The thickness and nature of the rock strata overlying the mine and the condition of the pillars indicates that trough subsidence is likely over southern portions of the landfill. The maximum amount of subsidence is expected to be 0.7 m, and differential settlement of the landfill cap resulting from such uniform subsidence is estimated to be negligible. Design provisions were made to reduce the potential head of 6.1 m acting on the bedrock over the mine roof in order to minimize the flow of contaminated water from the shallow aquifer in the landfill to the coal mine aquifer through rock fractures.

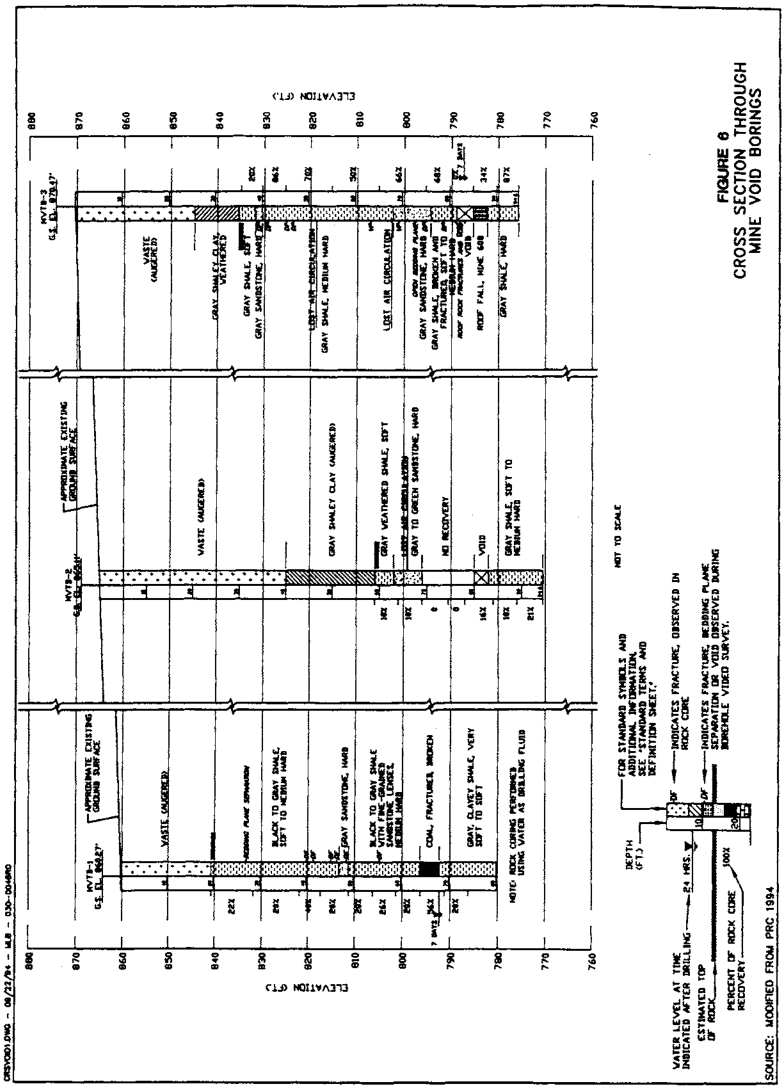

FIGURE 6
CROSS SECTION THROUGH MINE VOID BORINGS

GROUNDWATER INVESTIGATION AND DESIGN

The shallow aquifer in the landfill was tested to determine the amount and quality of water that might be introduced into the coal mine aquifer. In addition, background groundwater quality and coal mine aquifer water quality were measured in selected monitoring wells. The potentiometric head in the shallow aquifer was measured by monitoring water levels in two pumping test wells, eight observation wells, and eight piezometers installed in the shallow aquifer.

Two aquifer pump tests were conducted to define the hydraulic conductivity and specific yield in the shallow aquifer. Two 6-inch diameter polyvinyl chloride pumping wells were installed in the mine spoil underlying waste at the north side of the site. Four piezometers were installed at various distances from each of the pumping wells to determine drawdown. Antecedent water levels were measured in all wells and nearby ponds for three days prior to the tests to establish baseline water levels.

