Temperature Dependent Behaviour of Low Percentage Bentonite – Granular Soil Mixtures: Remarkable Results

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ABSTRACT
This paper describes laboratory and field results obtained for various sands mixed with 5-8% bentonite (EnviroGel® 8) with focus on hydraulic conductivity. The research objective was to develop low permeability sand and bentonite (S-B) mixtures and a commercially available bentonite. A remarkable result was that under a fluctuating temperature regime, the hydraulic conductivity of S-B mixtures was inversely proportional to temperature. This phenomenon can be explained by the Gouy-Chapman theory. The hypothesis is that increasing temperature leads to 1) increased Brownian motion resulting in fewer water molecules in the diffuse double layer of bentonite which in turn increases the dielectric permittivity of the water that moved from the double layer to the bulk fluid, and 2) lower dielectric permittivity of the 'original' bulk water. The net effect is a thicker double layer and lower hydraulic conductivity. The laboratory results are confirmed by field results. In a S-B test plot at Whistle Mine (~46°40'N, 81°00'W), volumetric water content (TDR), which is directly related to dielectric permittivity, correlated strongly with soil temperature (R^2> 0.99). In a S-B plot at the Premier Gold Project (~ 56°05'N, 130°00'W), scaled frequency counts of capacitance probes also correlated strongly with soil temperature (R^2>0.99). This temperature dependent behaviour was not observed in a till field test plot that contained solely non-swelling clays.

RÉSUMÉ
Ce papier décrit les résultats de laboratoire et au terrain ont obtenu pour les divers sables mélangés avec 5-8% bentonitique (EnviroGel® 8) avec le foyer sur la conductivité hydraulique. Un résultat remarquable était que sous un régime de température variant, la conductivité hydraulique de mélanges de S-B était inversement proportionnel à la température. Ce phénomène peut être expliqué par la théorie de Gouy-Chapman. L'hypothèse est cela augmentant la température mene au mouvement Brownian augmenté a pour résultat de moins molécules d'eaux dans la couche double de bentonitique. Ceci augmente la constante diélectrique de l'eau qui s'est déplacée de la couche double au liquide de masse. La température qui augmente aussi causes abaissent la constante diélectrique du 'l'original' l'eau de masse. Cette hypothèse est confirmée par les résultats au terrain. A Whistle Mine (~46°40'N, 81°00'W), le contenu d'eau volumétrique (TDR), qui est directement relaté la constante diélectrique, correspondue avec la température de sol (R^2> 0.99). A Premier Gold Project (~ 56°05'N, 130°00'W), les comptes de sondes de capacitance ont correspondu aussi à la température de sol (R2>0.99). Cette relation de température n'a pas été observée pour un glacial que les contenu seulement argiles de non-grossissant.

1. INTRODUCTION

One of the major known benefits of adding bentonite, a clay high in montmorillonite, to a granular soil, such as silty sand, is a reduction of the permeability due to the high mineralogical activity (high swelling capacity) of bentonite. Bentonite swells with the absorption of water and expands into the pores of the granular soil. Soils with a broad range of grain sizes usually require a small amount of bentonite (<= 6%) whereas uniform-sized soils, such as dune sand, require more bentonite (10 to 15%) to achieve low hydraulic conductivity (Koerner and Daniel, 1997). Wong and Haug (1991) measured hydraulic conductivities of 3 x 10^{-10} m/s and 1.1 x 10^{-10} m/s for specimens of very uniform and spherically shaped sand (Ottawa sand) mixed with 4.5% and 6% bentonite, respectively. Chapius et al. (1992) found that a minimum bentonite content of 7% was required in a sand and bentonite mixture to yield a hydraulic conductivity of less than 2 x 10^{-8} m/s.

It is generally accepted that clay minerals hold water molecules primarily with hydrogen bonds (Yong and Warkentin, 1966), and that the dielectric permittivity of bound water near clay surfaces is between that of ice and free water. The dielectric permittivity has been estimated to be 6, 32, and 80 (similar to 'free' water') for the first, second, and third molecular layers of water adsorbed to clay minerals, respectively (Wraith, 1999).

According to Mitchell (1993), saturated clayey soils follow D'Arcy's law and have viscosity and diffusion characteristics very similar to that of pure water. However, conflicting temperature responses have been reported for unsaturated soils (e.g. Mitchell, 1993; Wraith, 1999; Wraith and Or, 1999; Baumhardt et al., 2000).

1.1 Reseach Objective

The research objective was to develop a cost-effective low permeability S-B mixture consisting of sand and gravel (M18 sand) from the vicinity of the Premier Gold Project (PGP) and a commercially available bentonite. To achieve this object the following tasks were performed:

- PHASE I – Laboratory Work:

- Characterization of potential construction materials,
- Conduct of constant flow hydraulic conductivity tests,
- Conduct of falling head hydraulic conductivity tests,
- Conduct of flexible wall hydraulic conductivity tests.

- PHASE II – Laboratory Work:
  - Conduct of rigid-wall, constant gradient hydraulic conductivity tests.

