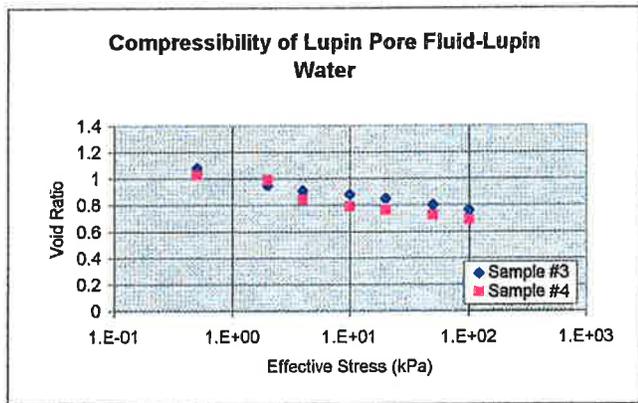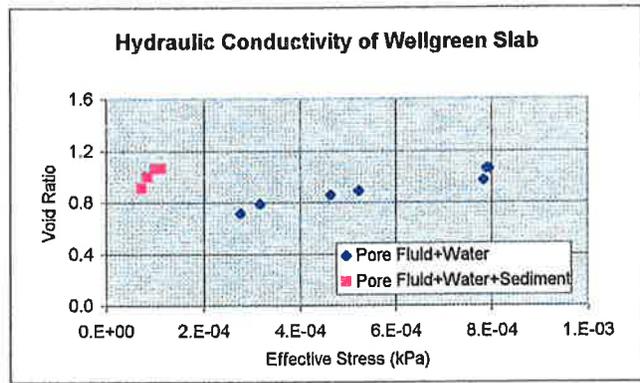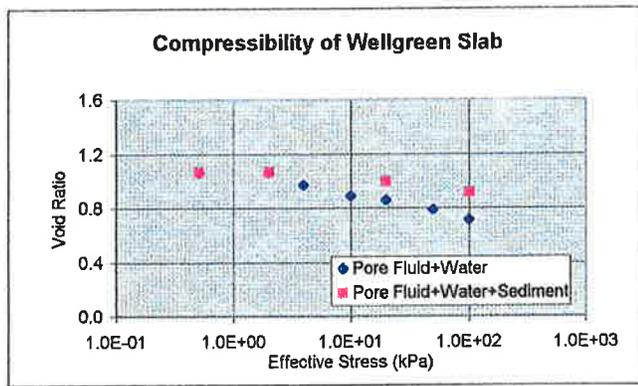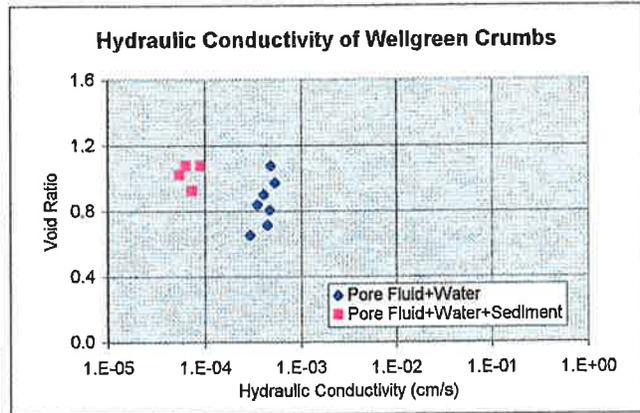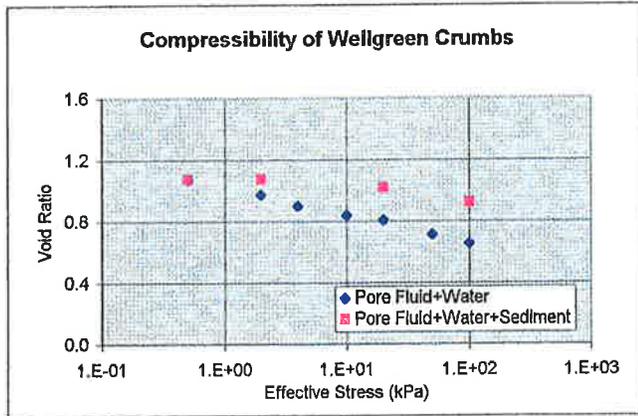
FIGURE 7   Compressibility and Unfrozen Hydraulic Conductivity
of Tailings Samples (at 20° C)

Lupin Tailings
Soil-Moisture Characteristic Curves

(Chart: Volumetric Water Content (%) vs. Matric Suction (kPa); labels "Air Entry Value" and "Residual Water Content")
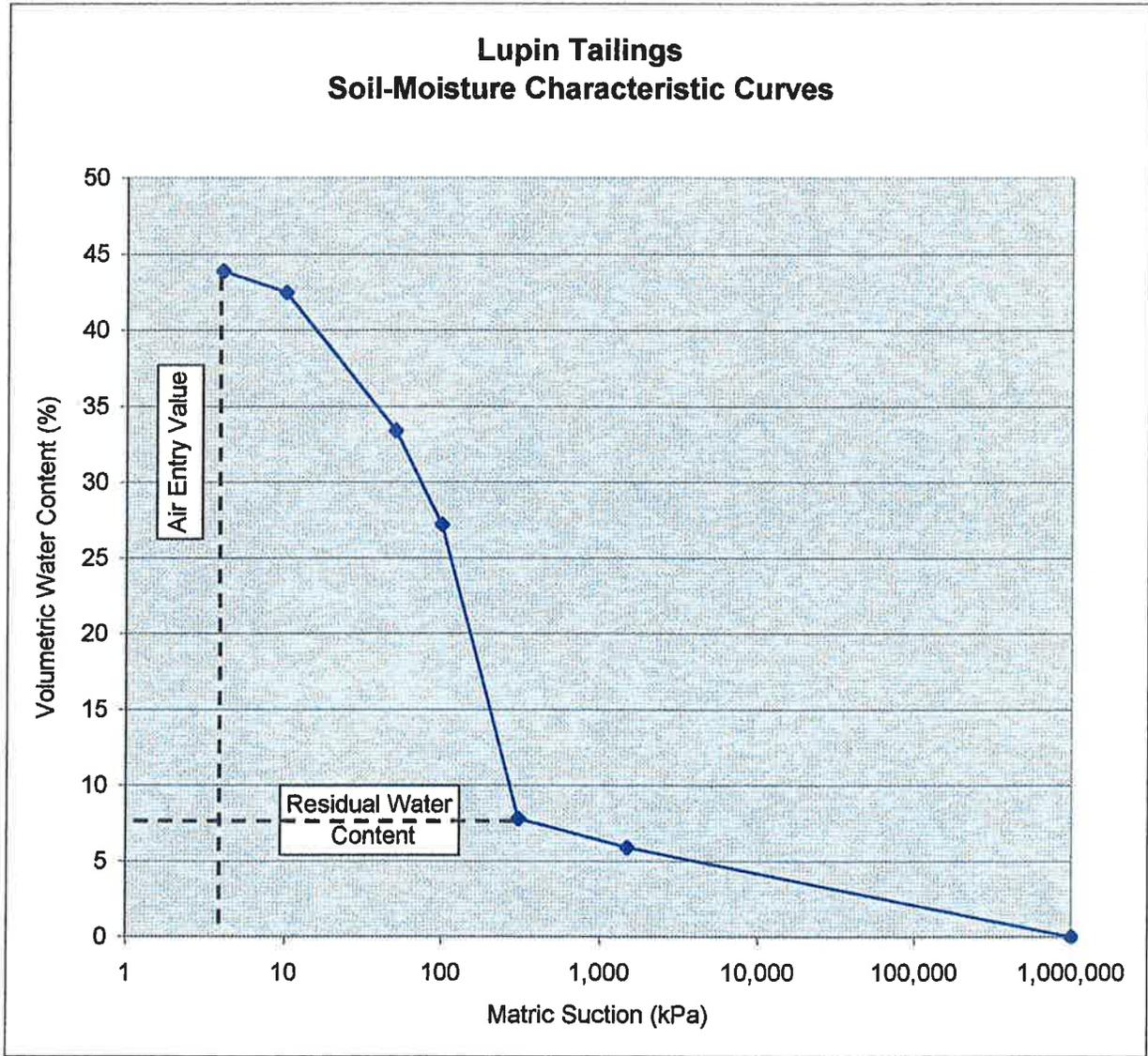
FIGURE 8   Water Characteristic Curve for Lupin Tailings

NorWest
Mine Services Ltd.

Estimated Volumetric Water Content versus Hydraulic Conductivity
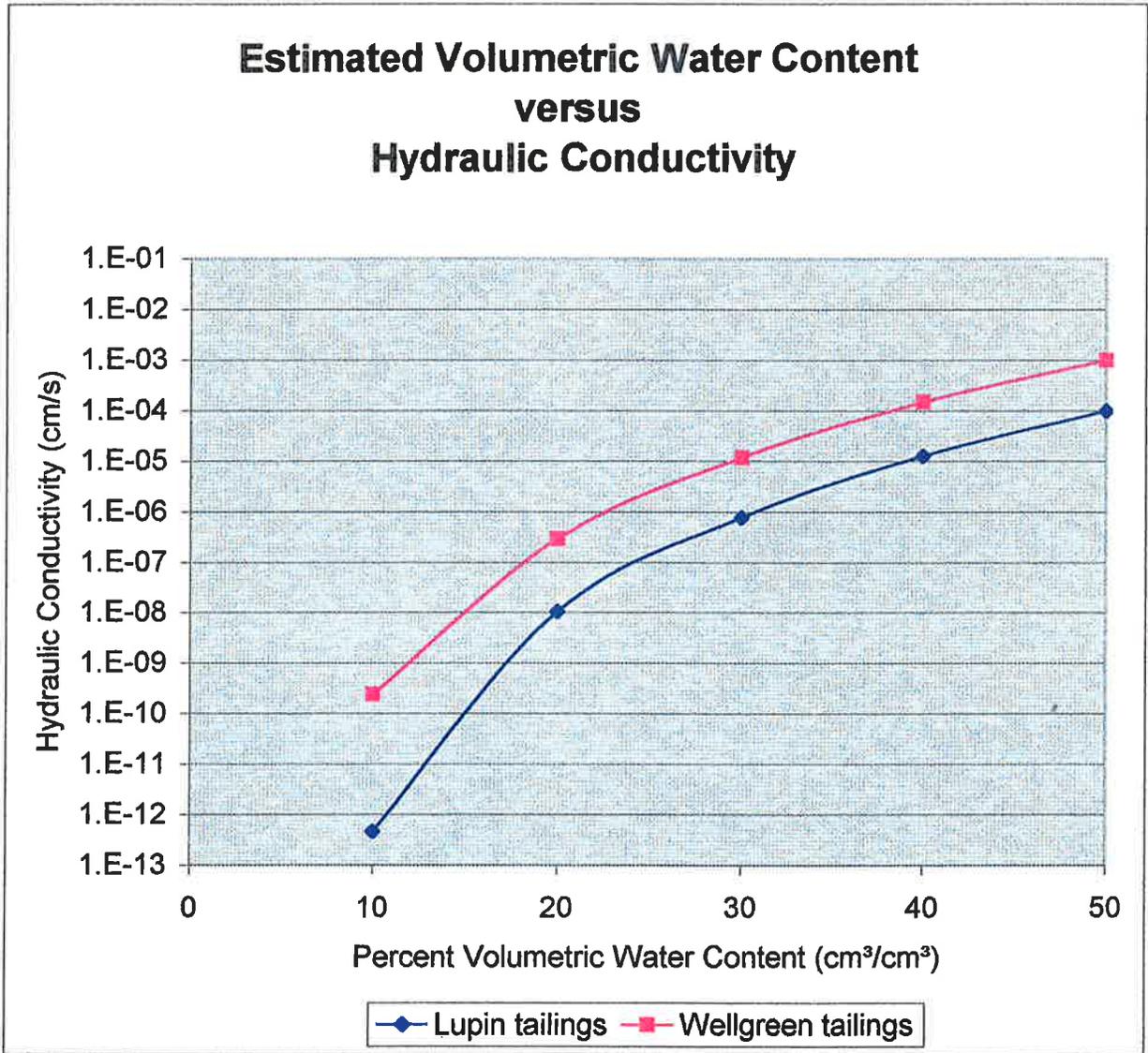
Figure 9   Estimated Unsaturated Hydraulic Conductivity for Lupin and Wellgreen Tailings