The testing program included slug permeability tests in all wells prior to aquifer testing, followed by step-drawdown pumping tests and constant rate pumping tests. Step-drawdown data were evaluated using Bierschenk's method (Driscoll 1986), which indicated pumping rates of 7.5 and 19 L/min for PTW-1 and PTW-2, respectively. The constant rate tests were run for 38 and 48 hours at actual pumping rates averaging 6.8 and 19 L/min.

Hydraulic conductivity values were calculated using Boulton's method (Kruseman and Ridder 1989), which assumes an unconfined aquifer with delayed yield, and Walton's method (Fetter 1980), which assumes a semiconfined aquifer and enables the evaluation of leakage. Water levels were measured for a 26-hour recovery period after the termination of pumping, and the data were evaluated using the Theis recovery method (Driscoll 1986). This method yields transmissivity and provides an independent check of the previous methods because it is not dependent on constant pumping rates. Averaging the results of the Boulton, Walton, and Theis methods discussed above yielded hydraulic conductivities at the pumping wells of 5.9×10^{-4} and 1.5×10^{-3} centimeters per second. Specific yields ranged from 0.10 to 0.24.

Radius of influence was evaluated by distance-drawdown graph analysis and by estimating potentiometric contours at the end of pumping. The radius of influence of each pump test well was estimated to range from 36 to 49 m. Based on these data, the shallow aquifer would be dewatered by installing four wells drilled to the top of the bedrock surface and screened through the bottom 3 m of landfill waste and mine spoils overlying the bedrock. The pumping level would be approximately 1.5 m above the existing mean coal mine aquifer elevation to prevent the withdrawal of water from this aquifer. Well level controls would be used to maintain this pumping level. Shallow aquifer dewatering would remove contaminated water from this aquifer and reduce the head on the coal mine aquifer.

COAL MINE AQUIFER WATER QUALITY MONITORING AND CONTINGENCY PLAN

To protect potential coal mine aquifer users from contaminants in the shallow aquifer, coal mine water quality will be monitored in eight wells downstream of the landfill. If the water in the coal mine is contaminated, a contingency plan will be implemented. This plan consists of construction of a grout curtain in the coal mine just outside the southeast boundary of the landfill and pumping and treating the water in the coal mine aquifer upstream of the curtain. The grout mix for this curtain will be designed to prevent adverse effects on coal mine water quality and to create a low-permeability wall.

SUMMARY

The RD studies at the Fultz site defined landfill limits and provided data needed to estimate the surface subsidence resulting from coal mine voids underlying the landfill. Based on the surface subsidence estimate, it was determined that 1) the landfill cap would not be adversely affected by differential settlement and 2) that stabilizing the mine voids is unnecessary. This resulted in cost savings of more than $12 million. The hydraulic characteristics of the shallow aquifer overlying the coal mine aquifer was defined using pump tests, and a groundwater extraction system was designed. A contingency plan was also developed to prevent potential coal mine aquifer contamination resulting from the movement of contaminated water through bedrock fractures underlying the site.

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Chapter 10

Gasoline Transport and Air Venting Removal in a Fractured Clayey Till: A Laboratory Study

Scott M. Mackiewicz, Bruce H. Kjartanson, and John M. Pitt

INTRODUCTION

Approximately 295,000 leaking petroleum hydrocarbon (PHC) underground storage tanks in the United States require remediation (U.S. EPA 1993). Many of these tanks are located in surficial, clayey till of the northern United States and Canada. Due to physical weathering processes, the top 3 to 4 meters of these deposits are fractured and fissured and possess values of hydraulic conductivity orders of greater magnitude than the unweathered material. Flow through these interconnected fractures and fissures can lead to increased mobility and spreading of PHC contamination (McKay et al. 1993).