- PHASE III – Related Field Results
  - Comparison of S-B field test plot data with laboratory results.

2. LABORATORY TEST WORK

2.1 Phase I – Laboratory Work

2.1.1 Phase I – Methods and Materials

Potential construction materials were collected from the PGP field site and characterized in terms of grain size, mineralogy, and specific surface area. Subsequently, several hydraulic conductivity tests were conducted under varying laboratory conditions in an attempt to simulate field conditions as much as possible. Based on literature results, various sand gradations were mixed with 5-8% bentonite in this research (see Table 1).

Rigid-wall constant flow hydraulic conductivity tests were used to establish the saturated hydraulic conductivities under controlled flow conditions on small specimen (~45 cm^3). The constant flow apparatus and method of operation were the same as detailed by Fernandez and Quigley (1985, 1991).

Falling head hydraulic conductivity tests were conducted to study the effect of confining pressures ranging from 6-29 kPa on specimen. Falling head tests were conducted in four compaction permeameters (similar to EL 28-425 in ELE Catalog, 1968). The cylinders of these compaction permeameters had the same dimensions as those of standard Proctor devices, but unlike standard Proctor devices, water could be applied to the top and drained from the bottom after compaction of the soil specimens.

Flexible wall hydraulic conductivity tests were conducted for several specimens following the ASTM D5084 to determine the saturated and unsaturated hydraulic conductivity under a constant hydraulic gradient and confining pressure.

2.1.2 Phase I - Soil Characterization Results

The grain size distribution of M18 sand and gravel, silt, and glacial till used in the study are illustrated in Figure 1. Based on the United Soil Classification System (USCS), all sand and gravel samples screened to Minus ¾" (<1.9 cm) were 'SP' or poorly graded sands or gravelly sands with little or no fines. The clay size fraction in the M18 sand and gravel, consisting of particles less than 0.002 mm, was less than 0.15 %. M18 sand and gravel had a field water content of 5.5% and a relative density of 2.74.

The silt used for laboratory work had a field water content of 25% and a relative density of 2.76.

In this research, the granular bentonites EnviroGel® 8 and EnviroGel® 12 (supplied by Wyo-Ben Inc in Billings, Montana) were used. These bentonites are mineralogically the same and contain only sodium montmorillonite as clay minerals. EnviroGel® 8 has a bulk density of 1,073 kg/m^3 at 20^oC and a relative density of 2.45 to 2.55. EnviroGel® 8 has granules with a minimum of 98% passing No. 4 Mesh (4.75 mm) and a maximum of 5% passing No. 20 Mesh (0.85 mm). EnviroGel® 12 contains smaller granules than EnviroGel® 8 (69.3% retained on 16-40 mesh sieves).

The till tested (PGP till) was a well graded glacial till with a field water content of 9.7% and a relative density of 2.8. The till contained the non-swelling clay minerals chlorite, illite, and kaolinite.

Based on the ethylene glycol (EG) retention method, the specific surface areas were as follows:

- 330 m^2/g for EnviroGel® 8 and 12, and
- 210 m^2/g for M18 sand and gravel plus 6% EnviroGel® 8 by weight, and
- 20 m^2/g for PGP till.

2.1.3 Phase I - Hydraulic Conductivity Results

Results of the constant flow tests are summarized in Table 1 and depicted in Figure 2. In Figure 2, the hydraulic conductivity data is presented on the bottom graph with its scale given on the left y-axis. Temperature data is graphed at the top and the temperature scale is shown on the right y-axis. Details regarding the materials tested and the confining pressures are listed at the top of Figure 2.

The most remarkable result of the constant flow hydraulic conductivity tests of the investigated S-B mixtures is the inverse relationship between temperature and hydraulic conductivity. This response seemed to be almost instantaneous (i.e. no phase lag). It appears that as the temperature increased, void space occupied by "free or bulk water" decreased. This behaviour, in turn, decreased the hydraulic conductivity of the S-B mixtures. The average hydraulic conductivity increased 2.0 to 3.4 times for a temperature difference of 6.1^oC (21.4-27.5^oC) for the coarse S-B specimens.

In the falling head hydraulic conductivity tests, conducted on three S-B mixtures, the S-B mixture first absorbed water before stabilizing (after 2 to 4 months). This behaviour is due to the swelling of bentonite, since the samples were at optimum water content at the beginning of the hydraulic conductivity tests.

After 355 days of submergence under water in FHT-Cell 1 (containing the mixture '2/3 Minus 4 M18 sand and gravel' plus '1/3 silt' plus '8% EnviroGel® 8'), a 1 cm thick layer of primarily bentonite gel was found at the top of the falling head apparatus. Thus, bentonite migrated out of the S-B mixture that had been homogeneous at the beginning of the test to form this gel layer. After approximately 635 days of free access to water, two other S-B specimens had swollen by approximately 28.5%.

As expected, the flexible wall hydraulic conductivity of samples decreased as the percentage of bentonite increased in the sand and bentonite mixtures (see Table 1).