SECTION 6   CONCLUSIONS

This report presents the results of thermal testing for unfrozen water and thermal conductivity for two different mine tailings material mixed with different mine process water pore fluids. In addition, some estimates of frozen hydraulic conductivity have been made based on the unfrozen hydraulic conductivity and semi-empirical analytic techniques. The main findings of this research work are summarized as follows:

1.   The unfrozen water content measurements were all in the range of 7 to 10 % at -1°C and about 5% below -5°C. A comparison of the measured values with those from published information for naturally occurring soil indicates that the total dissolved solids and fines content can be used to estimate unfrozen water contents. In sandy soils, large increases in unfrozen water content below 1° C only occurs as the salinity approaches that of seawater (30 ppt).

2.   The thermal conductivity measurements were all in the range of 1 to 3 W/m°C. Similar values were obtained using empirical methods developed for naturally occurring soils. Large departures (>40%) from the predicted values were observed for the Wellgreen tailings indicating that the thermal conductivity of oxidized materials differs from unweathered soils.

3.   Soils show a dramatic decrease in hydraulic conductivity with a de-saturation. Similarily, frozen soils also show a large decrease in hydraulic conductivity as the temperature is lowered and the unfrozen water content drops to residual values. Estimates of frozen hydraulic conductivity made using this analogy show that the permeability is reduced to negligible values at temperatures below about 1°C.

A general finding from the work that is presented here is that freeze-back of most types of mine tailings in a continuous permafrost environment is a viable long term containment strategy. Freeze-back should occur at similar rates, or slightly lower for weathered materials, than could be expected for naturally occurring materials. Thermal protection of the active zone is necessary to ensure that seasonal thawing does not cause acidic drainage.

SECTION 7   REFERENCES

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Appendix A

X-RAY DIFFRACTION ANALYSIS

University of Alberta
X-RAY DIFFRACTION ANALYSIS
OF THREE SOLID MATERIAL SAMPLES
Work Order A6867

November, 1997

AGAT Laboratories

3801 - 21 Street N.E.
Calgary, Alberta
T2E 6T5

X-RAY DIFFRACTION ANALYSIS

Three solid material samples, Wellgreen Tailings - slab, Wellgreen Tailings - crumb, and Lupin Tailings from base metal mine waste were submitted to Agat Laboratories for compositional analysis.

The sample was analyzed using X-ray diffraction (XRD) techniques for mineral identification.

The XRD results (Figure 1) indicate that the Wellgreen Tailings - slab sample mainly contains goethite ($FeO(OH)$), and greigite (Fe_3S_4), with minor amounts of calcite ($CaCO_3$), and trace amounts of quartz (SiO_2), and cuprite (Cu_2O). For the Wellgreen Tailiings - crumb sample it consists mainly of mackinawite (Fe_9S_8), with lesser amounts of cuprite (Cu_2O), greigite (Fe_3S_4), sulphur (S), aragonite ($CaCO_3$), and quartz (SiO_2). The Lupin tailings sample consists mainly of a unidentified iron mineral, and quartz (SiO_2), with lesser amounts of a iron-chlorite (Cronstedite - $(Fe)(Si_3Fe)O_{10}(OH)_8$), greigite (Fe_3S_4), and calcite ($CaCO_3$). For the Lupin Tailings samples there was a series of X-ray diffractogram peaks which were not identifiable with our in house literature. Elemental analysis was completed on this sample and indicated that it consists mainly of iron. Therefore, it was concluded that the series of unidentifiable X-ray diffractogram peaks may represent a possible iron mineral.

The analysis for the three samples suggest that the Wellgreen Tailings - slab sample consists predominantly of iron oxide (goethite - corrosion product?), iron sulphide (greigite - corrosion product?), with and lesser amounts of calcium carbonate (calcite - precipitated from fluids?), and trace amounts of sand (quartz), and copper oxide (cuprite - corrosion product?). The Wellgreen Tailings - crumb sample consists predominantly of iron sulphide (mackinawite & greigite - corrosion product?), with lesser amounts of copper oxide (cuprite - corrosion product?), calcium

carbonate (precipitated from fluids?), sulphur (corrosion product?), and sand (quartz). For the Lupin Tailings sample it mainly consists of a Fe-mineral (corrosion product?), and sand (quartz), with lesser amounts of Fe-chlorite (cronstedite - alteration product?), iron sulphide (greigite - corrosion product?), and calcium carbonate (calcite - precipitated from fluids?).

Figure 1
X-ray Diffraction Analysis

Sample Id.: Wellgreen Tailings - slab
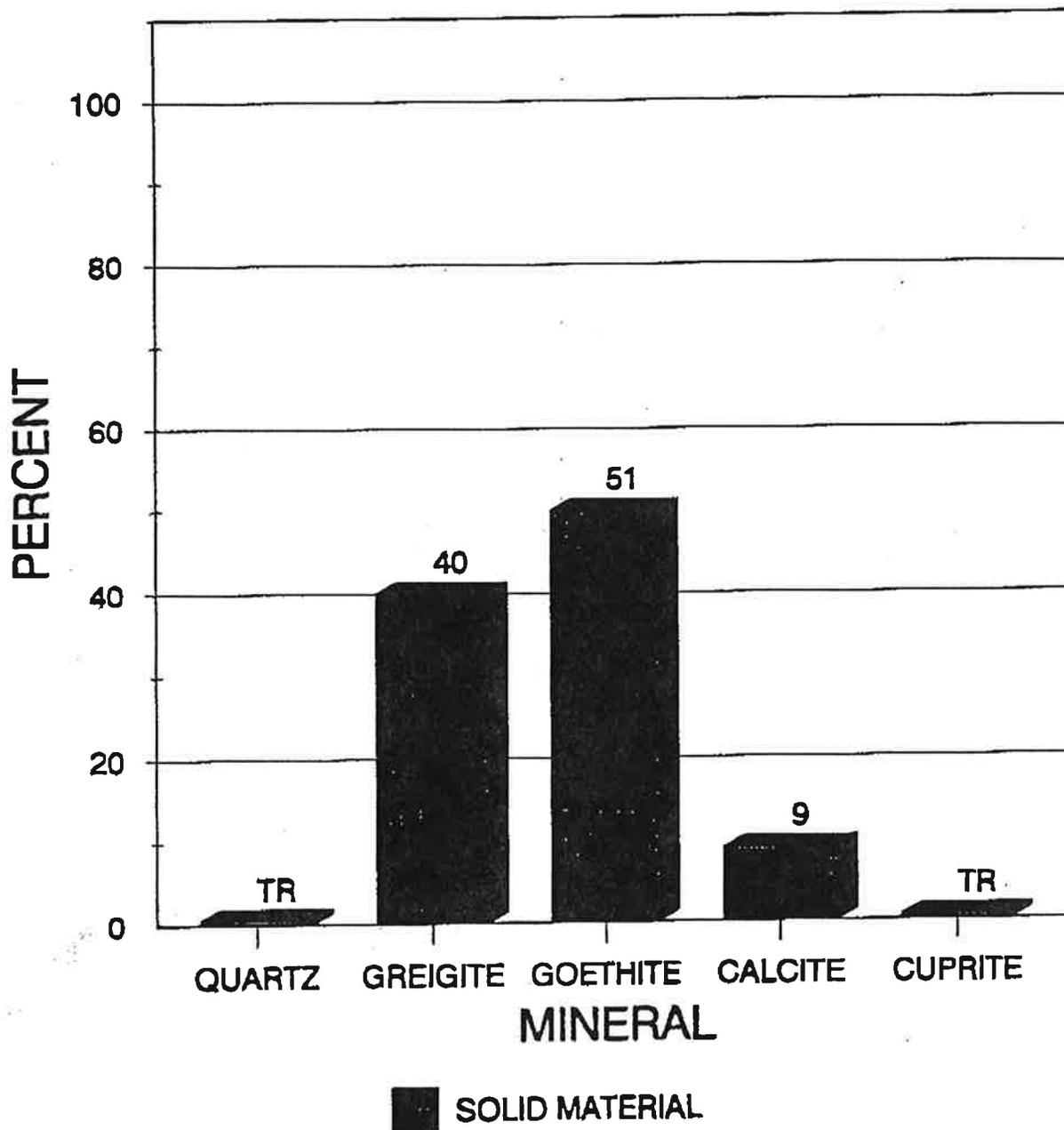
Note: XRD identifies crystalline material only