This paper describes a laboratory study of gasoline transport characteristics in a fractured clayey till and the effectiveness of air venting for removing the gasoline from fractured materials. A series of flexible wall permeability tests (column tests) were performed on undisturbed samples of a weathered clayey till. The column tests were performed at confining pressures equal to the measured in situ lateral earth pressures using a $CaSO_4$ solution, a $CaCl_2$ tracer solution, gasoline, and air as the permeants. The purposes of the $CaSO_4$ solution permeation tests were to examine the hydraulic conductivity properties of the undisturbed clayey till samples using a representative groundwater solution and to compare them with data from similar lab studies. The $CaCl_2$ solution and gasoline permeation tests allowed determination of important transport parameters such as breakthrough porosities (i.e., the pore volume of flow at which a contaminant first appears) and comparison of travel times for a conservative tracer, Cl^-, with that of a petroleum hydrocarbon, gasoline. The breakthrough porosity is an important parameter in assessing contaminant transport in soil/water/contaminant systems (McBride et al. 1987). Air permeation tests were

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performed at the completion of the gasoline permeation phase to determine air venting removal characteristics of the fractured clayey tills.

TEST SITE AND MATERIALS

The clayey till test samples were obtained from an Iowa State University research farm located in central Iowa, approximately 18 kilometers west of Ames. The fractured, clayey till samples were obtained from the weathered zone of the Des Moines lobe of the Wisconsin glacial period, at depths from 1.5 m to 2.6 m below ground surface. Previous subsurface explorations at the site indicated that the weathered zone extends to a depth of approximately 4 m (Jones et al. 1992). Grass covers the site with grass roots and remnant root channels present to depths of approximately 2.0 m. The color of the till is brown mottled gray with iron oxidation halos around many of the channels (i.e., macropores) and fractures. The fracture network consists of fractures and macropores in a near vertical orientation with spacings ranging from about 2 cm to 7 cm (Lee 1991). Representative properties of the till are shown in Table 10-1.

Table 10-1. Summary of Glacial Till Properties.

Depth below ground surface	1.5 - 2.6 m
Natural moisture content	16.2 ± 1.2%
Field saturation	96 ± 2.1%
Porosity	0.30 ± 0.04
Specific gravity	2.69
Clay size fraction	24 ± 3.1%
Silt size fraction	31 ± 1.9%
Sand size fraction	45 ± 8.1%
Liquid limit (LL)	36 ± 3.2%
Plasticity index (PI)	24 ± 3.9%
Unified classification	SC, CL
Organic content	0.17 ± .04 %

EXPERIMENTAL METHODS

A flexible wall permeameter system, as described in Daniel (1994) and ASTM D 5084 (1993), was used in this laboratory study to eliminate the effects of side wall flow that could occur in fixed wall permeameter testing and to allow test samples to be tested at stress conditions representing in situ stress conditions. It consisted of a control board, permeability cell, toxic interface, and burette systems. The toxic interface was placed in line between the measuring influent burette and the sample influent port. This interface prevents the movement of contaminant into the measuring board by using a Viton-coated membrane to separate the two chambers of the interface. The membrane moves with flow but prevents cross contamination. Components in contact with the gasoline permeant were composed of either Viton, Teflon, or stainless steel.

The 10.2 cm diameter test samples were extruded and trimmed to a length ranging from 10 cm to 14 cm. The ends of the samples were carefully trimmed with a knife, with the last few millimeters being chipped off to prevent smearing of visible vertical channels and fractures. Each of the test samples contained visible remnant root channels and vertical fractures in an apparent interconnected network that could potentially provide a pathway for preferential flow. After measuring the sample dimensions, the sample was weighed and placed within the permeation cell. Porous stones were located on the top and bottom of the sample, and a thin (0.076 mm) Teflon sheet was wrapped around the sample to protect the Viton-coated membrane during consolidation. A Viton membrane was then stretched over the sample by using a vacuum actuated membrane expander and sealed with rubber O-rings. The sealed chamber was filled with deaired water and the consolidation phase initiated. The confining pressure was set at 96.5 kPa, corresponding to the measured in situ lateral earth pressures at the time of sampling. Measurements of water outflow and volume change were recorded and compared to detect any leaks in the system.

On completion of the consolidation phase, the fractured till samples were permeated with a 0.01N $CaSO_4$ solution, a 0.025M $CaCl_2$ solution, or gasoline. A summary of the testing program is presented in Table 10-2.