2.2 Phase II - Methods and Materials

2.2.1 Rigid-wall Hydraulic Conductivity Tests

Since temperature related changes in porosity were indicated by the rigid-wall constant flow test results (see Figure 2), the flexible wall hydraulic conductivity test apparatus was modified to quantify these temperature effects on larger soil specimens than is possible in the constant flow test apparatus. The modification involved placing the soil specimens in stainless steel cylinders (diameter ~7.2 cm, heights ranging from 5.0 to 7.3 cm). Therefore, these modified tests constitute rigid-wall, constant gradient hydraulic conductivity tests.

The rigid-wall, constant gradient hydraulic conductivity tests were conducted on two specimens of the S-B mixture (Minus ¾"(< 19 mm) 'M18 Sand and Gravel' plus '6% EnviroGel® 8' bentonite by weight) that had been installed in the PGP field test plot. The hydraulic conductivity for the specimens was evaluated first at one temperature, then at another temperature, and then again at the first temperature.

The mixtures were tested at 8°C, which is the average summer soil temperature at PGP, and at normal laboratory temperature (which averaged to ~20°C but ranged from 15 to 30°C). Estimation of hydraulic conductivity was limited to the average response at laboratory temperature as the apparatus was not automated. The S-B specimens underwent the following temperature regimes:

Series 1.
- Phase 1. Sample was first tested at 15-21.5°C,
- Phase 2. then at 8°C (system blew out),
- Phase 3. then at 8°C, and
- Phase 4. and finally at 15-21.5°C.

Series 2.
- Phase 1. Sample was first tested at 15-21.5°C,
- Phase 2. then at 8°C (apparatus started to fail),
- Phase 3. then at 8°C,
- Phase 4. then at 13°C (interrupted refrigeration),
- Phase 5. then at 8°C, and
- Phase 6. finally at room temperature (18.4-30.0°C).

It should be noted that the specimens were not taken out or reassembled after each phase when the specimen was moved from one temperature regime to another. Exceptions to this were Phase 3 in Series 1 and Phase 3 in Series 2. Since effluent 'blew' out in Phase 2 of Series 1 (i.e. effluent shot through the sample and flooded the receiving pipette, regulator and tubing on the panel), the control panel had to be completed dried out and the soil specimen was remolded prior to the start of Phase 3 in Series 1. The 'blowout' was likely due to the contraction of the sand and bentonite mixture in response to the temperature change, which resulted in side-wall leakage. The effluent that flooded the pipette was brownish in colour and likely contained some bentonite.

Similar to Phase 2 in Series 1, Phase 2 in Series 2 became unstable after approximately 75 hours. However, a blow out of effluent water was averted by stopping the test and restarting it after 24 hours to allow the specimen to acclimatize to the lower temperature (8°C) by swelling. Although realizing that leaving the sample to acclimatize would mask some of the initial temperature effects expected after a temperature drop, continuation of the test without stoppage would have likely resulted in another blowout as was experienced in Phase 2 of Series 1.

2.2.2 Rigid-wall Hydraulic Conductivity Test Results

As illustrated in Figure 3, flow volumes in Phases 1 and 4 of Series 1 are indicative of saturated soil conditions with the influent flow and the effluent flow being almost the same. This was not the case after the sample was moved from the normal laboratory temperature to the controlled temperature room at 8°C in Phases 2 and 3. In Phases 2 and 3, the flow volumes indicate that the soil sample was not saturated anymore as the influent flow in Figure 3 is much larger than the effluent flow, despite the fact that the sample had been saturated in the previous phase, that the sample had not been disturbed in the move, and that no other parameters besides temperature had been changed.

As is also illustrated on Figure 3, the rate of flow was much higher in the initial stage of Phases 2 and 3 of Series 1 which is likely due to side wall leakage (since the specimen were contained in rigid cylinders) as well as temperature related effects. Finally, after approximately 720 hours (or 30 days), the Phase 3 influent flow rate measured at 8°C was similar to the influent flow rate measured at normal laboratory temperature (see Table 2).

As shown on Figure 4, the hydraulic behaviour for the Series 2 rigid-wall, constant gradient tests was similar to what was described for the Series 1 tests. In Figure 4, the initial high flow rate for Phase 1 is not shown to not obstruct that behaviour recorded for Phase 3.

The influent and effluent flow rates in Phase 1 of Series 2 are indicative of a saturated (up to 360 hours) to nearly saturated specimen (thereafter). Again, the flow rate is higher for both the influents and effluents of Phases 3 and 5 as a response to a temperature drop from 20 to 8°C and 13 to 8°C, respectively. Again, in time the influent flow rate at 8°C became more similar to the Phase 1 influent flow rate, however, even after 800 hours or 33 days of testing, the Phase 5 rate was still twice the Phase 1 flow rate (see Table 2).

It is important to note that the hydraulic conductivities at 8^{o}C in Phase 2 and early Phase 3 in Series 2 (the Series that did not blow out) were approximately 15 to 20 times higher than what was measured in Phase 1 at normal laboratory temperature.