Figure 2
X-ray Diffraction Analysis
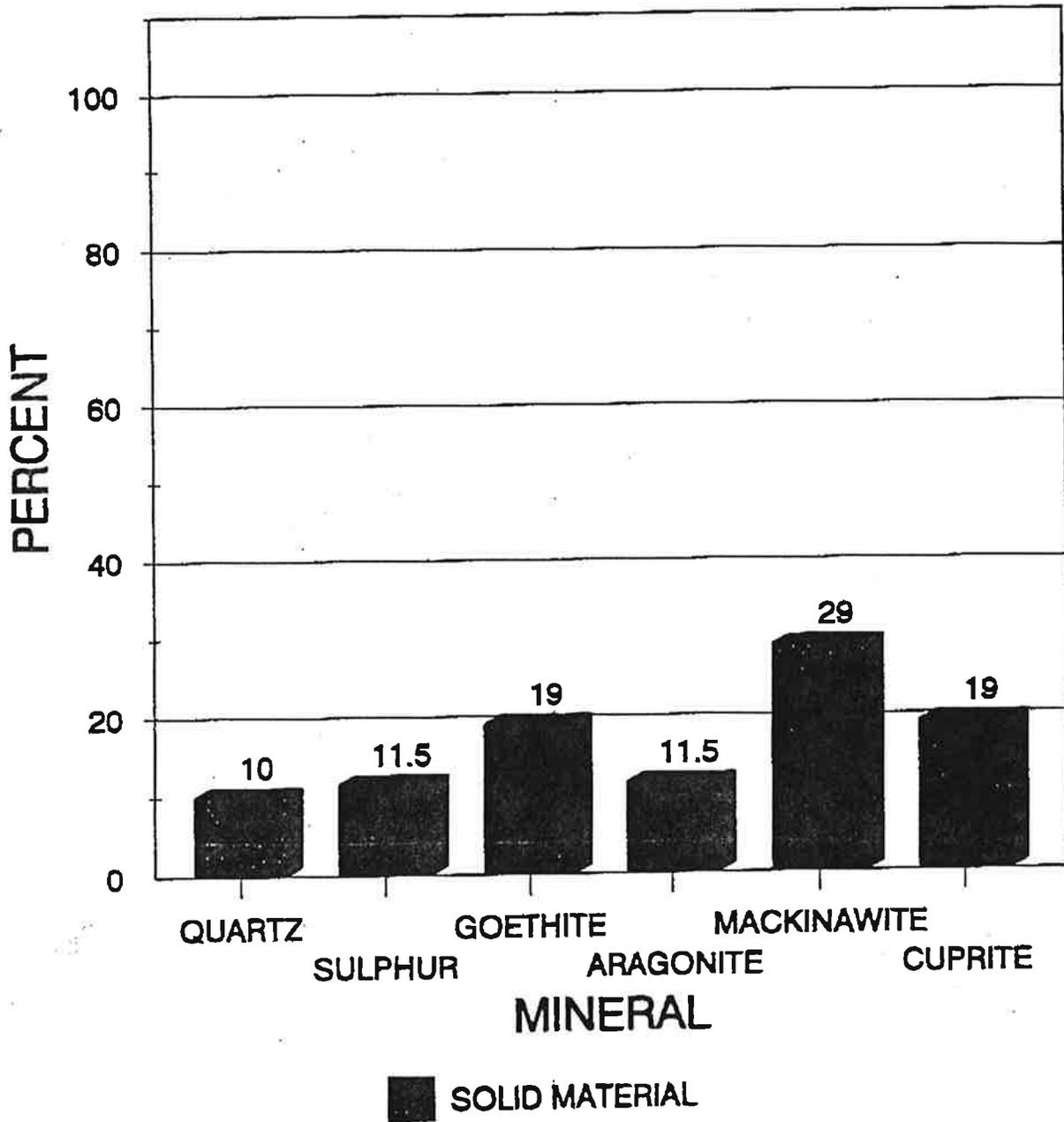
Sample Id.: Wellgreen Tailings - crumb

Note: XRD identifies crystalline material only

Figure 3
X-ray Diffraction Analysis

Sample Id.: Lupin Tailings
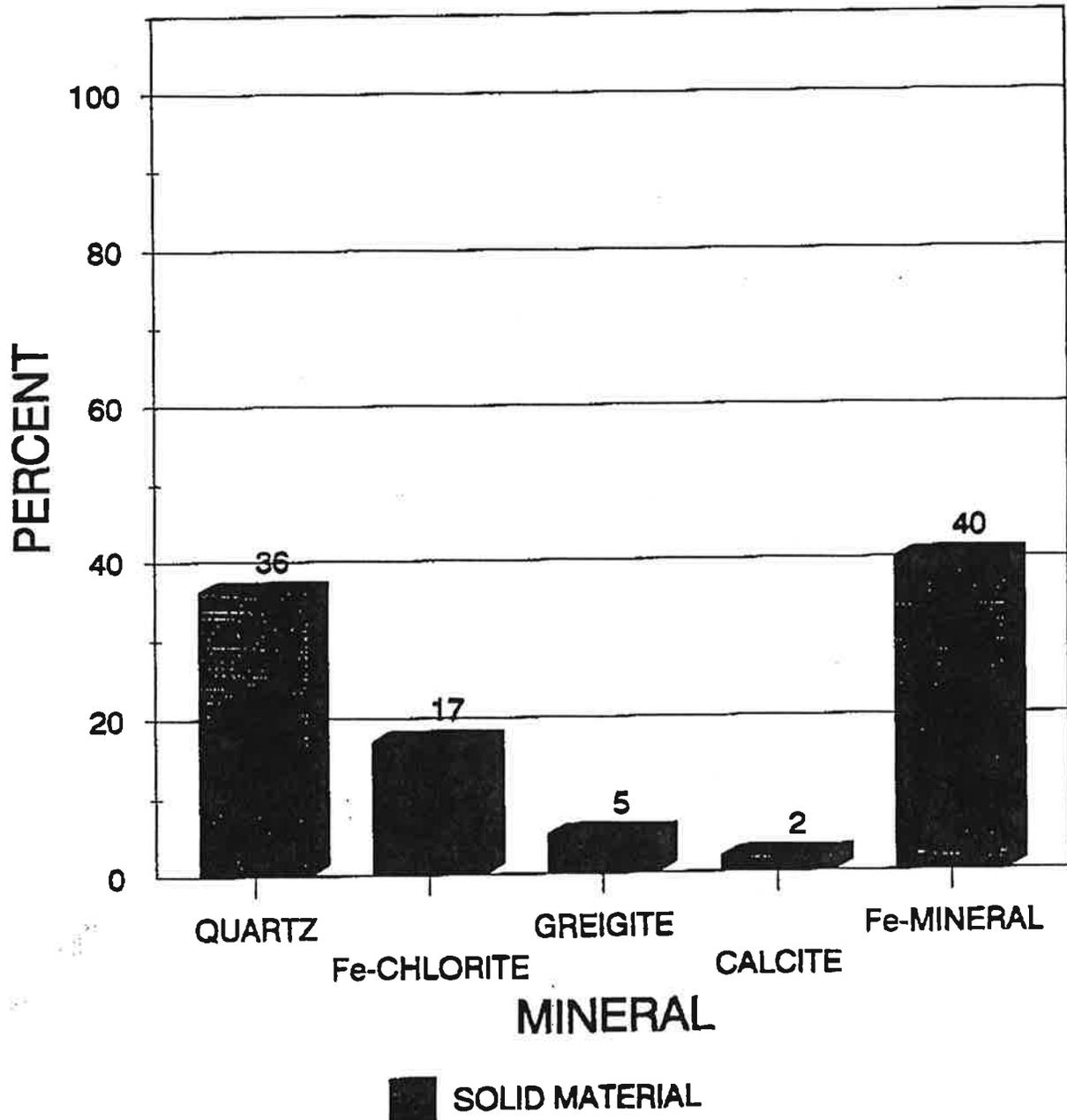
Note: XRD identifies crystalline material only

Appendix B

CHEMICAL ANALYSIS

University of Alberta
Edmonton

Canada T6G 2G7

Department of Civil Engineering

220 Civil/Electrical Engineering Building
Telephone (403) 492-4235

FAX COVER SHEET

Date: May 30, 1997

TO: Fax No.:   **1-604-984-0218**

Name: Carolyn Low

Address: Chemex Lab

FROM: Name: D.C. Sego
Fax: (403) 492 - 8198 (Canada) Phone: (403) 492 - 2059

Number of Pages Including Cover Sheet: Original send by : Mail_____
                                                                        Courier_____
                                                                        Not send_____ x

Re: **Acid Base Accounting and Chemical Testing**

Carolin:

After reviewing the test description and the price list you telefaxed and further to our discussion of this morning about testing of the mine tailings and water from the Wellgreen and Lupin sites, the following tests are required:

Acid Base Accounting (Sobek Method) (Chemex Code G368) of as received tailings
- Wellgreen Tailings - slab
- Wellgreen Tailings - crumb
- Lupin Tailings

Chemical Analysis (Chemex Code G392-30 element) of as received waters
- Anvil A
- Anvil B
- Lupin water
- Distilled water

Chemical Analysis of water release after it is mixed with tailings at ratio of 70% solids content ie solids content = mineral mass / (mineral mass + water mass)

The mineral and water should be throughly mixed and allowed to stand for a minimum of two hours then filter water for chemical analysis. Please perform pH and EC immediately after mixing, at 1 hr and at 2hr.

The following chemical analysis (Chemex Code G392-30 element) are required on water prepared using the above procedure:

- Wellgreen - slab mixed with Anvil Range A
- Wellgreen -slab mixed with Anvil Range B
- Wellgreen -slab mixed with Distilled water
- Lupin tailing mixed with Lupin water
- Wellgreen - crumb mixed with Anvil Range A
- Wellgreen - crumb mixed with Anvil Range B
- Wellgreen - crumb mixed with Distilled water

The samples will be forwarded to your laboratory today via a courier.

Regards,

Dave Sego

Chemex Labs Ltd.

Analytical Chemists * Geochemists * Registered Assayers

212 Brooksbank Ave.,   North Vancouver
British Columbia, Canada   V7J 2C1
PHONE: 604-984-0221 FAX: 604-984-0218

To: UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
220 CIVIL/ELECTRICAL ENGINEERING BUILDING
EDMONTON, AB
T6G 2G7

A9728024

Comments: ATTN: DAVID SEGO

CERTIFICATE   A9728024

(NLF) - UNIVERSITY OF ALBERTA

Project: TAILINGS
P.O. # :

Samples submitted to our lab in Vancouver, BC.
This report was printed on 26-JUN-97.

SAMPLE PREPARATION

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION
225	3	Run as received
234	3	0-7 Kg splitting charge

ANALYTICAL PROCEDURES

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION	METHOD	DETECTION LIMIT	UPPER LIMIT
1119	3	Paste pH	POTENTIOMETER	0.0	14.0
1379	3	Sulfate S %: Acid or H2O leach	GRAVIMETRIC	0.01	100.00
1066	3	S %: HNO3-bromide digestion	GRAVIMETRIC	0.01	100.00
1380	3	S %: Leco furnace	LECO-IR DETECTOR	0.01	100.0
368	3	CO2 %: Inorganic	LECO-GASOMETRIC	0.2	100.0
1117	3	Maximum potential acidity	CALCULATION	1	4000
1118	3	Neutralization potential	TITRATION	-1000	1000
1970	3	Net neutralization potential	CALCULATION	-2000	2000
1971	3	Neutraliz. pot. acidity ratio	CALCULATION	-10.0	1000.0
3731	3	Fizz test		1	10000

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T6G 2G7

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Total Pages : 1
Certificate Date: 26-JUN-97
Invoice No. : I9728024
P.O. Number :
Account : NLF

CERTIFICATE OF ANALYSIS A9728024

SAMPLE	PREP CODE	PASTE pH	S % * Sulfate	S % *** Sulfide	S % Total	CO2 % inorg	Max Pot Acid **	Neutral Poten**	Net Neu Poten**	Ratio NP/MPA	Fizz Test
WELLGREEN-SLAB	225 234	2.9	1.24	12.61	14.70	< 0.2	459	-4	-463	-0.01	1
WELLGREEN-CRUMB	225 234	2.6	1.25	12.62	14.00	< 0.2	438	-6	-444	-0.01	1
LUPIN	225 234	7.0	0.03	2.75	2.82	< 0.2	88	8	-80	0.09	1

NOTE: * HYDROCHLORIC ACID SOLUBLE SULFATE
NOTE: ** UNITS = KILOGRAMS CaCO3 EQUIVALENT PER METRIC TONNE (Kg/MT)
NOTE: *** NITRIC ACID SOLUBLE SULFIDE

CERTIFICATION:

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A9728025

Comments: ATTN: DAVID SEGO

CERTIFICATE A9728025

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Project: TAILINGS
P.O. # :

Samples submitted to our lab in Vancouver, BC.
This report was printed on 26-JUN-97.

