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MECHANISMS AND PATTERNS OF LEACHATE FLOW IN MUNICIPAL SOLID WASTE LANDFILLS*

CHRIS ZEISS, PH.D., P.ENG.

MARK UGUCCIONI, B.SC.ENG.

University of Alberta

ABSTRACT

Vertical moisture flow through municipal solid waste landfills has been represented primarily as one-dimensional Darcian flow in homogeneous media, though channeling of flow through large pores in the waste has been shown to be an important flow mechanism at high loading rates. Channeling of flow through test cells containing compacted municipal solid waste appears to be a significant flow mechanism even at low infiltration rates (0.17 mm/hr) and after steady-state conditions (infiltration = discharge) have been reached. Practical field capacity is significantly lower at 0.0996 than the HELP model field capacity of 0.294, while the average experimental porosity is identical to the HELP default value (0.52). Experimental unsaturated hydraulic conductivity values are one to two orders of magnitude higher than the HELP default value at field capacity (1.2×10^{-7} cm/s), however, these values appear to be influenced by the experimental loading rate. In order to better understand the mechanisms and patterns of moisture flow in solid waste, more detailed information on the channels such as nature of flow in the channels and the spatial distribution of the channels is needed. Also, to more accurately represent the physical system, any new leachate generation models should account for both Darcian and channeled flow.

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INTRODUCTION

Water percolation through the waste layers in municipal solid waste landfills determines the volume and flow rate of leachate. The flow patterns and velocity also affect the biodegradation processes and, simultaneously, the mass transfer of contaminants into the leachate. Therefore, the flow patterns and characteristics determine both quantity and quality of landfill leachate over time and warrant careful analysis and prediction.

The popular water balance models (HELP in particular) initially assumed one dimensional vertical Darcian flow. Recently, however, observations have shown significant flow channeling through municipal solid waste layers, albeit measured with high infiltration rates [1]. The pore size distribution index, λ, the slope of the linear function of the logarithms of effective saturation and capillary pressure, too, differs from HELP's default value and affects the estimates of the Campbell equation linking saturated and unsaturated hydraulic conductivities. These findings result in lower field capacities and breakthrough times and higher unsaturated hydraulic conductivities and leachate discharge rates than obtained from models that assume homogeneous Darcian flow.

Low infiltration rates, however, are less likely to lead to pronounced channeling than high rates, because slow application of water will allow more time for the absorption into waste particles, and capillary action in the smaller pores redistribute moisture so that the matrix flow regime in the waste layer may contribute more to the overall discharge. As a result, channeling may only occur in the initial phase of landfilling. Slow increases in moisture content may form a wetting front that then moves according to the Richards equation for Darcian flow in unsaturated zones. The resulting flow velocities and flow rates will consist of channeled and porous flow components and will therefore result in moisture movement fronts that will more intensively leach and react with biodegradation mechanisms than channeled flow would. The purpose of this research is to determine the flow patterns and flow characteristics to test the principle flow mechanisms of leachate through municipal solid waste layers.

BACKGROUND, THEORY AND LITERATURE REVIEW

Most commonly used methods of predicting leachate generation from municipal solid waste landfills apply a water balance approach with a simplified set of equations to predict moisture movement through the solid waste layer (see e.g., [2]). The HELP model, for example, represents the moisture movement through the waste layer as one dimensional Darcian flow through a homogeneous porous matrix in the unsaturated drainage domain [2]. The hydraulic gradient is assumed to be constant with value of unity throughout the flow field. The field capacity, porosity, capillary pressure and pore size distribution are used to correct the saturated hydraulic conductivity for unsaturated conditions by applying a modified version of the Richards equation to account for two phase flows of water and air in porous medium as developed by Brooks-Corey [3] and Campbell [4]. While water balance approaches [5, 6], have been shown, under some circumstances for averaged flows over long periods of time, to provide estimates of discharge rates in the order of 1.32 to 5.4 percent within measured leachate discharge quantities, several observations (see e.g., [7]) of flows in soils have noted channeling or fingering of flows through narrow flow pathways. Specifically for solid waste [8-11], note channeled flows. Very recently, Zeiss and Major measured flow channel cross-sectional areas, practical field capacities, and estimated practical unsaturated hydraulic conductivities at field capacity in the waste layer of 1.7×10^{-2} to 1.2×10^{-3} cm/s, fully 4 to 5 orders of magnitude higher than the suggested HELP model default values [1].

Several attempts have been made to determine accurate waste and flow characteristics in order to account for channeling. Korfiatis et al. determined with lab scale tests that the field capacity continues to increase after drainage has started, indicating that secondary absorption and capillary action redistribute moisture into the waste from the primary flow channels [8]. They note further that the time it takes for the field capacity to be exceeded within one layer varies and that this, too, illustrates the channeling effects. Their results suggest a non-linear relationship between soil moisture content and capillary pressure. Though, as expected, drainage begins when the capillary pressure throughout the column reaches zero, in the test cells with the initial moisture content of the waste, at about 220 hours after precipitation started. In test cells where the refuse was brought to field capacity, the drainage began thirty hours after precipitation. The large difference in breakthrough time for waste at as-received and at field capacity moisture contents indicated to the authors that the redistribution process from the channels into the waste layer was very slow. The apparent hydraulic conductivity of the waste was measured at 1.1×10^{-4} to 7.7×10^{-4} cm/s for as-received and field capacity moisture contents, respectively. A study within a similar thrust [1] measured distinct channeling in the flow patterns and determined that key parameters of field capacity and breakthrough time were significantly lower in channeled flow through a 1.8 m thick waste layer than the HELP default values. Further, the apparent unsaturated hydraulic conductivity and the flow velocity were significantly higher than the HELP model's values. The apparent hydraulic conductivity ranged from 1.1×10^{-3} to 2.1×10^{-2} cm/s and fell within the range of Korfiatis et al. values for saturated hydraulic conductivity. While these results show that channeling results in different values for key waste and flow characteristics, they do not illuminate the actual flow mechanisms and thus implicitly still assume a Darcian flow. Beven and Germann discuss flow through soil layers as two separate, but interacting domains: 1) the channeled flow through macropores and 2) the Darcian flow through the matrix (or micropores) [7]. Although the difference between macro- and micropores is not uniquely defined by aperture size or capillary pressure, practical flow tests in soil show that the differences in breakthrough times are as large as one to two days for macro- to six months for matrix flows in a soil column of 220 cm height. Their discussion suggests a two domain flow model that comprises (see Figure 1) the precipitation P(t), the surface flow O(t), the direct infiltration components $I_1(t)$ from the surface into the matrix and $I_2(t)$ from the channels to the matrix, and, finally, $S_1(t)$ the seepage into the channels at the surface and $S_2(t)$ the flow in the channels. While Beven and Germann do not attempt to relate their conceptual model to the water balance