3. DISCUSSION

3.1 Temperature Behaviour

The observed temperature dependent behaviour of hydraulic conductivity is of practical importance, since fluctuating rather than constant temperatures are typically experienced in the field. Fluctuating flow rate in response to changing temperatures may result in localized piping and the formation of preferential flow paths that may lead to poorer performance of a S-B barrier system than desired. This effect may be especially pronounced at the interface of S-B and rigid structures such as walls or pipes. The observed temperature dependent behaviour provides an additional explanation for reported failures of S-B barriers and piping of bentonite (e.g. Chamberlain et al., 1997; Wong and Haug, 1991; Chapius et al., 1992).

Typically, it is assumed that the hydraulic conductivity of a porous medium increases as temperature increases due to changes in water viscosity and density. Thus, the observed behaviour of decreased hydraulic conductivity with increasing temperature cannot solely be explained with the change in the viscosity of water as it would have the opposite effect of higher hydraulic conductivity at higher temperatures.

Since neither the charge of the bentonite nor the composition of the sand and gravel matrix are expected to be temperature dependent, the observed temperature behaviour is likely due to the combined effects of:

1) increased Brownian motion of the adsorbed water molecules resulting in fewer water dipoles in the diffuse double layer of the bentonite which in turn leads to higher dielectric permittivity of the water dipoles that move from the double layer to the bulk fluid, and
2) lower viscosity of water and lower dielectric permittivity of 'original' bulk water (which has an opposite effect to the one observed).

These reasons are discussed in more detail below after a brief review of the Gouy-Chapman Double Layer theory.

3.1.1 Temperature and the Gouy Chapman Double Layer Theory

The Gouy-Chapman theory was developed to describe the distribution of the electrical potential in the clay-water-electrolyte system surrounding individual clay layers (Yong and Warkentin, 1966; Mitchell, 1993; Shang et al., 1994). In the Gouy Chapman theory, clay minerals are surrounded by a Stern-Gouy double layer. The layer closest to the clay mineral, the Stern layer, is thought to consist of one layer of water molecules (rigid water). In the layer surrounding the Stern layer, the Gouy layer or diffuse double layer, the electric charge drops off exponentially from the outer edge of the Stern layer to the outer edge of the Gouy layer. As the thickness of the double layer increases, the hydraulic conductivity decreases and vice versa. The thickness of the double layer, $1/\kappa$, can be estimated according to Eq. 1 (Mitchell, 1993):

$$\frac{1}{\kappa} = \sqrt{\frac{\varepsilon_o \varepsilon_r k T}{2 n_o e^2 z^2}} \qquad \text{[Equation 1]}$$

where

ε_o is the dielectric permittivity for vacuum,
ε_r is medium's relative dielectric permittivity,
k is the Boltzmann constant,
T is the temperature in degree Kelvin,
ν_0 is the electrolyte concentration,
e is the elementary electric charge, and
z is the valence of cation.

Assuming that all other parameters in Eq. 1 remain the same and recognizing that ε_r is temperature dependent (e.g. Mitchell, 1993; Shang et al., 1994; Wraith, 1999), Eq. 1 can be simplified to Eq. 2. Based on Eq. 2, the change in double layer thickness with respect to temperature is equal to the partial derivative of Eq. 2.

$$\frac{1}{\kappa} = const - \alpha \times \sqrt{\varepsilon_r(T) \times T} \qquad \text{[Equation 2]}$$

$$\frac{\partial(\frac{1}{\kappa})}{\partial T} = \frac{(const. - \alpha)}{2 \times \sqrt{\varepsilon_r(T) \times T)}} \times (\frac{\partial \varepsilon_r}{\partial T} \times T + \varepsilon_r(T)) \qquad \text{[Equation 3]}$$

where
const$-\alpha$ is the proportionality constant
all other parameters as defined above

For soils with no swelling clays, no significant outward migration of water molecules from the diffuse double layer with increasing temperature is expected, since the number of interlayer water molecules is low. Therefore, the hydraulic behaviour of that type of soil is controlled by the properties of the bulk fluid. Thus, as temperature increases, the dielectric permittivity decreases and the viscosity of the bulk water decreases, and as a result the hydraulic conductivity increases.

However, for soils with a high proportion of swelling clays, such as sodium bentonite, the number of water molecules that migrate out of the diffuse double layer and into the bulk pore water as temperature increases is significant. Since water in the diffuse double layer is characterized by a dielectric permittivity lower than that of the bulk pore water (Yong and Warkentin, 1966), the outward migration of water molecules in response to increasing temperature results in a higher overall dielectric permittivity. This is despite the fact that the dielectric permittivity of the water that was originally in the bulk water, decreases as temperature increases. In the transition period from a lower temperature to a higher temperature, the increased thickness of the double layer results in a decrease of the hydraulic conductivity and vice versa.