Table 10-2. Summary of Testing Program.

Test Performed	Sample Number					
	B2-2, #1	B2-3, #1	B4-3, #1	B4-3, #2	B6-3, #2	B7-3, #2
$CaSO_4$ solution - conductivity	X	X	X	X	X	X
$CaCl_2$ solution - tracer					X	X
Gasoline permeation	X	X	X	X		
Air venting	X	X	X	X		

All permeation tests were performed under a constant gradient of 10, following ASTM D-5084. The influent and effluent volumes were measured by reading the levels of the air/water/gasoline interfaces in the burette systems. The influent line was connected to the top of the sample and the effluent line was connected to the bottom of the sample. Overall sample volume change was measured using a burette connected to the cell chamber. For the gasoline permeation tests, the sample was allowed to gravity drain for 8 to 12 hours prior to initiation of the air venting phase. At the end of the gravity drainage period, air was vented through the sample from top to bottom under an applied gradient of 10. The volume of air, water, and gasoline being expelled from the sample were measured by reading the levels of the air/water/gasoline interfaces in the burette systems. The recorded volumes were used to determine the amount of each phase remaining in a sample's pore volume using mass balance. The gasoline permeation and air venting times were monitored; in addition, soil samples for benzene, ethyl benzene, toluene, and xylene (BETX) analysis were obtained from the fractures and matrix of the permeameter samples at the completion of the air venting phase.

TEST RESULTS AND DISCUSSION

Consolidation Phase Results

All samples were consolidated under a confining pressure of 96.5 kPa. Hydraulic conductivity values were computed for each of the samples using Terzaghi's consolidation theory. The consolidation phase yielded hydraulic conductivity values, which essentially represent the hydraulic conductivity of the matrix, ranging from 1.4 x 10^{-9} to 8.3 x 10^{-9} cm/s (see Table 10-3). Other comparisons of hydraulic conductivity values determined from consolidation data on weathered tills from the Laidlaw Site in Sarnia, Ontario have been reported to range from 1.2 to 2.1 x 10^{-8} cm/s (McKay et. al. 1993).

$CaSO_4$ Solution Permeation Tests

Hydraulic conductivity values ranging from 1.4 x 10^{-6} to 2.1 x 10^{-5} cm/s were determined from the $CaSO_4$ solution permeation tests (see Table 10-2). These values are 2 to 3 orders of magnitude higher than the matrix hydraulic conductivity values measured during the consolidation phase, which suggests preferential flow through the fractures and/or macropores during the permeation tests. Other comparisons of laboratory hydraulic conductivity values determined from weathered tills have been reported. The reported laboratory hydraulic conductivity values for weathered till from the Laidlaw Site in Sarnia, Ontario were on the order of 10^{-6} to 10^{-7} cm/s (Middleton et. al. 1990; Goodall and Quigley 1977). The variation in calculated hydraulic conductivity values from our study and those performed by Goodall and Quigley and Middleton et. al. could be attributed to the varying clay content, degree of weathering, and other factors that contribute to fracture development. As noted, the weathered tills used in the studies performed by Goodall and Quigley and Middleton et. al. were obtained from the Laidlaw site in Sarnia, Ontario and contain approximately 45 to 55% clay sized particles as compared to approximately 25% for the tills examined in this study.

Table 10-3. Summary of Consolidation and $CaSO_4$ Permeation Test Results.

	Sample Number			
Test Result	**B2-2, #1**	**B2-3, #1**	**B4-3, #1**	**B4-3, #2**
Matrix hydraulic conductivity, cm/s	1.4×10^{-9}	3.7×10^{-9}	8.3×10^{-9}	1.7×10^{-9}
Hydraulic conductivity, cm/s	1.4×10^{-6}	3.0×10^{-6}	8.4×10^{-6}	2.1×10^{-5}

Fracture aperture, porosity, and flow velocity were computed using "the Cubic Law" relationships and the values for hydraulic conductivity calculated from the laboratory test results. The calculations of fracture aperture, porosity, and velocity are based on the assumptions that the fractures are vertical, smooth, and of constant aperture, and flow is laminar. From Snow (1968), the fracture aperture, 2b, can be determined by

$$2b = \left(\frac{12K\mu}{N\rho g} \right)^{1/3} \tag{10-1}$$

where ρ = fluid density, g = gravitational constant, K= hydraulic conductivity, N = fracture density (number of fractures per unit length), μ = dynamic viscosity of the fluid.