SAMPLE PREPARATION

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION
268	3	Assay ring entire sample

ANALYTICAL PROCEDURES

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION	METHOD	DETECTION LIMIT	UPPER LIMIT
1119	3	Paste pH	POTENTIOMETER	0.0	14.0
1379	3	Sulfate S %: Acid or H2O leach	GRAVIMETRIC	0.01	100.00
1066	3	S %: HNO3-bromide digestion	GRAVIMETRIC	0.01	100.00
1380	3	S %: Leco furnace	LECO-IR DETECTOR	0.01	100.0
368	3	CO2 %: Inorganic	LECO-GASOMETRIC	0.2	100.0
1117	3	Maximum potential acidity	CALCULATION	1	4000
1118	3	Neutralization potential	TITRATION	-1000	1000
1970	3	Net neutralization potential	CALCULATION	-2000	2000
1971	3	Neutraliz. pot. acidity ratio	CALCULATION	-10.0	1000.0
3731	3	Fizz test		1	10000

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220 CIVIL/ELECTRICAL ENGINEERING BUILDING
EDMONTON, AB
T6G 2G7

Project : TAILINGS
Comments: ATTN: DAVID SEGO

CERTIFICATE OF ANALYSIS   A9728025

SAMPLE	PREP CODE	PASTE pH	S % * Sulfate	S % *** Sulfide	S % Total	CO2 % inorg	Max Pot Acid **	Neutral Poten**	Net Neu Poten**	Ratio NP/MPA	Fizz Test
WELLGREEN-SLAB	268 --	3.5	1.21	12.78	14.20	< 0.2	444	-11	-455	-0.02	1
WELLGREEN-CRUMB	268 --	3.2	1.38	12.44	14.70	< 0.2	459	-15	-474	-0.03	1
LUPIN	268 --	7.7	0.04	2.77	2.82	< 0.2	88	10	-78	0.11	1

NOTE: * HYDROCHLORIC ACID SOLUBLE SULFATE
NOTE: ** UNITS = KILOGRAMS CaCO3 EQUIVALENT PER METRIC TONNE (Kg/MT)
NOTE: *** NITRIC ACID SOLUBLE SULFIDE

CERTIFICATION: _____

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Project:
P.O. # :

Samples submitted to our lab in Vancouver, BC.
This report was printed on 18-JUN-97.

SAMPLE PREPARATION

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION
221	4	Water sample

ANALYTICAL PROCEDURES

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION	METHOD	DETECTION LIMIT	UPPER LIMIT
5501	4	Ag ug/L: Water samples	ICP-MS	0.05	1000
5502	4	Al ug/L: Water samples	ICP-MS	1	1000
5503	4	As ug/L: Water samples	ICP-MS	1	1000
5504	4	Ba ug/l: Water samples	ICP-MS	0.05	1000
5505	4	Be ug/l: Water samples	ICP-MS	0.5	1000
5506	4	Bi ug/L: Water samples	ICP-MS	0.05	1000
5507	4	Ca ug/L: Water samples	ICP-MS	50	50000
5508	4	Cd ug/L: Water samples	ICP-MS	0.1	1000
5509	4	Co ug/L: Water samples	ICP-MS	0.02	1000
5510	4	Cr ug/L: Water samples	ICP-MS	0.5	1000
5511	4	Cu mg/L: Water samples	ICP-MS	0.1	1000
5512	4	Fe ug/L: Water samples	ICP-MS	10	50000
5513	4	Hg ug/L: Water samples	ICP-MS	1	1000
5514	4	K ug/L: Water samples	ICP-MS	50	50000
5515	4	Mg ug/L: Water samples	ICP-MS	0.5	50000
5516	4	Mn ug/L: Water samples	ICP-MS	0.05	1000
5517	4	Mo ug/L: Water samples	ICP-MS	0.1	1000
5518	4	Na ug/L: Water samples	ICP-MS	50	50000
5519	4	Ni ug/L: Water samples	ICP-MS	0.2	1000
5520	4	P ug/L: Water samples	ICP-MS	100	50000
5521	4	Pb ug/L: Water samples	ICP-MS	2	1000
5522	4	Sb ug/L: Water samples	ICP-MS	0.05	1000
5523	4	Se ug/L: Water samples	ICP-MS	1	1000
5524	4	Sn ug/L: Water samples	ICP-MS	0.5	1000
5525	4	Sr ug/L: Water samples	ICP-MS	0.05	1000
5526	4	Ti ug/L: Water samples	ICP-MS	1	1000
5527	4	Tl ug/L: Water samples	ICP-MS	0.05	1000
5528	4	U ug/l: Water samples	ICP-MS	0.05	1000
5529	4	V ug/L: Water samples	ICP-MS	1	1000
5530	4	Zn ug/L: Water samples	ICP-MS	0.5	1000

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　　T6G 2G7

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Comments:　ATTN: D. C. SEGO

Page Number　: 1-A
Total Pages　: 1
Certificate Date: 18-JUN-97
Invoice No.　: I 9727307
P.O. Number　:
Account　　　: NLF

CERTIFICATE OF ANALYSIS　　　A9727307

SAMPLE	PREP CODE	Ag ug/L	Al ug/L	As ug/L	Ba ug/L	Be ug/L	Bi ug/L	Ca ug/L	Cd ug/L	Co ug/L	Cr ug/L	Cu ug/L	Fe ug/L	Hg ug/L	K ug/L	Mg ug/L	Mn ug/L	Mo ug/L	Na ug/L	Ni ug/L
Anvil Range A	221 --	< 0.05	< 1	< 1	20.7	< 0.5	< 0.05	>50000	< 0.1	91.9	7.5	< 0.1	1250	< 1	12750	>50000	9850	1.2	50000	240
Anvil Range B	221 --	< 0.05	< 1	14	59.5	< 0.5	0.25	>50000	17.5	21.5	< 0.5	< 0.1	1000	< 1	19250	20200	977	1.5	26800	60.9
LUPIN WATER	221 --	4.75	199	10100	24.8	< 0.5	< 0.05	>50000	0.9	81.7	12.3	5180	23100	< 1	35000	655	30.3	80.4	>50000	652
DISTILLED WATER	221 --	< 0.05	< 1	1	0.05	< 0.5	< 0.05	< 50	< 0.1	< 0.02	< 0.5	254	< 10	< 1	< 50	8.5	0.70	0.2	100	2.8

CERTIFICATION:

Chemex Labs Ltd.

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Project :
Comments: ATTN: D. C. SEGO

CERTIFICATE OF ANALYSIS   A9727307

SAMPLE	PREP CODE		P ug/L	Pb ug/L	Sb ug/L	Se ug/L	Sn ug/L	Sr ug/L	Ti ug/L	Tl ug/L	U ug/L	V ug/L	Zn ug/L
Anvil Range A	221	--	< 100	< 2	1.00	< 1	< 0.5	3150	< 1	0.25	11.25	< 1	4230
Anvil Range B	221	--	< 100	330	21.5	< 1	< 0.5	128.5	< 1	4.25	0.25	< 1	4770
LUPIN WATER	221	--	< 100	< 2	4.00	15	< 0.5	656	< 1	< 0.05	< 0.05	4	21300
DISTILLED WATER	221	--	< 100	14	< 0.05	< 1	< 0.5	0.45	< 1	< 0.05	< 0.05	< 1	56.0

CERTIFICATION:

Chemex Labs Ltd.

Analytical Chemists * Geochemists * Registered Assayers

212 Brooksbank Ave.,   North Vancouver
British Columbia, Canada   V7J 2C1
PHONE: 604-984-0221   FAX: 604-984-0218

To: UNIVERSITY OF ALBERTA
DEPARTMENT OF CIVIL ENGINEERING
220 CIVIL/ELECTRICAL ENGINEERING BUILDING
EDMONTON, AB
T6G 2G7

A9727747

Comments: ATTN: DAVE SEGO

CERTIFICATE   A9727747

(NLF) - UNIVERSITY OF ALBERTA

Project:
P.O. # :

Samples submitted to our lab in Vancouver, BC.
This report was printed on 18-JUN-97.

SAMPLE PREPARATION

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION
1337	21	Environmental solids
246	21	Deionized water leach

ANALYTICAL PROCEDURES

CHEMEX CODE	NUMBER SAMPLES	DESCRIPTION	METHOD	DETECTION LIMIT	UPPER LIMIT
659	21	pH	POTENTIOMETER	0.1	14.0
655	21	Conductivity umhos/cm	CONDUCTIVITY MTR	1	100000
5501	7	Ag ug/L: Water samples	ICP-MS	0.05	1000
5502	7	Al ug/L: Water samples	ICP-MS	1	1000
5503	7	As ug/L: Water samples	ICP-MS	1	1000
5504	7	Ba ug/l: Water samples	ICP-MS	0.05	1000
5505	7	Be ug/l: Water samples	ICP-MS	0.5	1000
5506	7	Bi ug/L: Water samples	ICP-MS	0.05	1000
5507	7	Ca ug/L: Water samples	ICP-MS	50	50000
5508	7	Cd ug/L: Water samples	ICP-MS	0.1	1000
5509	7	Co ug/L: Water samples	ICP-MS	0.02	1000
5510	7	Cr ug/L: Water samples	ICP-MS	0.5	1000
5511	7	Cu mg/L: Water samples	ICP-MS	0.1	1000
5512	7	Fe ug/L: Water samples	ICP-MS	10	50000
5513	7	Hg ug/L: Water samples	ICP-MS	1	1000
5514	7	K ug/L: Water samples	ICP-MS	50	50000
5515	7	Mg ug/L: Water samples	ICP-MS	0.5	50000
5516	7	Mn ug/L: Water samples	ICP-MS	0.05	1000
5517	7	Mo ug/L: Water samples	ICP-MS	0.1	1000
5518	7	Na ug/L: Water samples	ICP-MS	50	50000
5519	7	Ni ug/L: Water samples	ICP-MS	0.2	1000
5520	7	P ug/L: Water samples	ICP-MS	100	50000
5521	7	Pb ug/L: Water samples	ICP-MS	2	1000
5522	7	Sb ug/L: Water samples	ICP-MS	0.05	1000
5523	7	Se ug/L: Water samples	ICP-MS	1	1000
5524	7	Sn ug/L: Water samples	ICP-MS	0.5	1000
5525	7	Sr ug/L: Water samples	ICP-MS	0.05	1000
5526	7	Ti ug/L: Water samples	ICP-MS	1	1000
5527	7	Tl ug/L: Water samples	ICP-MS	0.05	1000
5528	7	U ug/l: Water samples	ICP-MS	0.05	1000
5529	7	V ug/L: Water samples	ICP-MS	1	1000
5530	7	Zn ug/L: Water samples	ICP-MS	0.5	1000

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Project :
Comments: ATTN: DAVE SEGO

Page Number : 1
Total Pages : 3
Certificate Date: 18-JUN-97
Invoice No. : I9727747
P.O. Number :
Account : NLF

CERTIFICATE OF ANALYSIS A9727747

Handwritten column group labels: Wellgreen Slab A | Wellgreen Slab B | Wellgreen Slab C / Distilled H2O | Lupin