Assuming that the dielectric permittivity of water changes with temperature according to Eq. 4 (e.g. see Or and Wraith, 1999):

$$\frac{\partial \varepsilon_w}{\partial T} = 78.54 \times (4.579 \times 10^{-3} + 2.38 \times 10^{-5}(T - 298.15) - 8.4 \times 10^{-8}(T - 298.15)^2)$$

[Equation 4]

and that the double layer thickness changes according to Eq. 3, a temperature drop from 20°C to 8°C (that was applied in the rigid-wall tests) decreases the double layer thickness by 4.2%. For the same temperature difference, but assuming that the temperature had been constant for a prolonged period, the double layer would be 0.68% thicker. For a temperature transition from 27.5°C to 21.4°C that was applied in the constant flow tests, the double layer thickness will decrease by 2.2% according to Eqs. 3 and 4. For the same temperature difference, but assuming that the temperature had been constant for a prolonged period, the double layer would be 0.37% thinner.

3.2 Phase III – Related Field Results

To demonstrate that it is the dielectric permittivity that is primarily responsible for the temperature dependent behaviour of S-B mixtures, volumetric water contents and scaled frequency counts are presented for two field sites. For the equipment used, these two parameters are directly related to soil's apparent dielectric permittivity. One S-B test plot is located at Whistle Mine (~46°40'N, 81°00'W), and the other at the Premier Gold Project (PGP) (~ 56°05'N, 130°00'W) (O'Kane Consultants Inc. 2001; Renken et al., 2002, 2003). The S-B barriers at the two sites were constructed out of locally available sands and EnviroGel® 12 and EnviroGel® 8 sodium bentonite, respectively.

In the Whistle Mine project, changes in water content in, above, and below the barriers were assessed with time domain reflectometry (TDR) probes and soil temperature with thermocouples. TDR probes estimate the volumetric water content based on changes in the soil's apparent dielectric permittivity (e.g. Or and Wraith, 1999). As clearly illustrated in Figure 5, as the soil temperature in the S-B barrier increased, the estimated volumetric water content increased (see response of sensors 2-8 and 2-11 with R^2>0.99). Therefore, the apparent dielectric permittivity of the soil must have increased.

In the PGP test plots, the volumetric water content was measured with multicapacitance probes (EnviroScan ® sensors) and soil temperature with thermocouples (Campbell Scientific 229 Soil Water Potential Probes). Capacitance probes consist of a pair of electrodes that are connected to an oscillator. When a capacitance probe is activated: 1) the soil-water-matrix acts as a dielectric medium for the capacitor, 2) the electrical field that surrounds the capacitor aligns the water dipoles in the soil, and 3) the electromagnetic field resonates at a frequency that is dependent of the soil's apparent dielectric permittivity. Changes in the soil's capacitance result in different resonant frequencies that are usually reported as scaled (normalized) frequency (SF) counts.

Figure 6 depicts the measured SF counts versus time as well as soil temperature versus time for one soil profile in the PGP S-B cover system. The correlation between soil temperature and SF was very strong in the spring and summer months of 2003 (R^2> 0.99). This is again an indication that the soil's apparent dielectric permittivity is increasing with increasing soil temperature. The recorded increase in SF, depicted on Figure 6, corresponds to an apparent increase in volumetric water content of 7% from May to mid-July, 2003.

The temperature dependent behaviour observed for the S-B test plot was not measured for the PGP till test plot, despite the fact that the till had undergone the same soil temperature fluctuations.

4. CONCLUSIONS AND RECOMMENDATIONS

It has long been suspected that freeze-thaw episodes contribute to failures or poor performance of field installations of S-B barriers or GCLs, although testing of hydraulic conductivity on sand and bentonite samples in the laboratory did not seem to confirm those suspicions (e.g. Wong and Haug, 1991). However, these tests are typically conducted at a constant temperature, usually at room temperature, and corrected to 20°C using the ASTM 5084 or equivalent protocols to account for changes in water viscosity and density with temperature. Also, tests are typically conducted in flexible wall apparatuses, in which voids that might have been present due to temperature fluctuations would likely be squeezed shut in response to the high cell pressures (usually ≥ 200 kPa) that are typically applied.

The most remarkable result of the hydraulic conductivity tests of the investigated S-B mixtures was the inverse relationship between temperature and hydraulic conductivity. This response seemed to be almost instantaneous.

To establish the maximum hydraulic conductivity, sand-bentonite mixtures intended for field installations (e.g. mixtures for grout walls and sand and bentonite barriers) should be subjected to hydraulic conductivity tests under fluctuating temperature regimes that are representative of expected field conditions.

Based on the presented research findings, following steps are recommended to collect and interpret soil water balance parameters for S-B barriers:

1. Establish the mineralogy and specific surface area of the S-B mixture to qualitatively determine the type of material and whether a temperature dependent behaviour of hydraulic conductivity and soil moisture should be expected.
2. Measure the soil temperature at several depths in the barrier (at least two profiles are suggested),

3. Measure the soil suction for the same locations as in Step 2,
4. Assess changes in the soil moisture for the abovementioned soil profiles.
   - ⇨ If equipment is used that relies on the soil's dielectric permittivity to estimate soil water content (e.g. capacitance or TDR probes), the instrument readout should be used to quantify the change in the soil's apparent dielectric permittivity, ε_r. However, soil moisture should be estimated based on soil suction data collected in Step 2.
5. Assess vertical percolation rate (hydraulic conductivity)
   - ⇨ via a calibration equation based on ε_r established in Step 4, or
   - ⇨ based on soil suction and relying on D'Arcy's Law (Benson et al., 1994).