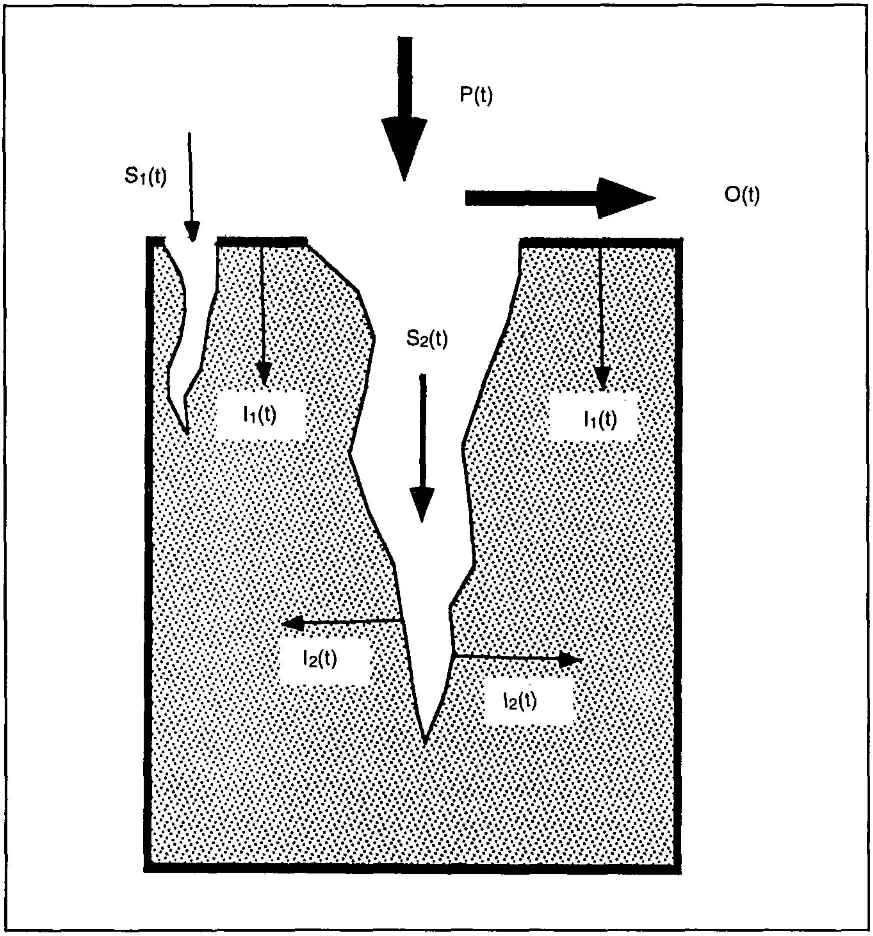

Figure 1. Two domain flow model.
P(t): precipitation; O(t): surface flow; $I_1(t)$: direct infiltration into matrix; $I_2(t)$: infiltration from channels into matrix; $S_1(t)$: direct seepage into channels; $S_2(t)$: flow into channels.

model, they identify five components of the two domain flow mechanisms that need to be analyzed:

1. The nature of the flows in the matrix which are usually modeled as Darcian, with the Richards correction for degree of saturation, but might also be affected by air pressure in the matrix;
2. The nature of the flows in the macropores, which are likely governed by hydraulics, so that flows might occur as "rivulets," laminar or turbulent mechanisms and might be affected by the irregular geometry of the connected pores;
3. The spatial and temporal characteristics of the macropore network that consists of variations in size, irregularity of shape and "connectivity," and changes of size, shape and connectivity with time caused by settlement, leaching, and biodegradation;
4. The interactions between macro- and matrix domains which determine the redistribution of water from the channels to the matrix (and vice versa) and, as a result, the ratio of flow contributions by the channels and the matrix;
5. The initiation of flows in the macropores which depends on the precipitation rates and overland flow, the infiltration rate of the matrix and the local surface storage capacity.

Although channeling and its effects on leachate flow characteristics have been mentioned [8-11] and observed [12], the concept of two domain flows has not been commonly applied to the prediction of leachate flows through municipal solid waste layers in landfills. The accurate understanding and modeling of flows through waste layers is, however, essential for the prediction of peak discharges, and the correct design of leachate collection and storage systems. Further, the accurate estimation of surface area and contact time of water with solid particles in landfills is essential for understanding of mass transfer and equilibrium reactions in leachate generation.

This article presents initial results to identify and characterize flows and suggests the next research steps to derive and test predictive models for flows through waste layers.

Test Hypotheses and Objectives

Based on the conceptual understanding of the flow mechanism in waste, the thrust of this article is to measure basic waste and flow characteristics over time and space and estimate the principal values for a unit volume of municipal solid waste to represent both matrix and macropore flow contributions. The investigation and prediction of flow mechanisms, as suggested under points 1 and 2 of [7] will be addressed in the next stage of research.