PARAMETER DESCRIPTIONS	SAMPLE WG/SLAB+WG H2O-0 (t=0)	SAMPLE WG/SLAB+WG H2O-1 (t=1hr)	SAMPLE WG/SLAB+WG H2O-2 (t=2hr)	SAMPLE WG/SB+WGH2O+SED0 (t=0)	SAMPLE WG/SB+WGH2O+SED1 (t=1hr)	SAMPLE WG/SB+WGH2O+SED2 (t=2hr)	SAMPLE WG/SLAB+WG H2O-0 (t=0)	SAMPLE WG/SLAB+WG H2O-1 (t=1hr)	SAMPLE WG/SLAB+WG H2O-2 (t=2hr)	SAMPLE LUP TL+LUP H2O-0 (t=0)
Sample preparation code	1337	1337	1337	1337	1337	1337	1337	1337	1337	1337
Sample preparation code	246	246	246	246	246	246	246	246	246	246
pH	3.1	3.1	2.8	3.2	3.0	2.9	3.1	3.0	2.9	7.8
Conductivity (umhos/cm)	4940	5340	5400	3360	4490	4630	3470	4370	4520	3480
Ag ug/L	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----
Al ug/L	-----	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----
As ug/L	-----	-----	38	-----	-----	29	-----	-----	25	-----
Ba ug/L	-----	-----	25.0	-----	-----	17.75	-----	-----	13.25	-----
Be ug/L	-----	-----	10.0	-----	-----	12.5	-----	-----	12.5	-----
Bi ug/L	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----
Ca ug/L	-----	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----
Cd ug/L	-----	-----	43.1	-----	-----	54.1	-----	-----	41.0	-----
Co ug/L	-----	-----	19670	-----	-----	17060	-----	-----	17340	-----
Cr ug/L	-----	-----	387	-----	-----	399	-----	-----	380	-----
Cu ug/L	-----	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----
Fe ug/L	-----	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----
Hg ug/L	-----	-----	< 1	-----	-----	< 1	-----	-----	< 1	-----
K ug/L	-----	-----	10750	-----	-----	7000	-----	-----	1250	-----
Mg ug/L	-----	-----	>5000	-----	-----	>50000	-----	-----	>50000	-----
Mn ug/L	-----	-----	17130	-----	-----	8640	-----	-----	7930	-----
Mo ug/L	-----	-----	31.1	-----	-----	26.2	-----	-----	27.3	-----
Na ug/L	-----	-----	38800	-----	-----	20300	-----	-----	2000	-----
Ni ug/L	-----	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----
P ug/L	-----	-----	< 100	-----	-----	< 100	-----	-----	< 100	-----
Pb ug/L	-----	-----	167	-----	-----	46	-----	-----	79	-----
Sb ug/L	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----
Se ug/L	-----	-----	112	-----	-----	87	-----	-----	76	-----
Sn ug/L	-----	-----	< 0.5	-----	-----	< 0.5	-----	-----	< 0.5	-----
Sr ug/L	-----	-----	2430	-----	-----	533	-----	-----	511	-----
Ti ug/L	-----	-----	10	-----	-----	12	-----	-----	11	-----
Tl ug/L	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----
U ug/L	-----	-----	34.8	-----	-----	23.3	-----	-----	23.5	-----
V ug/L	-----	-----	< 1	-----	-----	< 1	-----	-----	< 1	-----
Zn ug/L	-----	-----	6760	-----	-----	6410	-----	-----	3330	-----

CERTIFICATION: _(signature)_

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      DEPARTMENT OF CIVIL ENGINEERING
      220 CIVIL/ELECTRICAL ENGINEERING BUILDING
      EDMONTON, AB
      T6G 2G7

Project :
Comments: ATTN: DAVE SEGO

CERTIFICATE OF ANALYSIS   A9727747

Handwritten column groupings: Lupin | Wellgreen Crumbs A | Wellgreen Crumbs B | Wellgreen Crumbs & Distilled H₂O

PARAMETER DESCRIPTIONS	SAMPLE LUP TL+LUP H20-1	SAMPLE LUP TL+LUP H20-2	SAMPLE WG CRMB+WG H20-0	SAMPLE WG CRMB+WG H20-1	SAMPLE WG CRMB+WG H20-2	SAMPLE WG CR+WGH20+SED0	SAMPLE WG CR+WGH20+SED1	SAMPLE WG CR+WGH20+SED2	SAMPLE WG CRMB+DI H20-0	SAMPLE WG CRMB+DI H20-1
(handwritten time)	t=1hr	t=2hr	t=0	t=1hr	t=2hr	t=0	t=1hr	t=2hr	t=0	t=1hr
Sample preparation code	1337	1337	1337	1337	1337	1337	1337	1337	1337	1337
Sample preparation code	246	246	246	246	246	246	246	246	246	246
pH	7.7	7.6	2.8	2.6	2.6	2.8	2.6	2.6	2.7	2.6
Conductivity (umhos/cm)	3580	3680	7490	9230	9420	5380	8250	8480	5330	5460
Ag ug/L	-----	38.3	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----
Al ug/L	-----	102	-----	-----	>50000	-----	-----	>50000	-----	-----
As ug/L	-----	291	-----	-----	51	-----	-----	58	-----	-----
Ba ug/L	-----	59.3	-----	-----	11.00	-----	-----	13.00	-----	-----
Be ug/L	-----	< 0.5	-----	-----	15.0	-----	-----	20.0	-----	-----
Bi ug/L	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----
Ca ug/L	-----	>50000	-----	-----	>50000	-----	-----	>50000	-----	-----
Cd ug/L	-----	1.4	-----	-----	82.6	-----	-----	96.1	-----	-----
Co ug/L	-----	158.0	-----	-----	30600	-----	-----	31600	-----	-----
Cr ug/L	-----	4.5	-----	-----	1730	-----	-----	1790	-----	-----
Cu ug/L	-----	8080	-----	-----	>50000	-----	-----	>50000	-----	-----
Fe ug/L	-----	8100	-----	-----	>50000	-----	-----	>50000	-----	-----
Hg ug/L	-----	< 1	-----	-----	< 1	-----	-----	< 1	-----	-----
K ug/L	-----	36300	-----	-----	3500	-----	-----	6000	-----	-----
Mg ug/L	-----	10990	-----	-----	>50000	-----	-----	>50000	-----	-----
Mn ug/L	-----	59.8	-----	-----	15620	-----	-----	9720	-----	-----
Mo ug/L	-----	123.5	-----	-----	45.0	-----	-----	44.8	-----	-----
Na ug/L	-----	>50000	-----	-----	32500	-----	-----	19250	-----	-----
Ni ug/L	-----	1580	-----	-----	>50000	-----	-----	>50000	-----	-----
P ug/L	-----	< 100	-----	-----	< 100	-----	-----	< 100	-----	-----
Pb ug/L	-----	< 2	-----	-----	46	-----	-----	39	-----	-----
Sb ug/L	-----	1.00	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----
Se ug/L	-----	18	-----	-----	166	-----	-----	177	-----	-----
Sn ug/L	-----	< 0.5	-----	-----	5.0	-----	-----	7.5	-----	-----
Sr ug/L	-----	1500	-----	-----	2180	-----	-----	562	-----	-----
Ti ug/L	-----	< 1	-----	-----	86	-----	-----	92	-----	-----
Tl ug/L	-----	< 0.05	-----	-----	< 0.05	-----	-----	< 0.05	-----	-----
U ug/L	-----	1.00	-----	-----	49.5	-----	-----	39.8	-----	-----
V ug/L	-----	< 1	-----	-----	< 1	-----	-----	< 1	-----	-----
Zn ug/L	-----	4760	-----	-----	10380	-----	-----	10410	-----	-----

CERTIFICATION: *(signature)*

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Project :
Comments: ATTN: DAVE SEGO

Page Number : 3
Total Pages : 3
Certificate Date: 18-JUN-97
Invoice No.   : I9727747
P.O. Number :
Account   : NLF

CERTIFICATE OF ANALYSIS   A9727747

Sample description (handwritten): Wellgreen Crumbs in Distilled H2O — WG CRMB+DI H2O-2 (= 2h?)

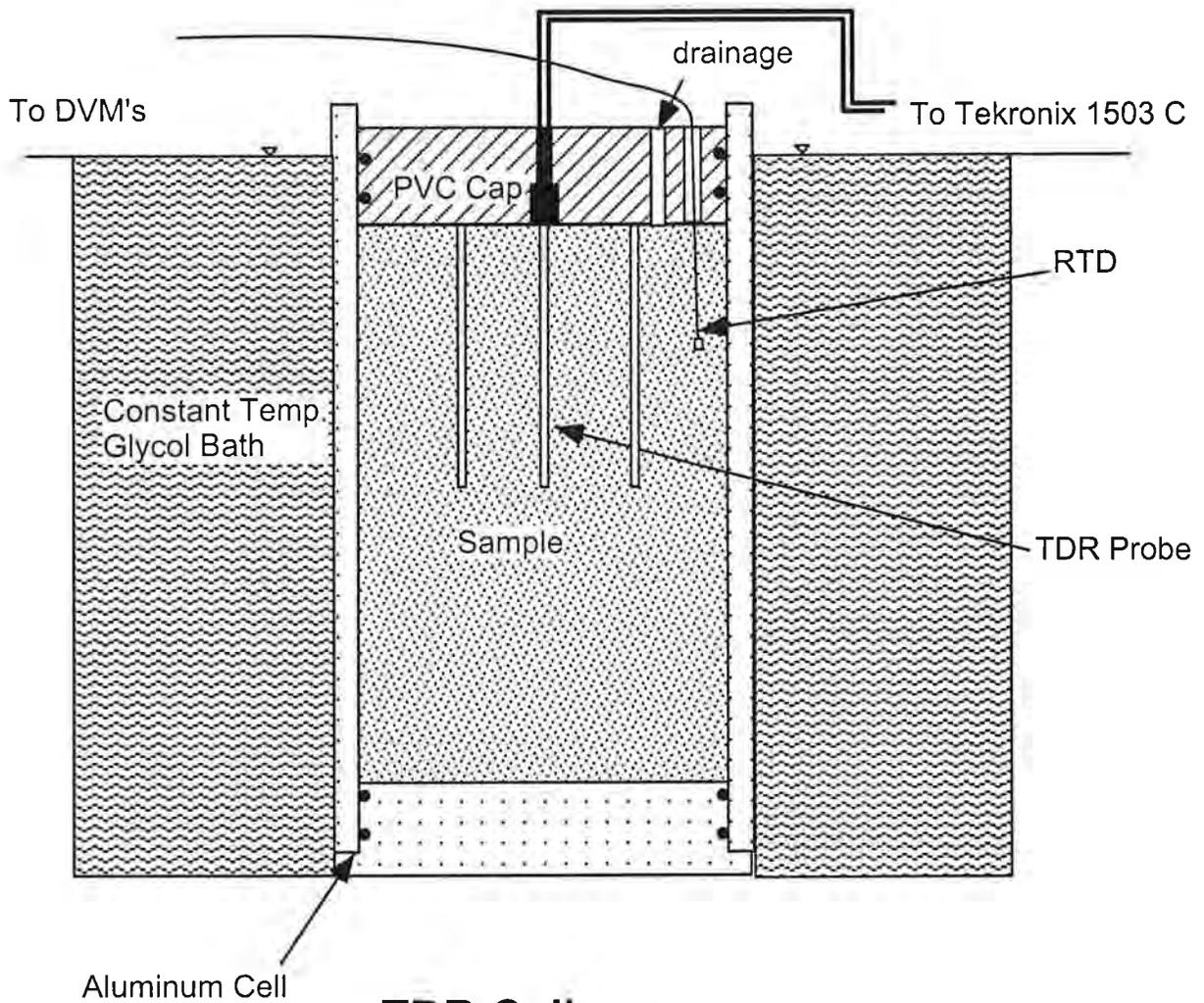| PARAMETER DESCRIPTIONS		SAMPLE
Sample preparation code		1337
Sample preparation code		246
pH		2.6
Conductivity	(umhos/cm)	6130
Ag	ug/L	< 0.05
Al	ug/L	>50000
As	ug/L	62
Ba	ug/L	15.25
Be	ug/L	15.0
Bi	ug/L	< 0.05
Ca	ug/L	>50000
Cd	ug/L	70.0
Co	ug/L	25300
Cr	ug/L	1470
Cu	ug/L	>50000
Fe	ug/L	>50000
Hg	ug/L	< 1
K	ug/L	750
Mg	ug/L	>50000
Mn	ug/L	7090
Mo	ug/L	36.1
Na	ug/L	1500
Ni	ug/L	>50000
P	ug/L	< 100
Pb	ug/L	31
Sb	ug/L	< 0.05
Se	ug/L	142
Sn	ug/L	5.0
Sr	ug/L	526
Ti	ug/L	80
Tl	ug/L	< 0.05
U	ug/L	33.8
V	ug/L	< 1
Zn	ug/L	5830