To confirm whether there is a drying or wetting trend in a soil cover system, the soil moisture status could be compared at the same soil temperature but at different times. This would ensure that the temperature related effect on dielectric permittivity is the same for the two times, and hence, changes dielectric permittivity or other parameters would be due to other climatic factors such as evapotranspiration, drainage, and recharge.

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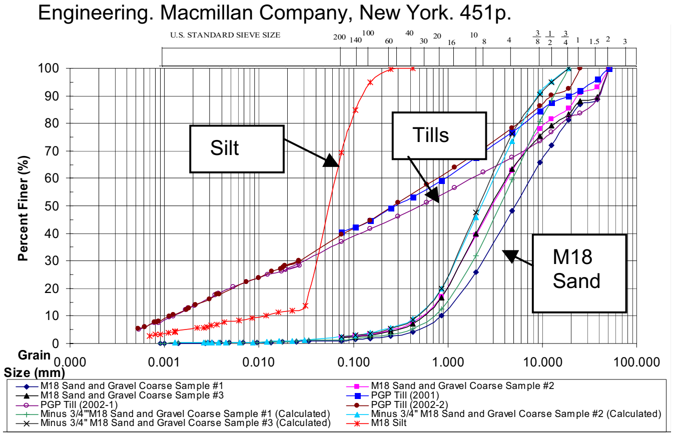

Figure 1. Grain Size Distributions of Test Soils

Table 1. Summary of Hydraulic Conductivity Test Results

GRANULAR MATRIX	SOIL MATERIAL	FALLING HEAD TEST RESULTS: Applied Head (kPa)	Temp. Range (°C)	Average K (cm/s)	ASTM 5084 Temperature Corrected K (cm/s)	CONSTANT FLOW TEST RESULTS: Confining Pressure (kPa)	Temp. Range (°C)	Average K (cm/s)	ASTM 5084 Temperature Corrected K (cm/s)	AVERAGE OF ALL TEMPERATURE CORRECTED Ks (cm/s)
Minus 4 M18 Sand & Gravel (< 4.75 mm)	Minus 4 M18 Sand & Gravel + 5% EnivroGel 8	15-28	19-24	3.30E-09 Run 4	**3.22E-09**					
	Minus 4 M18 Sand & Gravel + 5% EnviroGel 8					32 kPa	21.4-27.5	1.43E-09	**1.30E-09**	
	Minus 4 M18 Sand & Gravel + 5% EnviroGel 8					80 kPa	21.4-27.5	8.95E-10	**8.14E-10**	**1.34E-09**
	Minus 4 M18 Sand & Gravel + 8% EnviroGel 8					32 kPa	21.4-27.5	4.51E-10	**4.10E-10**	
	Minus 4 M18 Sand & Gravel + 8% EnviroGel 8					80 kPa	21.4-27.5	7.85E-10	**7.14E-10**	**5.62E-10**
	2/3 (Minus 4 M18 Sand & Gravel) + 1/3 Silt + 5% EnivroGel 8	12-23	19-24	3.22E-09 Run 5	**3.14E-09**					
	2/3 (Minus 4 M18 Sand & Gravel) + 1/3 Silt + 5% EnviroGel 8					32 kPa	21.4-27.5	7.45E-10	**6.78E-10**	**1.91E-09**
	2/3 (Minus 4 M18 Sand & Gravel) + 1/3 Silt + 8% EnivroGel 8	19-28	19-24	1.38E-09 Run 5	**1.35E-09**					
	2/3 (Minus 4 M18 Sand & Gravel) + 1/3 Silt + 8% EnviroGel 8					32 kPa	21.4-27.5	3.52E-10	**3.20E-10**	
	2/3 (Minus 4 M18 Sand & Gravel) + 1/3 Silt + 8% EnviroGel 8					80 kPa	21.4-27.5	3.68E-10	**3.35E-10**	**5.60E-10**
TILL	PGP TILL	6-29	19-24	3.67E-07	**3.58E-07**					

GRANULAR MATRIX	SOIL MATERIAL	TEST NUMBER	FLEXIBLE WALL TEST RESULTS: Cell Pressure (kPa)	Gradient ( )	Effective Stress (kPa)	Temp. Range (°C)	Degree of Saturation (%)	K-Influent (cm/s)	K-Effluent (cm/s)	Average of K at 19-26 C (cm/s)	AVERAGE OF ALL TEMPERATURE CORRECTED Ks (cm/s)
Minus 3/4" M18 Sand & Gravel (< 19 mm)	Minus 3/4" M18 Sand & Gravel + 6% EnivroGel 8		249	22	50	19-26	95	4.13E-08	3.72E-09	2.25E-08	**2.10E-08**
	Minus 3/4" M18 Sand & Gravel + 8% EnivroGel 8		248	20	50	21-25	96	2.65E-09	1.80E-09	2.23E-09	**2.07E-09**
	2/3 (Minus 3/4" M18 Sand & Gravel) + 1/3 Silt + 5% EnivroGel 8	1	248	20	49	21-25	95	7.08E-08	7.05E-08	7.07E-08	
	2/3 (Minus 3/4" M18 Sand & Gravel) + 1/3 Silt + 5% EnivroGel 8	2	251	22	51	19-25	99	1.23E-08	1.32E-08	1.28E-08	**4.17E-08**
TILL	PGP TILL		251	23	51	19-26	100	2.71E-08	2.70E-08	2.71E-08	**2.52E-08**