The research reported in this article tests three hypotheses that pertain to points 3, 4, and 5 of [7] (see above):

1. The development of flow patterns and moisture content over time—determines whether leachate movement occurs predominantly through channels or through matrix flows at very low moisture loading rates. Flow distribution over the cross-section of a waste column should be constant in homogeneous matrix flow, while narrowly constricted flow channels will appear if channeled macropore flows predominate. While channeled flow is distinct for high moisture loading rates [1], low application rates will allow more time for redistribution from macropores into the matrix and, hence, eventually a more pronounced development of matrix flow. The null hypothesis here states that, at steady-state, channeling will not be significant and, instead, that homogeneous moisture movement will occur as a flow front. The spatial flow pattern is measured with three flow sensor plates inserted at three different heights in test waste columns. Constant, homogeneous flow would be indicated by all sensors, while under channeling only a small number of sensors would indicate flow. Should initial channeled flow then develop into matrix flow through redistribution, then a larger fraction of flow sensors is expected to indicate a flow over a larger cross-section as time progresses until steady state conditions are reached. Moisture content and capillary pressure are predicted to vary over the cross-section, but then with time to become more evenly distributed as absorption and capillary suction redistribute moisture to the initially drier matrix volumes. Thus, moisture content and flow should initially be high around channels and should then increase to an equal and constant value throughout the cross-section with time if redistribution effectively increases matrix flow to the point where homogeneous Darcian flow through the matrix becomes the significant flow mechanism.
2. The variation of waste and flow characteristics over space will also reflect the main flow mechanisms in the waste layer. The flow cross-section will vary vertically in the waste column and might shift horizontally as flow channels develop and redistribution occurs. Thus, tests of preferred areas and location of flow throughout the waste will indicate macropore flow. Similarly, moisture content will vary horizontally and vertically if flow occurs in distinct channels. With time, moisture contents should become constant throughout the column if matrix flow predominates once field capacity is reached. The null hypothesis therefore states that under low moisture loading conditions and steady state in- and outflow balances, flows, moisture content and capillary pressures should be constant throughout the waste column. The key variables of flow area, moisture content and capillary pressures are measured at four locations over each horizontal cross-section at three heights in the test column.
3. The seven most important waste and flow characteristics are measured in three test waste columns in order to establish representative values for bulk volumes of municipal solid waste layers. Particle sizes, compaction ratio

and porosity are determined to characterize the waste and compaction. Flow areas, field capacity, moisture content and capillary pressure are determined as spatial and temporal variables for the first two tests listed above and are used to test the Campbell relationship between capillary pressure and effective situation. Most importantly for practical use by waste engineers, however, is the determination of the "bulk" values for the breakthrough time, apparent unsaturated hydraulic conductivity and discharge rates at first drainage as well as at steady-state drainage. These values can serve as baseline values for comparison with conventional (HELP) default values in order to account for realistic channeled flow conditions through waste.

The test methodology, procedures and results are presented in the following section.

METHODS AND PROCEDURES

Experimental Designs

Three test cells were used for the experiment. The first run, utilizing one cell was started in September 1993, while the other run, using the two other cells began in March 1994. Each cell consisted of two fifty-five-gallon steel drums welded together to form a cylinder 1.8 m high with a diameter of 0.57 m. The cells had a sloping bottom and discharge valves to allow free drainage of water (see Figure 2). Municipal solid waste and instrumentation were first loaded into the cells, followed by, approximately 7.5 cm of cover soil. Each cell was then covered with a 100 kg concrete compression plate to simulate landfill compaction. Holes at depths of 1/9, 1/3, and 2/3 (21 cm, 67 cm and 106.5 cm) cell height were drilled into each cell to facilitate the placement of instrumentation.

Instrumentation consisted of tensiometers ("Jet Fill" series 2725, Soilmoisture Equipment Corp.), and flow sensor plates. The tensiometers provided a measure of the suction head in the waste column, as well as an indirect measure of moisture content, since at a suction head of zero the medium surrounding the tensiometer is completely saturated. Flow sensor plates enabled the observation of moisture movement through the column. The sensor plates consisted of a circular frame with a wire grid through which porous cups were evenly strung. Two electrodes placed in each cup were attached to a light panel on the outside of the cell. When water flowed through a cup a complete circuit would be formed and the corresponding light emitting diode (LED) would be activated. When water completely drained from a cup, the LED would deactivate. Twenty-one 1.3 cm diameter porous cups were strung to each plate. The chosen instrumentation allows the relationship of moisture content and capillary pressure with cumulative moisture loading to be determined. Also, the instrumentation allows for the observation of flow patterns over time and cumulative moisture loading.

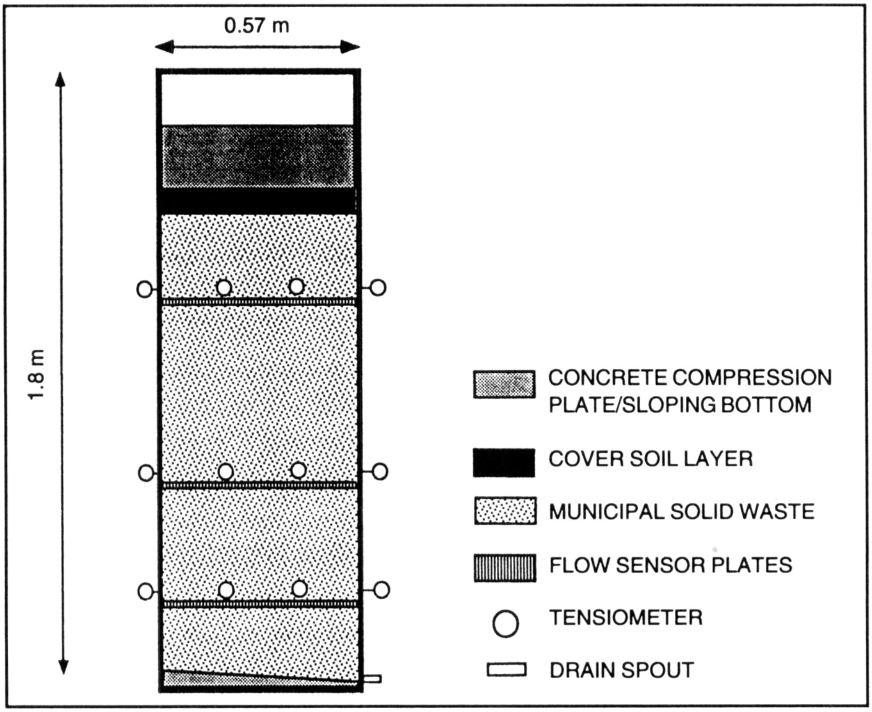

Figure 2. Experimental waste cell.