CERTIFICATION: *[signature]*

Appendix C

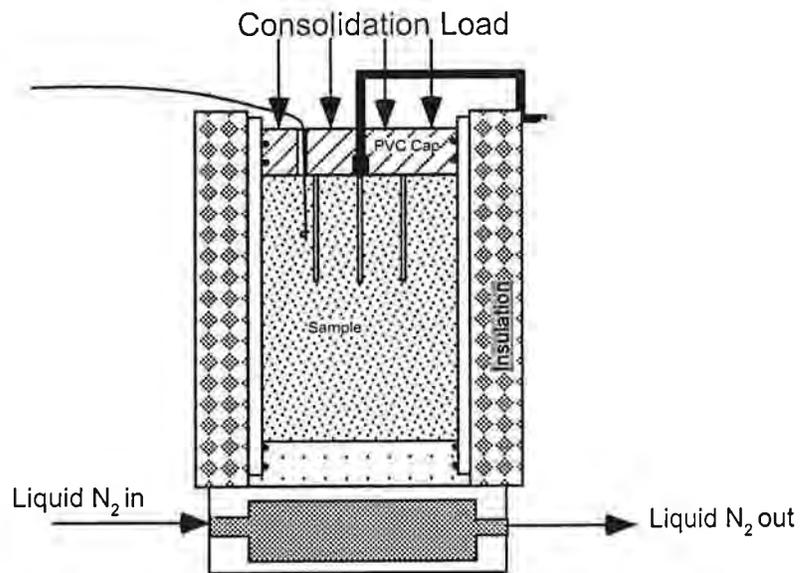**TIME DOMAIN REFLECTOMETRY TEST RESULTS**

Time Domain Reflectometry
(Unfrozen Water Content Determination)
as Performed at The University of Alberta
Department of Civil and Environmental Engineering

0) The sample dimensions are recorded.

1) The sample is mounted into the aluminum cell from the top. The bottom cap is then pushed into the cell so as to not allow an air gap between the sample and the bottom cap.

2) The top cap, TDR probe and RTD's are then installed by pushing them into the cell. In the case of an undisturbed sample, the sample is drilled to accommodate the probe and RTD's.

3) The sample is then consolidated to the desired stress. The expelled water volume is noted.

4) When consolidation is complete the new height of sample is recorded. The coolant is then allowed to flow through the cooling plate. RTD readings and expelled water volume are monitored during freezing.

5) A set of TDR readings is taken after freezing. The sample temperature is approximately -80° C.

6) After freezing, the sample is removed to a controlled temperature (-10°C)room overnight. This allows the sample to warm up before putting it the constant temperature bath.

7) After approximately 12 hours the sample is in a test condition, that is, it has reached thermal equilibrium.

8) The probe and RTD's are then connected to the Tektronix 1503 C TDR unit and DVM's respectively.

9) A set of 5 readings are used to get an average of the dielectric constant (Ka). Using the Smith and Tice (1988) correlation, Ka is converted to volumetric unfrozen water content.

10) The bath and sample are warmed to the next test temperature level. It is important to allow sufficient time between tests so that the sample has come to thermal equilibrium.

11) Upon completion of the final "frozen" test the sample can be warmed to room temperature and a test in the thawed state maybe performed. This thawed state test can be performed immediately after the consolidation phase if it is convenient at that time.

To DVM's

drainage

To Tekronix 1503 C

PVC Cap

RTD

Constant Temp. Glycol Bath

Sample

TDR Probe

Aluminum Cell

**TDR Cell
X-section**

Consolidation Load

PVC Cap

Insulation

Sample

Liquid N$_2$ in

Liquid N$_2$ out

**Freezing System
X-section**

Unfrozen Volumetric Water Content versus Temperature

Data for Figure 4 Unfrozen Water Content versus Temperature for Tailings Samples
for Wellgreen A and Control Data

Temperature (°C)	Wellgreen Crumbs A (m³/m³)	Wellgreen Slab A (m³/m³)	Control Sample (m³/m³)
23.0	0.621	0.661	0.428
-15.1	0.042	0.052	-0.001
-9.2	0.041	0.055	-0.002
-3.2	0.053	0.065	-0.003
-1.3	0.086	0.082	0.000
-0.8	0.134	0.105	0.000
-0.8	0.139	0.108	0.001
-0.7	0.253	0.166	-0.002
-0.4	0.264	0.162	-0.002
-0.4	0.263	0.163	-0.002
-0.1	0.371	0.268	0.015
0.0	0.410	0.390	0.015
0.5	0.389	0.444	0.329

Unfrozen Volumetric Water Content versus Temperature

Data for Figure 4 Unfrozen Water Content versus Temperature for Tailings Samples
for Wellgreen B and Lupin Data

Temp (m³/m³)	Wellgreen Crumbs B (m³/m³)	Wellgreen Slab B (m³/m³)	Lupin (m³/m³)
-14.6	0.0437	0.0443	
-10.0	0.0495	0.0461	0.0470
-3.0	0.0713	0.0553	0.0545
-0.2	0.1571	0.0787	0.0744
-0.3	0.1829	0.1203	0.1152
-0.2	0.3213	0.2228	0.2325

Data for Figure 5 Unfrozen Water Contents at a Very Low Temperature
for Wellgreen B and Lupin Data

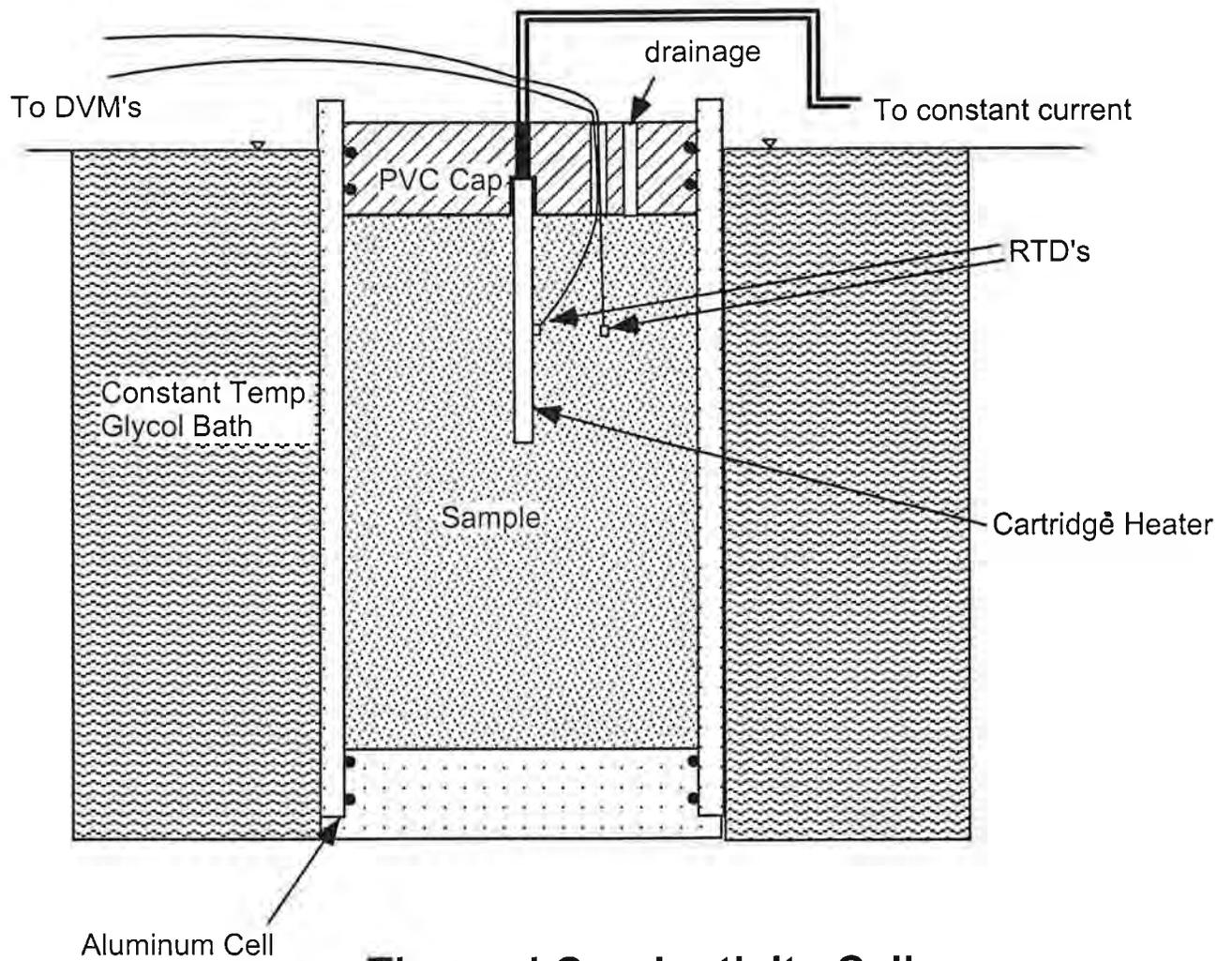| Temp (m³/m³)	Wellgreen Crumbs B (m³/m³)	Wellgreen Slab B (m³/m³)	Lupin (m³/m³)
-81.8	0.0215	0.0261	0.0284
-14.6	0.0437	0.0443	
-10.0	0.0495	0.0461	0.0470
-3.0	0.0713	0.0553	0.0545
-0.2	0.1571	0.0787	0.0744
-0.3	0.1829	0.1203	0.1152
-0.2	0.3213	0.2228	0.2325

Appendix D

THERMAL CONDUCTIVITY TEST RESULTS

Thermal Conductivity Test Procedure
as Performed at The University of Alberta
Department of Civil and Environmental Engineering