The fracture porosity, n_f, following Snow (1968), can be calculated by

$$n_f = 5.45 \left(\frac{N^2 K\mu}{\rho g} \right)^{1/3} \tag{10-2}$$

The spacing of the vertical fractures in the weathered till of the Des Moines Lobe, reported by Lee (1991), ranges from 2 to 7 cm. This range of fracture spacing correlates to a fracture density ranging from 0.5 to 0.14 fractures/cm. Using the fracture densities in conjunction with the calculated hydraulic conductivity values, Equations 10-1 and 10-2 were used to compute the fracture aperture and fracture porosity values, as shown in Table 10-4.

Table 10-4. Summary of Computed Fracture Properties.

Test Result	Sample Number B2-2, #1	B2-3, #1	B4-3, #1	B4-3, #2
Fracture aperture, μm	32-49	42-63	59-89	80-120
Fracture porosity ($x10^{-4}$)	17-38	21-50	30-70	41-95

By comparison, McKay et. al. (1993) found fracture apertures ranging from 5 to 43 μm and fracture porosities ranging from 0.3 to 10 x 10^{-4} for fracture spacings ranging from 0.02 to 1.0 meters, and hydraulic conductivity values ranging from 5 to 13,000 x 10^{-8} cm/s for weathered tills located at the Laidlaw Site near Sarnia, Ontario.

The average fracture velocity, v_f, can be determined using Darcy's equation with an adjustment for porosity (Desaulniers and Cherry 1989)

$$v_f = \left(\frac{Ki}{n_f} \right) \tag{10-3}$$

where (i) is equal to the hydraulic gradient. Fracture velocities computed for the samples tested in this program ranged from 4.3 to 61 x 10^{-3} cm/s (3.7 to 52.7 m/day), based on a hydraulic gradient of 10. By comparison, McKay et. al. (1993) reported fracture flow velocities ranging from 5 to 24 m/day, based on a gradient of 0.24. The corresponding velocities are a function of the gradient at which the tests were performed, thus larger velocities were anticipated in the experiments performed at higher gradients.

The relatively high fracture flow velocities in conjunction with a small fracture porosity indicate that a majority of flow could occur through the fractures and result in faster contaminant breakthrough times.

$CaCl_2$ Tracer Tests

To examine the transport characteristics of the weathered clayey till, Cl^- tracer tests were performed on two samples, B6-3, #2 and B7-3, #2, which were initially permeated with a 0.01 N $CaSO_4$ solution. The chloride tracer, a de-aired 0.025 M $CaCl_2$ solution, was used because of the non-sorbing characteristics of Cl^- ions. The effluent from each sample was collected at approximately equal increments of flow for a total of two pore volumes of flow and analyzed for Cl^- concentration using a Hach CD-DT digital titration test kit. The resulting breakthrough curves were plotted and used for the determination of the one-dimensional advection, dispersion, and diffusion characteristics of the two tested samples (see Figure 10-1). It may be noted that the two curves are quite similar.