Municipal solid waste (MSW), generated in a residential area, was obtained from an Edmonton area landfill. The waste was hand picked from freshly deposited loads on the tipping face. The tipping face was grided off in 1 m squares and waste was collected from one square which was randomly selected. Before addition of MSW to the cell, particle size distribution and initial moisture content determinations were performed on representative 3 to 5 kg samples of MSW. Waste was weighed as it was loaded into a cell, and was continuously tamped down in the cell with a 25 kg metal plate. The setup of the instrumentation differed slightly between runs. For the first run three tensiometers were placed at three different levels corresponding to the instrumentation holes at 1/9, 1/3, and 2/3 the cell height. One tensiometer at the top and middle levels was placed inside a plastic bag to determine the changes in capillary pressure within the bag under continuous moisture loading. Three sensor plates were also added at approximately 65 cm, 122 cm and 160 cm from the bottom of the cell. The cover layer of soil was placed directly above the top level sensor plate. For the second set of experimental runs, waste was added to approximately 7.5 cm below the instrumentation holes. A flow sensor plate was then placed in the cell, followed by four tensiometers. Each tensiometer was placed in the center of the different "quadrant" of the circular cell. The above procedure was performed for each level of instrumentation. One tensiometer in the middle level in each cell was placed inside of a plastic bag in order to determine if waste inside of an enclosed waste object would become saturated with continuous moisture loading. For both experimental runs, waste was added to approximately 160 cm above the base of the cell. Approximately 7.5 cm of clay cover soil was then placed on top of the waste. A 100 kg concrete compression plate was then placed on the column. Before the start of the test each column was allowed to stand for approximately seven days in order for instrumentation to equilibrate.

Loading rates between runs differed. In the first run one liter of water was added every twenty-four hours corresponding to a loading rate of 0.17 mm/hr. In the second test the loading rate was doubled with water added at six and eighteen hours intervals, though, it should be noted that the average loading rate up to the time that practical field capacity was reached was approximately 0.17 mm/hr (see Figure 3). The water was added through a tube connected to the holes in the bottom surface of the compression plate. Instrumentation was read both before and after water addition in order to record any changes in suction head or flow patterns through the waste. LEDs corresponding to porous cups on flow sensors were monitored for approximately five to ten minutes after water was added to observe any flow through the porous cups. The first test lasted approximately ninety-three days and the second trial was discontinued at eighty-one days. Steady state conditions (inflow rate equal to discharge rate) were experienced for at least six days before the tests were discontinued.

Data Analysis

Analyses were conducted on the flow areas, the capillary pressures and on the waste and flow characteristics. The analyses were designed to test for 1) temporal changes, 2) spatial changes, and 3) waste and flow bulk parameters.

The active flow areas were tested with difference of means tests for flow area over time and between levels to test for temporal and spatial variation. The data was compiled as the mean flow area for time segments equivalent to approximately 10 L of moisture loading. Then analyses of variance were applied to test for variation over time and between levels of flow areas. Significance was chosen at the 95 percent confidence level. For the capillary pressure analysis, differences of mean tests were conducted between different time segments and between tensiometers at the same level in the waste. Analyses of variance were conducted to test for between level and within level variation. These tests assume that the means are normally distributed and that the values are independent.

The bulk waste and flow parameters were tested by calculating means and standard deviation of pore size distribution index, practical field capacity, and

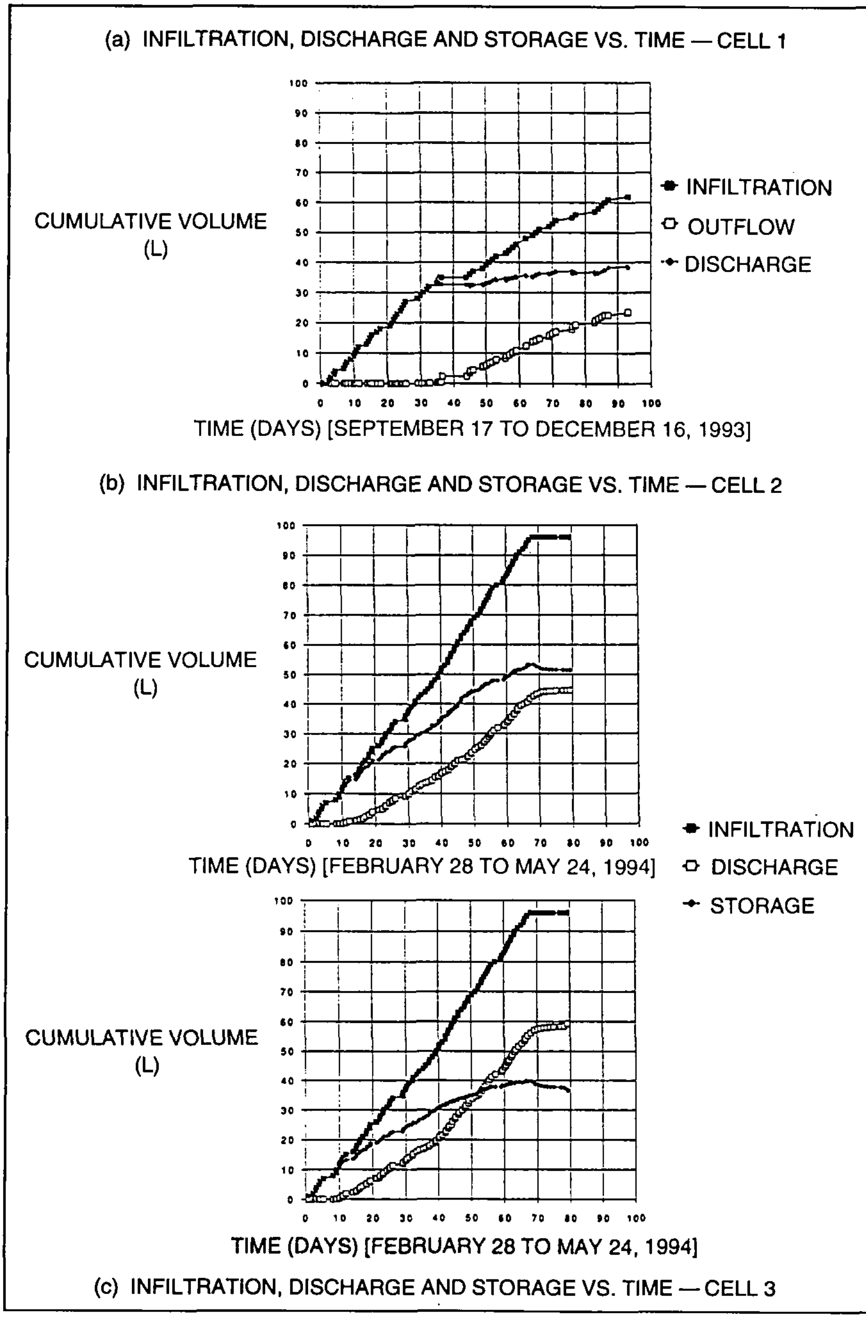

Figure 3. Moisture infiltration discharge and storage.

hydraulic conductivities and comparing them with HELP values and previous results [1].