Table 2. Summary of Rigid-wall Hydraulic Conductivity Results

Phase		Hydraulic Conductivity K measured			Temperature Corrected K; T = 20C (ASTM D 5084)		Ratio of Phase 1 to Phase x Temp. Corrected Hydraulic Conductivity
Series 1 Influent	**Phase 1 Influent**	1.72E-09	m/s	room temp	1.72E-09	m/s	1.00
	Early Phase 3 Influent	2.37E-09	m/s	at 8C	3.27E-09	m/s	1.91
	Late Phase 3 Influent	8.18E-10	m/s	at 8C	1.13E-09	m/s	0.66
	Phase 4 Influent	8.15E-10	m/s	room temp	8.15E-10	m/s	0.47
Series 1 Effluent	**Phase 1 Effluent**	1.69E-09	m/s	room temp	1.69E-09	m/s	1.00
	Early Phase 3 Effluent	1.20E-09	m/s	at 8C	1.65E-09	m/s	0.98
	Late Phase 3 Effluent	3.87E-10	m/s	at 8C	5.33E-10	m/s	0.32
	Phase 4 Effluent	7.90E-10	m/s	room temp	7.90E-10	m/s	0.47
Series 2 Influent	**Phase 1 Influent**	5.90E-11	m/s	room temp	5.90E-11	m/s	1.00
	Phase 2 Influent	5.80E-10	m/s	at 8C	8.00E-10	m/s	13.57
	Early Phase 3 Influent	6.88E-10	m/s	at 8C	9.49E-10	m/s	16.08
	Late Phase 3 Influent	2.07E-10	m/s	at 8C	2.85E-10	m/s	4.84
	Phase 4 Influent	1.67E-10	m/s	at 13C	2.00E-10	m/s	3.39
	Phase 5 Influent	9.73E-11	m/s	at 8C	1.34E-10	m/s	2.28
	Phase 6 Influent	8.78E-11	m/s	room temp	7.80E-11	m/s	1.32
Series 2 Effluent	**Phase 1 Effluent**	3.99E-11	m/s	room temp	3.99E-11	m/s	1.00
	Phase 2 Effluent	5.80E-10	m/s	at 8C	8.00E-10	m/s	20.04
	Early Phase 3 Effluent	4.36E-10	m/s	at 8C	6.01E-10	m/s	15.05
	Late Phase 3 Effluent	9.48E-11	m/s	at 8C	1.31E-10	m/s	3.27
	Phase 4 Effluent	9.19E-11	m/s	at 13C	1.10E-10	m/s	2.75
	Phase 5 Effluent	4.43E-11	m/s	at 8C	6.11E-11	m/s	1.53
	Phase 6 Effluent	6.69E-11	m/s	room temp	5.94E-11	m/s	1.49