0) The sample dimensions are recorded.
1) The sample is mounted into the aluminum cell from the top. The bottom cap is then pushed into the cell so as to not allow an air gap between the sample and the bottom cap.
2) The top cap, heater and RTD's are then installed by pushing them into the cell. In the case of an undisturbed sample, the sample is drilled to accommodate the heater and RTD's.
3) The sample is then consolidated to the desired stress. The expelled water volume is noted.
4) When consolidation is complete the new height of sample is recorded. The coolant is then allowed to flow through the cooling plate. RTD readings and expelled water volume are monitored during freezing
5) After freezing, the sample is removed to a controlled temperature (-10° C) room overnight. This allows the sample to warm up before putting it the constant temperature bath. Put the sample into the bath.
6) After approximately 12 hours the sample is in a test condition.
7) The heater and RTD's are then connected to the constant current source and DVM's respectively.
8) At time=0 the current is directed to the heater. The current and RTD readings are recorded at 5-15 second intervals to a maximum of 8 to 20 minutes.
9) A typical data and plot sheet is attached.
10) Warm the bath and sample to next test temperature. Allow sufficient time between tests so that the sample has come to equilibrium.
11) Upon completion of the final "frozen" test the sample can be warmed to room temperature and a test in the thawed state maybe performed. This thawed state test can be performed immediately after the consolidation phase if it is convenient at that time.
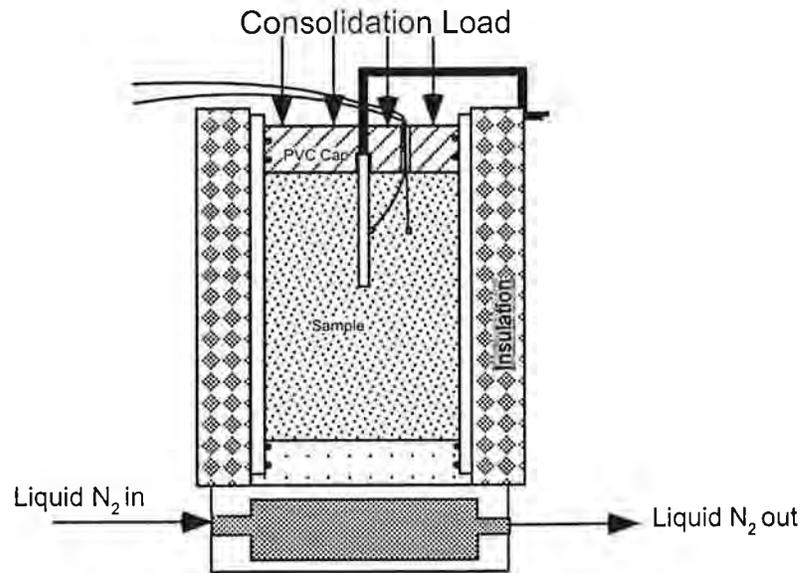
ASTM have a test procedure similar to the procedure outlined above. The specification for the ASTM test is D-5334 .

RTD: resistance temperature device - measures temperature to an accuracy of +/- 0.1°C

DVM: digital volt meter.

To DVM's

drainage

To constant current

PVC Cap

RTD's

Constant Temp.
Glycol Bath

Sample

Cartridge Heater

Aluminum Cell

Thermal Conductivity Cell
X-section

Consolidation Load

PVC Cap

Insulation

Sample

Liquid N₂ in

Liquid N₂ out

Freezing System
X-section

SUMMARY OF THERMAL CONDUCTIVITIES

	Wellgreen Crumbs A				Wellgreen Slabs A			Control Sample		
Test #	Temperature (°C)	Thermal conductivity (W/m°C)		Test #	Temperature (°C)	Thermal conductivity (W/m°C)	Test #	Temperature (°C)	Thermal conductivity (W/m°C)	
1	22.41	0.90		1	23.62	1.04	1	22.85	3.38	22.96
2	-15.08	1.49		2	-15.00	1.54	2	-15.13	4.46	-15.07
3	-9.18	1.47		3	-9.13	1.54	3	-9.23	4.42	-9.18
4	-3.13	1.59		4	-3.13	1.61	4	-3.28	3.91	-3.18
5	-1.33	2.71		5	-1.31	2.42	5	-1.44	4.23	-1.36
6	-0.82	5.03	1.34	6	-0.82	2.93	6	-0.92	4.52	-0.85
7	-0.49	8.40	1.22	7	-0.62	6.34	7	-0.38	2.91	-0.50

SUMMARY OF THERMAL CONDUCTIVITIES

Test #	Wellgreen Crumbs B Temperature (°C)	Thermal conductivity (W/m°C)	Test #	Wellgreen Slabs B Temperature (°C)	Thermal conductivity (W/m°C)	Test #	Lupin Temperature (°C)	Thermal conductivity (W/m°C)
1			1			1		
2	-8.87	1.51	2	-9.03	1.34	2	-8.64	2.69
3	-3.26	1.78	3	-2.92	1.44	3	-2.74	2.89
4	-0.33	2.72	4	-0.13	2.39	4	0.21	4.00
5	-0.79	2.66	5	-0.28	2.95	5	0.08	4.71
6	-0.38	2.15	6	-0.31	3.38	6	0.10	1.08
7	0.28	0.76	7	-0.23	2.14	7	0.18	0.24
8	0.67	0.74	8	0.33	0.79	8	0.95	1.57
9	-83.56	1.68	9	-83.46	1.72	9	-81.72	3.15
10	14.64	0.88	10	14.51	0.89	10	15.38	1.76

Appendix E

CRREL REPORT 90-5

CRREL Report 90-5

Three Functions That Model Empirically Measured Unfrozen Water Content Data and Predict Relative Hydraulic Conductivity

Patrick B. Black

May 1990

Three Functions That Model Empirically Measured Unfrozen Water Content Data and Predict Relative Hydraulic Conductivity

PATRICK B. BLACK

INTRODUCTION

The most basic of all soil functions used to characterize the physical behavior of frozen soil is the soil freezing curve. It is a graphical representation of empirically measured changes in unfrozen water content occurring with changes of state of ice and water in soil (Fig. 1). The thermal (Farouki 1981), hydraulic (Black and Miller 1985, 1990) and stress (Black and Miller 1985) properties of frozen soil are all dependent upon the amount of unfrozen water. It is important, therefore, that the soil freezing curve be represented by a function that both contains few parameters and allows its use to determine the other physical properties of frozen soil. The thermal conductivity and stress partition factor are simple functions of unfrozen water content, whereas hydraulic conductivity is not.

While there are many possible classes of functions to model unfrozen water content, some functions clearly offer significant advantages over others. Currently, most soil freezing data are fitted to a power curve that appears to be statistically sufficient but lacks physical meaning or does not offer the capability to predict hydraulic conductivity. There are, though, three relationships commonly used for describing the soil-water retention and relative hydraulic conductivity behavior of ice-free soil (Gardner 1958, Brooks and Corey 1964, van Genuchten 1980) that do offer some physical interpretation and the capability to predict one type of data from the other.

The purpose of this paper is to present a framework whereby the three commonly used deterministic relations for ice-free soil-water retention data can be used to describe unfrozen water changes in frozen soil. This will then allow the implementation of Mualem's (1976) model for unfrozen soil to predict the relative hydraulic conductivity for frozen soil.
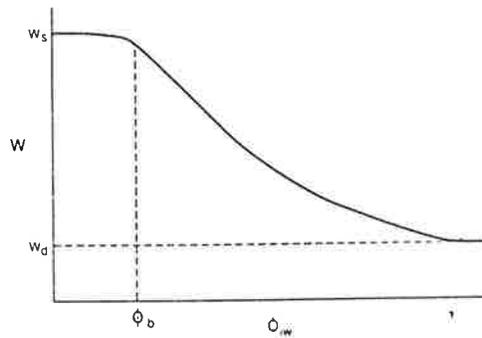

Figure 1. Representative unfrozen water content behavior.

AIR–WATER ICE–WATER SIMILARITY

When discussing the state of water in soil-water systems, it is convenient to introduce the variable ϕ_{bc}

$$\phi_{bc} = u_b - u_c \qquad (1)$$

which is simply the pressure difference between water in the two phases b and c (Black and Miller 1985, 1990; Black and Tice 1989; Black 1989). Thus, the matric pressure for ice-free soil is expressed as

$$\phi_{wa} = u_w - u_a \tag{2}$$

where u_w and u_a refer to, respectively, soil-water and air pressures. Likewise, the state of water in an air-free frozen soil is expressed as

$$\phi_{iw} = u_i - u_w \tag{3}$$

where u_i is the ice pressure. Most often though, the state of water in air-free frozen soil is expressed in terms of temperature, θ. If the soil is devoid of solutes, the Clapeyron equation

$$u_w - \frac{u_i}{\gamma_i} = \frac{h}{273} \theta \tag{4}$$

can be used to relate ice and water pressures to temperature, the specific gravity γ_i of ice and volumetric latent heat of fusion h. Solving eq 3 and 4 for u_i gives the connection between water pressure u_w, ice temperature θ and ϕ_{iw}

$$\phi_{iw} = (\gamma_i - 1) u_w - \frac{\gamma_i h}{273} \theta. \tag{5}$$

The concepts of adsorption space and capillary space are other useful classifications to employ in discussing the physical behavior of soil. Adsorption space is that zone in which soil water is strongly affected by surface forces (real or virtual) emanating from the soil. Capillary space is the remaining region in which water is not affected by soil force fields but is governed by the laws of surface tension. Granular soil will tend to contain mostly capillary water, while highly colloidal soils will be dominated by adsorbed water. The nature and formulation of the adsorption space will not be addressed in this paper but will only be employed in a general classification scheme for soils.

Miller (1965) hypothesized that, under certain constraints, the behavior exhibited by soil upon freezing and thawing should be similar to its behavior upon drying and wetting. He proposed that if the same state of soil-water retention and distribution is achieved by a freezing and thawing process as by a drying and wetting process, then the two states should be similar and interchangeable if and only if the soil is either colloidal (adsorption space>>capillary space) or colloid-free (adsorption space<<capillary space).

The laboratory experiments of Koopmans and Miller (1966) prove this hypothesis for colloidal and granular soils. They found that the ice-free soil-water retention data and air-free unfrozen water data for the same soil maintained to the same density and subjected to similar histories were directly related. They found a simple equivalence for the case of colloidal soils (i.e., $\phi_{wa} = \phi_{iw}$), while granular soils required an additional correction factor to account for differences in surface tensions (i.e., $\phi_{wa} = [\sigma_{wa}/\sigma_{iw}] \phi_{iw}$).

Recent work by Black and Tice (1989) showed that the strict similarity requirements imposed in the experiments of Koopmans and Miller can be relaxed and still result in agreement between ice-free soil-water retention and unfrozen water data. They successfully transposed their unfrozen water data onto ice-free soil-water retention data collected by other researchers a decade earlier for the same granular field soil.

With the theoretical and empirical basis for the similarity between ice-free soil-water retention and unfrozen water confirmed, relations that describe ice-free soil-water retention data should also describe unfrozen water data. This will allow the analytical methods for evaluating ice-free soil-water retention and unsaturated hydraulic conductivity characteristics to be used to describe the same properties in frozen soil.