RESEARCH RESULTS AND FINDINGS

The research aim is to test the waste and flow characteristics over time and space within the waste layer in order to account for channeled flow in macropores as well as Darcian flow in the matrix under low moisture infiltration rates. Changes in flow patterns, moisture content and capillary pressure are used to describe the redistribution of moisture from the macropores to the matrix and the subsequent development of matrix flows. Finally, the measurement of bulk characteristics of waste (particle size distribution, initial moisture content, compaction ratio, porosity) and flow regime (flow cross-section), field capacity, moisture content, capillary pressure, hydraulic conductivity, velocity and discharge rate provide bulk parameters to estimate flows in municipal solid waste layers. The results are presented below in three subsections covering 1) flow patterns, 2) moisture contents and capillary pressure, and 3) bulk waste and flow characteristics.

1. Flow Patterns

The analysis of the results determines 1) the extent of channeling that occurs as indicated by restricted flow areas, 2) the rate and extent of moisture redistribution from flow channels to the matrix through absorption and capillary action, and 3) the differences between the location and size of channels and the degree of redistribution over time at the top, middle and bottom locations in the waste layers. Figure 4 shows the active flow areas as fractions of the cross-section by approximate 10 L increments. The quadrant of the centroid of the active flow area is denoted at the top of the bars for each vertical position in the waste column.

Flow area is largest at the top, while middle and bottom layers alternate in being lowest. These differences are statistically significant as shown by difference of means (see Table 1) and ANOVA tests (Anova $p < 0.013$) throughout the entire test period for all three test cells. The differences in flow areas over time within the same layer, however, are not significant (Anova $p < 0.21$ to 0.99).

While the location of the flow centroid is consistent or shifts slowly over time in the same layer, the locations do not coincide between layers. In experiment 1, for example, the top flow location is consistently in the NW quadrant, while the middle shifts from the southwest to west to southwest to northwest, and the bottom shifts from northeast to east, to southeast, to southwest to south. So, the flow patterns show distinct constriction of flow into narrow channels in laterally consistent patterns over time within each waste layer. While flow channel areas are larger in the upper layers, the location of flow channel centroids shift slowly over time.

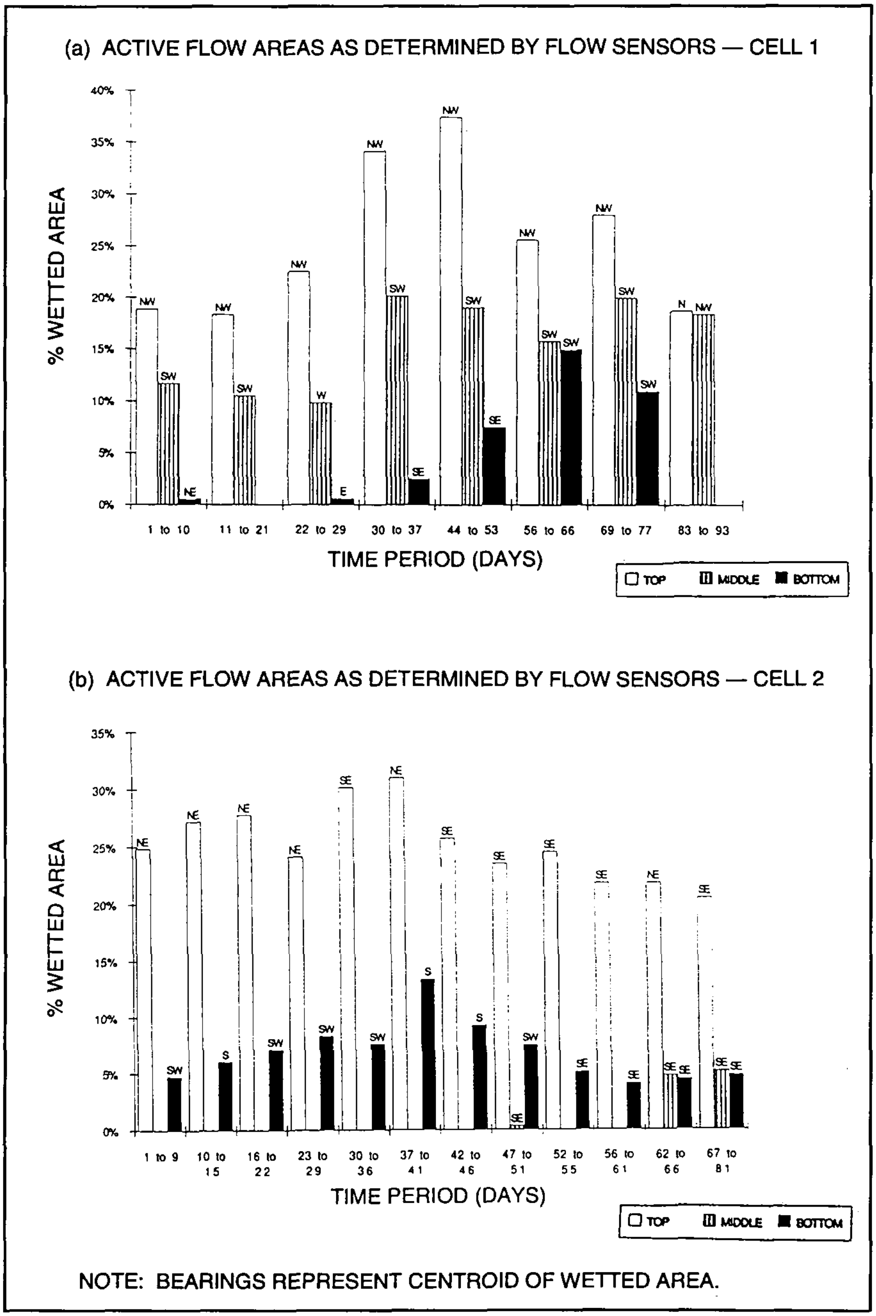

Figure 4. Active flow areas as determined by flow seasons.