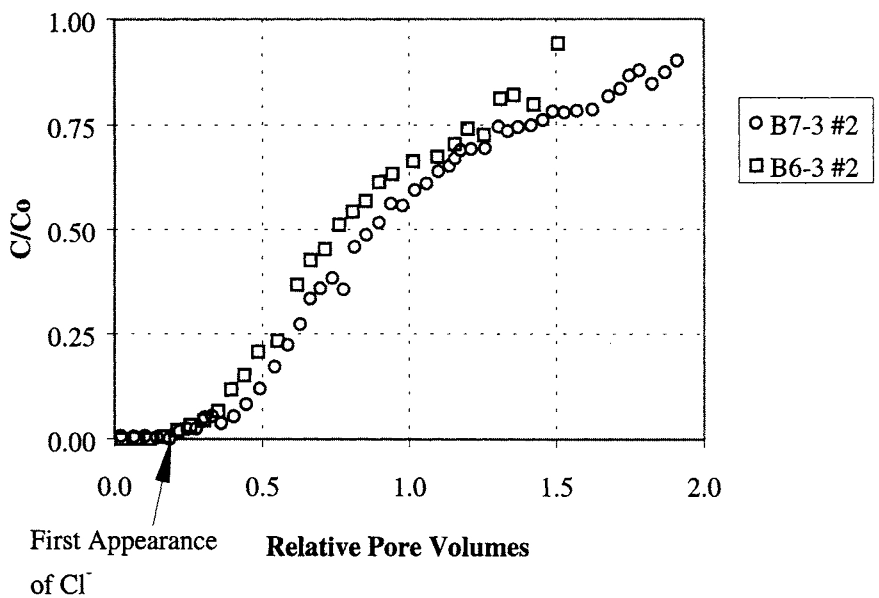

Figure 10-1. Cl^- Breakthrough Curves.

The breakthrough porosity and hydrodynamic dispersion coefficients were determined from analysis and interpretation of the breakthrough curve data. The breakthrough porosity is the porosity (i.e., pore volumes of flow) that accounts for the first appearance of a solute or contaminant through a porous medium and will dictate the transport time for first appearance of a contaminant at a specified point within a porous medium. The breakthrough porosity was computed by multiplying the pore volumes of flow at which the Cl^- first appeared at the end of column by the total porosity of the sample (McBride et al. 1987). The breakthrough curves were analyzed using a numerical simulation of the one-dimensional advection-dispersion equation to determine the hydrodynamic dispersion coefficient. The numerically calculated breakthrough curves were fitted to the experimental data by adjusting the dispersivity and flowrate variables accordingly during computer simulation. The trials continued until a best-fit solution was achieved with the resulting dispersion coefficient being reported.

Results of the two samples tested (see Table 10-5) indicate that the breakthrough porosity for this fractured clayey till is approximately 14.25% of the total porosity or 4.2 to 4.7%. For example, the breakthrough porosity for sample B6-3, #2 was computed by multiplying the total porosity (0.296) by the breakthrough pore volume (0.142), which equals 0.042 (4.2%). The hydrodynamic dispersion coefficient ranges from 3.7 x 10^{-5} cm^2/s to 4.5 x 10^{-5} cm^2/s (see Table 10-5) while the hydraulic conductivity values of samples B6-3, #2 and B7-3, #2 are 1.9 x 10^{-7} cm/s and 2.4 x 10^{-7} cm/s, respectively, which are two orders of magnitude higher than the matrix values.

Table 10-5. Summary Cl^- Tracer Test Results.

	Sample	Number
Test Result	**B6-3, #2**	**B7-3, #2**
Matrix hydraulic conductivity, cm/s	1.7 x 10^{-9}	3.9 x 10^{-9}
Hydraulic conductivity, cm/s	1.9 x 10^{-7}	2.4 x 10^{-7}
Total porosity	0.296	0.256
Cl^- breakthrough porosity	0.042	0.047
Hydrodynamic dispersion coefficient, cm^2/s	3.7 x 10^{-5}	4.5 x 10^{-5}

The fracture properties for these samples were also computed; the fracture aperture ranged from 16 to 27 μm; the fracture porosity ranged from 9 to 21 x 10^{-4}; and the fracture velocity was computed to range between 9.6 x 10^{-4} and 26 x 10^{-4} cm/s. Based on the computed fracture properties, it would be anticipated that transport through the weathered, fractured till materials would yield Cl^- breakthrough curves steeper than those shown in Figure 10-1, with the center of mass of the Cl^- plume (C/Co=0.5) showing breakthrough at a lower relative pore volume of flow. The flattening and apparent retardation of the Cl^- ions is most likely being caused by diffusion into the porous matrix as discussed by Grisak et. al. (1980) and Grisak and Pickens (1980). Entrapment of the Cl^- ions in dead-end pores or unconnected fractures, and diffusion into these same structures could also contribute to the apparent retardation.