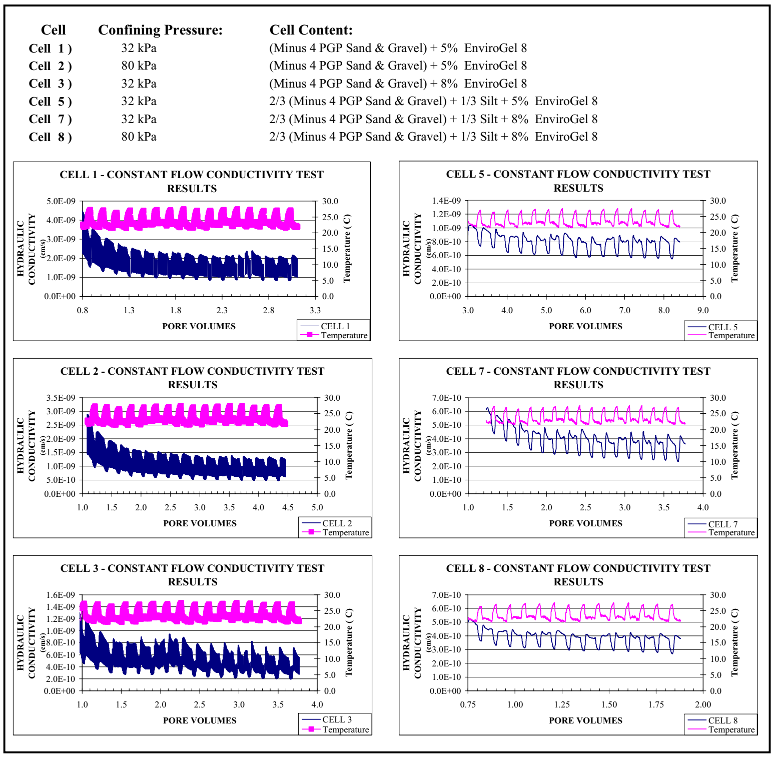

Figure 2. Constant Flow Hydraulic Conductivity Results

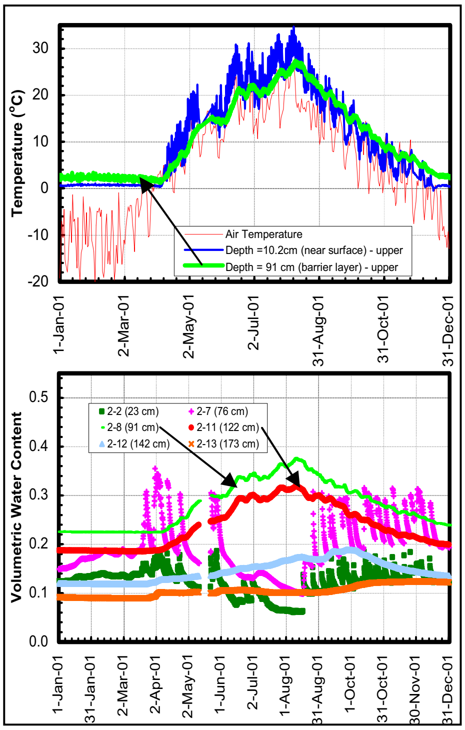

Figure 5. S-B Barrier – Whistle Mine (Adu-Wusu et al., 2002)

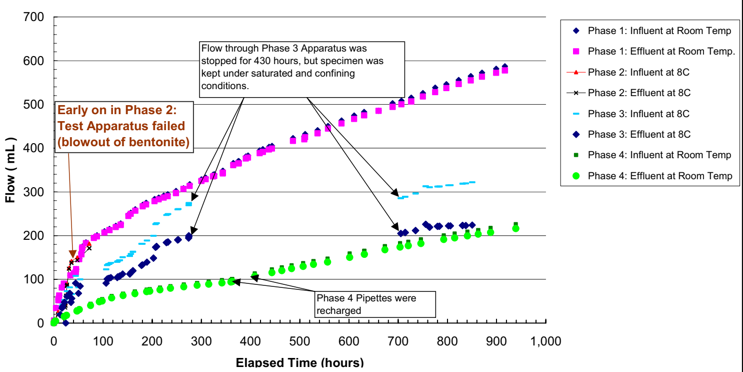

Figure 3. Series 1 Rigid-wall Hydraulic Conductivity Test Results

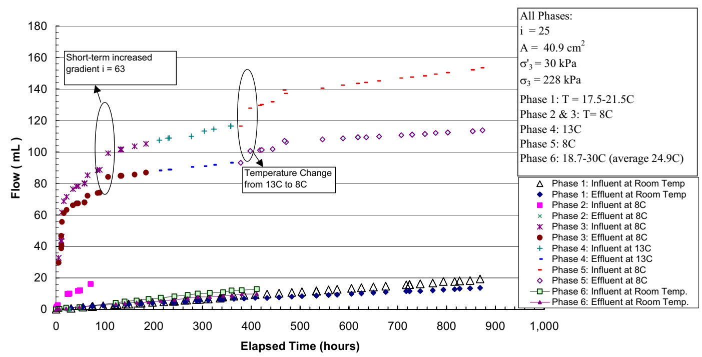

Figure 4. Series 2 Rigid-Wall Hydraulic Conductivitytest Results

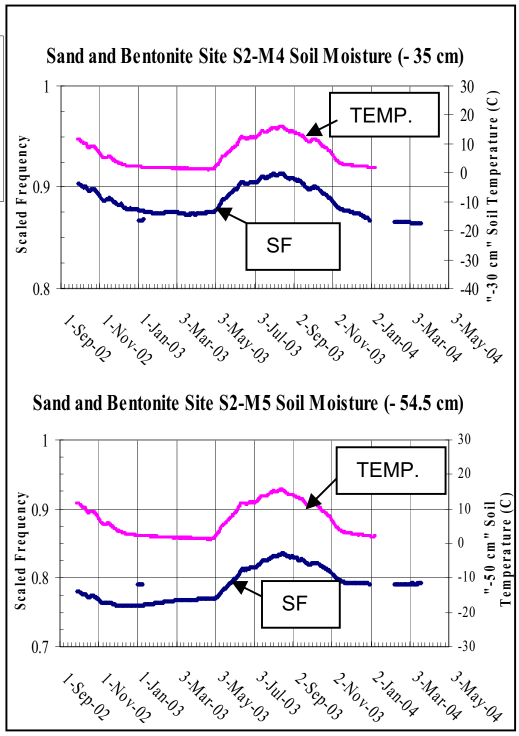

Figure 6. S-B Barrier - Premier Gold Project