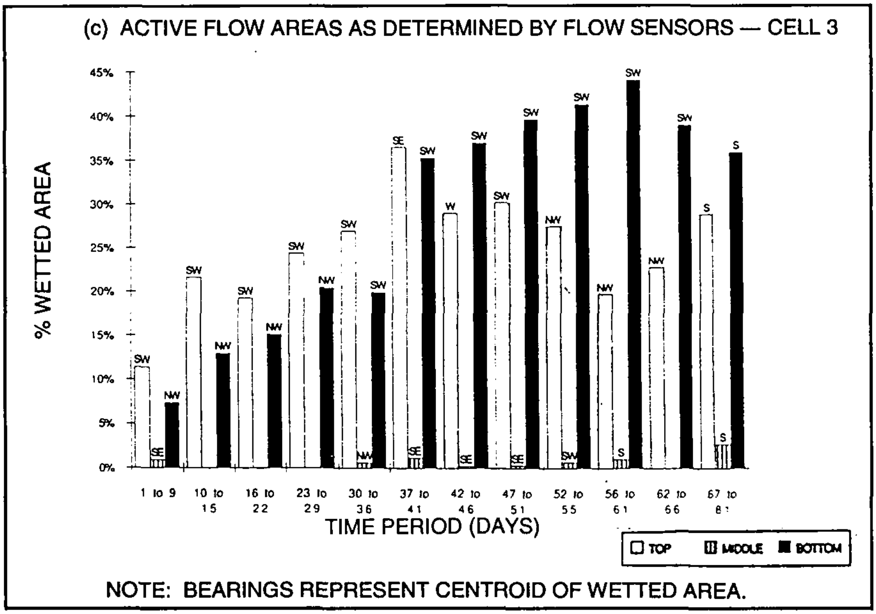

Figure 4. Continued.

The capillary pressure curves for the three test cells are shown in Figure 5. The top layer readings are generally higher than the medium and lower layers. Most tensiometers show slight downward trends. Some tensiometers on all levels, however, show decreasing levels which then rebound back to higher values in the later part of the tests (see M-5 in cell 1 and T-3 and B-4 in cell 2). Notably, the garbage bag tensiometer (see BAG in cell 3) increased steadily throughout the test.

The differences between capillary pressures at the same level test the presence of channeling. Over 90 percent of non-zero readings differ significantly between tensiometers in the same waste layer (see Table 2). Conversely, the differences of the average values between layers are generally not significantly different. Therefore, the spatial variation within a layer is greater than the vertical variation in the waste column. This result supports the presence of consistent vertical moisture and capillary channels. Finally, most tests of differences of means of capillary pressures over time are significant and confirms the observed variations in Figure 5.

Waste and Flow Characteristics

Waste particle size distribution and initial moisture contents were determined prior to placement in the cells. These variables are listed for comparison. Then,

Table 1. Flow Area Statistical Analysis Summary

Variation between Time Periods (e.g., Top Level Flow Sensor: Period 1 versus Period 2 Values)

Cell Number	Number of Significant Cases*	Range of Probability +
1	0/21	0.071 to 1
2	6/23	0.011 to 1
3	11/31	1.7 E-5 to 1

For each flow sensor (Top, Middle, Bottom) analysis between successive time periods (12) was performed

Variation between Levels (e.g., over Period 1: Top Flow Sensor versus Middle Flow Sensor Values)

Cell Number	Number of Significant Cases*	Range of Probability +
1	22/24	1.9 E-8 to 0.09
2	34/36	7.8 E-17 to 0.33
3	34/36	1.4 E-16 to 0.67

For each time period analysis between flow sensors (Top versus Middle, Top versus Bottom, Middle versus Bottom) was performed

Analysis of Variance between Time Periods (Temporal) and between Levels (Spatial)**

Cell Number	Significance*	Range of Probability +
1	Temporally: Not Significant	0.208
	Spatially: Significant	0.0012
2	Temporally: Not Significant	0.99
	Spatially: Significant	1.7 E-16
3	Temporally: Not Significant	0.99
	Spatially: Significant	3.3 E-14

Note: Analysis assumes values independent and normally distributed. Statistics evaluated over time periods shown in Figure 3 and for each level (Top, Middle, Bottom). Only non-zero cases evaluated (max. no. cases = 24 for cell 1 and 36 for cell 2 and 3).

*Significant if $P < 0.05$ at the 95 percent confidence level.

+Two-tailed probability values.