HYDRAULIC MODELS

Moisture characteristics

For ease of use, mathematical models purporting to describe the behavior of soil-water retention data should contain few free parameters and still accurately predict data. A polynomial of large degree could be made to fit the data exactly, but would offer no advantage over using spline fits to the data

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because of the large number of parameters required. There are two other functions with fewer parameters that have been observed to closely describe ice-free soil-water retention data (drying and wetting curves being treated as separate relations) as well as offering closed-form analytic expressions for predicting the unsaturated hydraulic conductivity. One function is that proposed by Brooks and Corey (1964). They found that, based upon a large number of observations for ice-free soils, the relative degree of saturation or dimensionless water content

$$S = \frac{W - W_d}{W_s - W_d} \tag{6}$$

could be reasonably described by the relationship

$$S = \begin{cases} \left[\dfrac{\phi_b}{\phi_{wa}}\right]^{-\alpha} & \phi_{wa} < \phi_b \\ \\ 1 & \phi_{wa} \geq \phi_b \end{cases} \tag{7}$$

where W, W_d and W_s are, respectively, the water contents at a given ϕ_{wa}, at the lower limit of drying and at saturation. ϕ_b is the air entry value and α is a free parameter determined from a "curve fit" to the data. Equation 7 is valid for the range $\phi_{wa} < \phi_{wb}$; otherwise, $S = 1$ (i.e., $W = W_s$) for $\phi_{wa} \geq \phi_b$.

To avoid the discontinuity at ϕ_b, van Genuchten (1980, 1978) proposed a different class of functions

$$S = \begin{cases} \left[\dfrac{1}{1 + (\lambda\phi_{wa})^n}\right]^m & \phi_{wa} < 0 \\ \\ 1 & \phi_{wa} \geq 0 \end{cases} \tag{8}$$

in which λ, n and m are free parameters also determined from a curve fit to the data.

The free parameter α in eq 7 was found to be related to the pore-size distribution of the soil. Small values of α are found to correspond to soils with a wide span of pore sizes; large α values are appropriate when grain sizes are nearly uniform. The free parameters in eq 8 on the other hand have no physical significance except for large negative ϕ_{wa} values. In that case, eq 8 approaches

$$W = \left[\frac{1}{(\lambda\phi_{wa})^n}\right]^m \tag{9}$$

from which we find that $\alpha = mn$ and $1/\lambda = \phi_b$.

Hydraulic conductivity

Several models exist that purport to predict the relative hydraulic conductivity, K_r, from the behavior of soil-water retention data (Childs and Collis-George 1950, Burdine 1953, Millington and Quirk 1961, Jackson et al. 1965, Mualem 1976). The model proposed by Mualem is most commonly employed today in obtaining closed-form analytical expressions and is used here. In addition to soil-water retention data, this model requires the hydraulic conductivity at saturation K_s, from which the relative hydraulic conductivity is predicted to be

$$K_r(S) = S^B \left[\frac{\displaystyle\int_0^S dx/h(x)}{\displaystyle\int_0^1 dx/h(x)}\right]^2 \tag{10}$$

Table 1. Brooks and Corey, van Genuchten and Gardner equations for unfrozen water content and relative hydraulic conductivity.

BROOKS AND COREY

$$
S = \begin{cases} \left[\dfrac{\phi_{iw}}{\phi_b}\right]^{-\alpha} & \phi_{iw} > \phi_b \\[2em] 1 & \phi_{iw} \leq \phi_b \end{cases}
$$

$$
K_r(\phi_{iw}) = \begin{cases} K_s \left[\dfrac{\phi_b}{\phi_{iw}}\right]^{(2+B)\alpha+2} & \phi_{iw} > \phi_b \\[2em] K_s & \phi_{iw} \leq \phi_b \end{cases}
$$

VAN GENUCHTEN

$$
S = \begin{cases} \left[\dfrac{1}{1+(\lambda\phi_{iw})^n}\right]^m & \phi_{iw} > 0 \\[2em] 1 & \phi_{iw} \leq 0 \end{cases}
$$

$$
K_r(\phi_{iw}) = \begin{cases} K_s \dfrac{\left[1-(\lambda\,\phi_{iw})^{n-1}\left[1+(\lambda\,\phi_{iw})^n\right]^{-(1-1/n)}\right]^2}{\left[1+(\lambda\,\phi_{iw})^n\right]^{B\,(1-1/n)}} & \phi_{iw} > 0 \\[2em] K_s & \phi_{iw} \leq 0 \end{cases}
$$

GARDNER

$$
S = \begin{cases} \left(e^{-0.5\beta\phi_{iw}}\left[1+0.5\beta\,\phi_{iw}\right]\right)^{2/(B+2)} & \phi_{iw} > 0 \\[2em] 1 & \phi_{iw} \leq 0 \end{cases}
$$

$$
K_r(\phi_{iw}) = \begin{cases} K_s\,e^{-\beta\phi_{iw}} & \phi_{iw} > 0 \\[2em] K_s & \phi_{iw} \leq 0 \end{cases}
$$

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where B is a new soil parameter that accounts for the effects of tortuosity and multiple interconnections at the pore level on water content. It can be either positive or negative.

Mualem applied eq 6 and 7 to eq 9 and obtained the relative hydraulic conductivity for the Brooks and Corey relationship

$$K_r(\phi_{wa}) = \begin{cases} K_s \left[\dfrac{\phi_b}{\phi_{wa}} \right]^{(2+B)\alpha+2} & \phi_{wa} < \phi_b \\[20pt] K_s & \phi_{wa} \geq \phi_b. \end{cases} \quad (11)$$

In order to apply eq 9 to eq 10, certain restrictions on n and m must be imposed. van Genuchten (1978) found that for the case of $m = 1-1/n$, eq 10 obtained the relative hydraulic conductivity

$$K_r(\phi_{wa}) = \begin{cases} K_s \dfrac{\left[1-(\lambda|\phi_{wa}|)^{n-1} \left[1+(\lambda|\phi_{wa}|)^n \right]^{-(1-1/n)} \right]^2}{\left[1+(\lambda|\phi_{wa}|)^n \right]^{B(1-1/n)}} & \phi_{wa} < 0 \\[24pt] K_s & \phi_{wa} \geq 0. \end{cases} \quad (12)$$

The third, and last, function often used to describe relative hydraulic conductivity as a function of ϕ_{wa} is the exponential model proposed by Gardner (1958). He suggested that relative hydraulic conductivity be expressed in terms of a single soil parameter

$$K_r(\phi_{wa}) = K_s e^{-\beta|\phi_{wa}|}. \quad (13)$$

In this case, the single parameter β assumes the importance that both α and ϕ_b have in eq 7 and the three soil parameters have in eq 8. Unfortunately, Gardner did not develop an equivalent expression for soil-water retention data.

Russo (1988) found a class of functions that, when applied to eq 10, resulted in eq 13. The expression for soil-water retention data that he suggests, which can be thought of as the Gardner equation for water retention, is

Figure 2. Changes in unfrozen water content in Fox Tunnel Silt for four different total gravimetric water contents attributable to changes in ϕ_{iw}.

$$S = \begin{cases} \left(e^{-0.5\beta|\phi_{wa}|} \left[1+0.5\beta|\phi_{wa}| \right] \right)^{2/(B+2)} & \phi_{wa} < 0 \\[12pt] 1 & \phi_{wa} \geq 0. \end{cases} \quad (14)$$

All three type of functions are presented in Table 1 in terms of ϕ_{iw}. Since unfrozen water content data are collected in terms of temperature, a value of ϕ_{iw} is obtained by applying eq 5. Most often the soil specimens are exposed to the atmosphere so u_w can be assumed to be zero and ϕ_{iw} is simply 11.1 bars/°C (Black and Tice 1989). The influence of air in frozen soil has been ignored so far. There will definitely be an effect in ice redistribution as the soil undergoes freezing (Miller 1973). However, it appears that, in the case of unfrozen water content measurements, the presence of air merely offsets
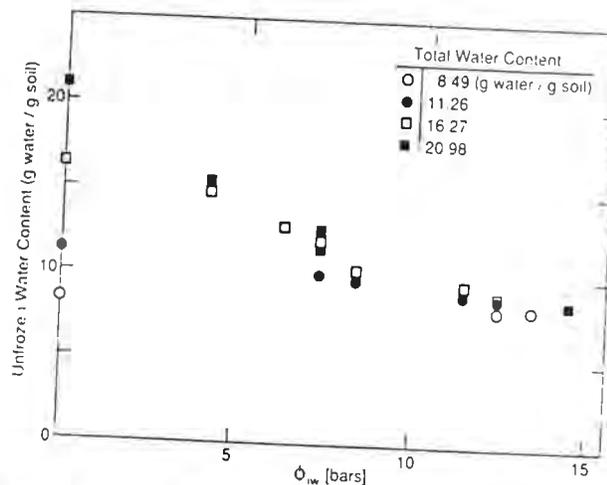
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the onset of freezing. That is, nonsaturated soils start freezing at a lower temperature than saturated soils, but then follow the unfrozen water content curve of the saturated soil (Fig. 2). This process is being studied in more detail in our laboratory.

DISCUSSION

Russo (1988) presented a statistical study of the relative predictive properties of these equations for ice-free soil. His results, along with those of others (van Genuchten 1980, Milly 1987, Lenhard et al. 1989), suggest that the van Genuchten equations offer superior performance. In the case of ice-free soil, especially field soils, the lack of an apparent pronounced ϕ_b value reduces the predictive ability of the Brooks and Corey equation (eq 7) and favors the van Genuchten equation (eq 8). Since the appropriate form of the Gardner equation for water retention data is relatively new, little can be said for eq 14 except that it has the fewest free-parameters and would therefore be the simplest to use.

In order to apply eq 6, which is used in eq 7, 8 and 14, a value for the lower limit of drying, W_d, is required. Unfortunately, data at very low ϕ_{wa} are seldom collected because of experimental complications. As a result, its value usually must be inferred by extrapolating outside the range of data through numerical or graphical procedures. Black and Tice (1989) have found that unfrozen water content data, transformed by eq 5, offer a source of low ϕ_{wa} data. Using this approach, they found compelling experimental evidence to suspect that $W_d \rightarrow 0$ for $\phi_{wa} \rightarrow -\infty$. This observation has the potential for minimizing the number of parameters in eq 6 by one.

Finally, and most important for the predictive property of these equations, is the uncertainty in the B parameter. While the other soil parameters are obtained from the easily acquired soil-water retention curve, B must initially be found by examining relative hydraulic conductivity data. This presents a problem owing to the experimental complexities of obtaining such data. Mualem determined that a value for B of 1/2 minimized the error between predicted and measured data for his data set. From the work of Bresler et al. (1978), on correctly scaling the data of Reichardt et al. (1972), an optimal value for B of −2/15 is obtained. Russo found that each of the soils he investigated might display a unique value. It is hoped that this parameter will turn out to be more general than the others; otherwise, there is no benefit to using eq 10.

CONCLUSIONS

While this paper is intended to discuss the proper way to express unfrozen water content data, most of the references have been to ice-free soil. This circumstance is caused by the meager effort that has been made to utilize unfrozen water content data to the level of sophistication that is exercised with soil-water retention data. Perhaps this can be singly attributed to the extreme experimental complications that are encountered in measuring the relative hydraulic conductivity of frozen soil and the resulting lack of data.

Black and Miller (1990) were able to make a limited number of simultaneous measurements of unfrozen water content and relative hydraulic conductivity. They found that the presence of a pronounced ice entry pressure allowed the Brooks and Corey type of equation to give results superior to the van Genuchten equation. The Gardner equation was not tested. They also found that the −2/15 value of B provided by Bresler et al. (1978) gave satisfactory prediction of the measured relative hydraulic conductivity when only the unfrozen water content data were used to predict.

It is clear that much more experimental work is needed to determine the strong connection (B parameter) between unfrozen water content data and relative hydraulic conductivity. Until this task is accomplished, these two types of data will continue to be treated separately.

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