**Evaluated over entire test duration for all sensors (Top, Middle, Bottom inclusive).

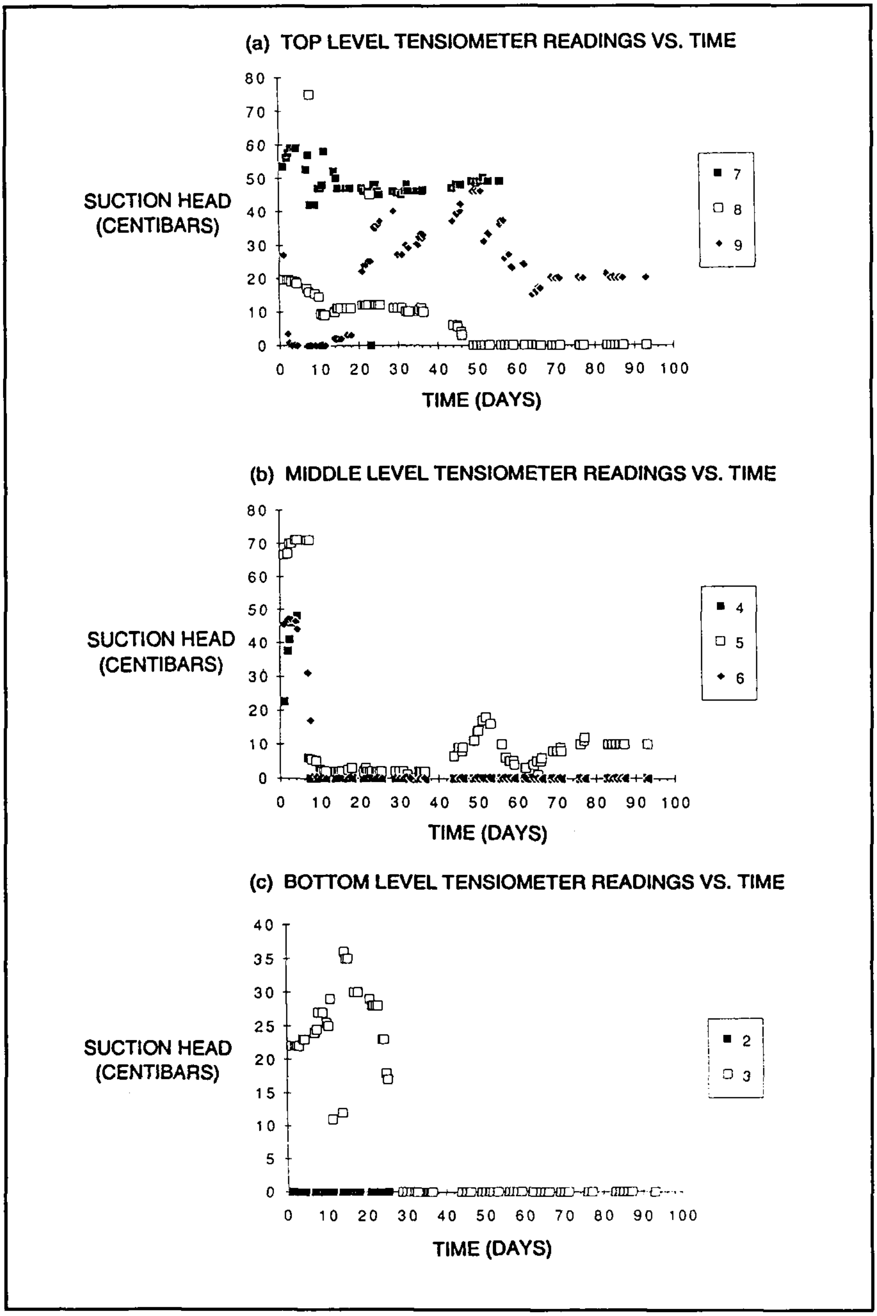

Figure 5. Capillary pressure curves, Cell 1.

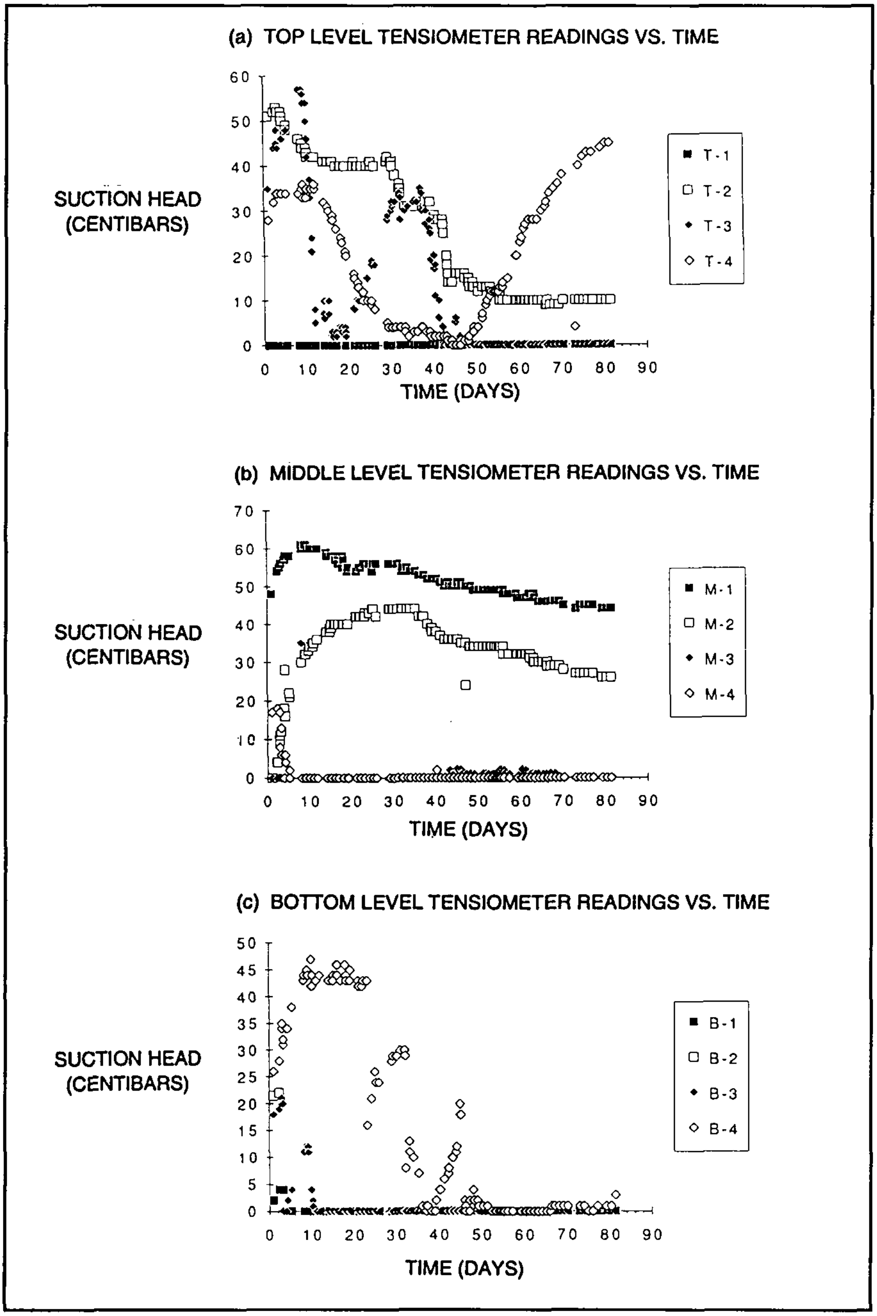

Figure 5. Capillary pressure curves, Cell 2.

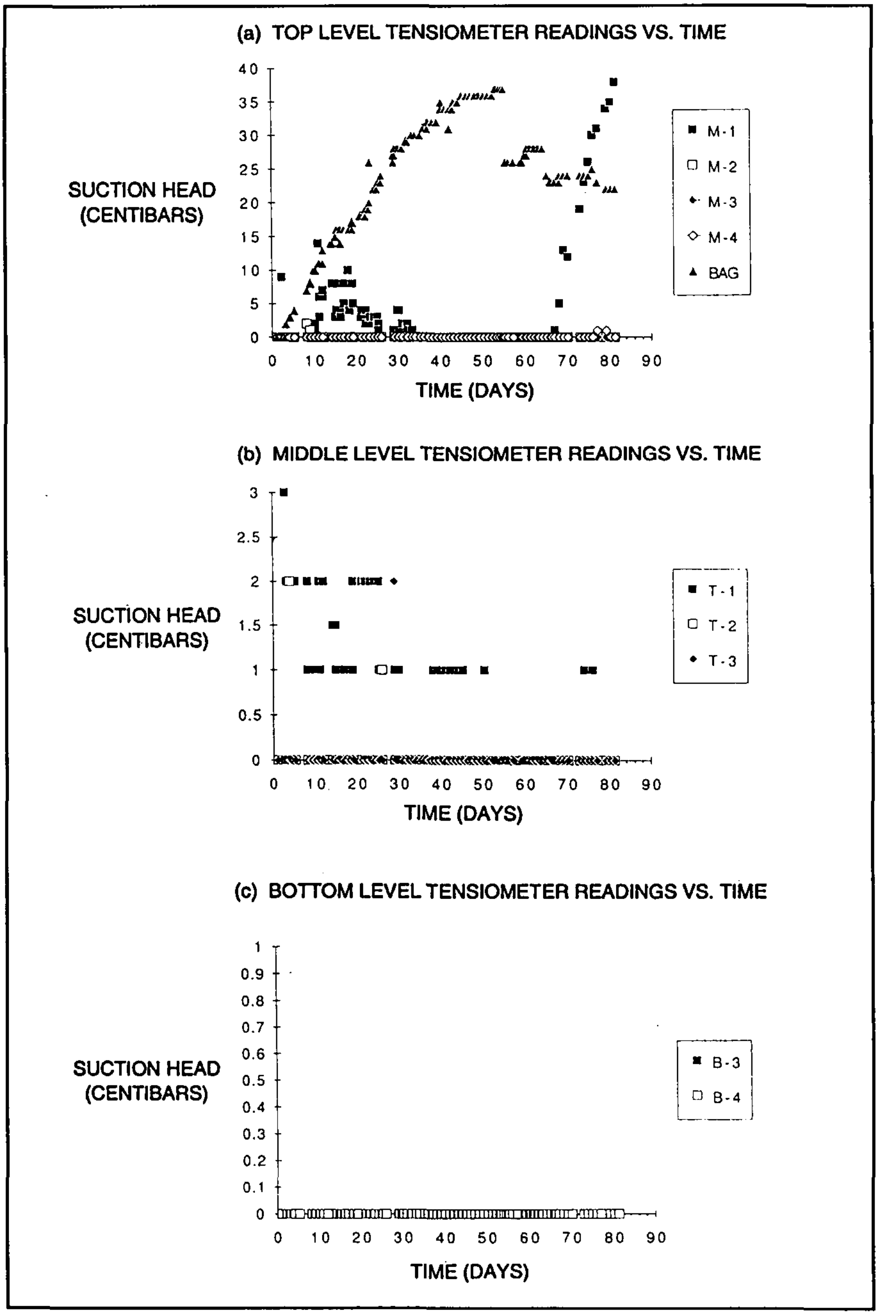

Figure 5. Capillary pressure curves, Cell 3.

Table 2. Tensiometer Statistical Analysis Summary

Variation between Time Periods (e.g., Cell 1: Tensiometer 5 Period 1 versus Period 2)

Cell Number	Number of Significant Cases*	Range of Probability +
1	14/27	3.4 E-9 to 0.58
2	64/74	5.9 E-14 to 1
3	15/28	2.4 E to 0.71

For each tensiometer analysis between successive time periods was performed.

Variation Within Levels (e.g., Cell 1: Top Level, Tensiometer 7 versus Tensiometer 8)

Cell Number	Number of Significant Cases*	Range of Probability +
1	15/22	6.4 E-11 to 0.56
2	64/70	2.38 E-34 to 0.92
3	13/17	1.0 E-18 to 0.68

For each time period analysis between tensiometers of the same level were performerd for each cell.

Comparison of Variation Within and Between Levels**

Cell Number	Significance*	Range of Probability +
1	$\frac{\text{Within}}{\text{Between}}$: 1/4	0.25 to 0.01
	$\frac{\text{Between}}{\text{Within}}$: 2/4	0.25 to 0.01
2	$\frac{\text{Within}}{\text{Between}}$: 0/12	0.25 to 0.05
	$\frac{\text{Between}}{\text{Within}}$: 0/0***	—
3	$\frac{\text{Within}}{\text{Between}}$: 0/12	0.25
	$\frac{\text{Between}}{\text{Within}}$: 0/0***	—

Note: Analysis assumes values independent and normally distributed. Statistics evaluated over time periods shown in Figure 3 and between tensiometers of the same level. Only non-zero cases evaluated (maximum number of cases varies with number of tensiometers in cell and time period of test).

*Significant if $P < 0.05$ at the 95 percent confidence level.

+Two-tailed probability values.

**Evaluated over each time period to determine if horizontal variation in capillary pressure greater than vertical variation.

***$\frac{\text{Between}}{\text{Within}}$ ratio < 1 for all twelve time periods.

Table 3. Waste and Flow Bulk Parameters

Parameter	Experimental Average ($n = 3$)	Standard Deviation	Zeiss and Major, 1993	HELP Default
Mass of waste (kg)	44.5	8	NA	NA
Initial height of waste (m)	1.26	0.13	NA	NA
Initial density (kg/m^3)	141	36	166	NA
Compaction ratio	1.27	0.116	1.6	NA
Rosin-Rammler particle size (cm)	12.7	9.9	9.1	13.4*
Rosin-Rammler *n*	1.89	0.81	1.1	1.3*
Residual moisture content (vol/vol)	0.0347	0.0099	0.06	0.015
Air-dry moisture content (vol/vol)	0.0061	0.005	0.0128	0.14a
Initial moisture content (vol/vol)	0.0759	0.0162	0.1068	NA
Practical field capacity (vol/vol)	0.0996	0.0478	0.136	NA
HELP field capacity (vol/vol)	0.2936	0.0884	0.299	0.294
Porosity	0.5196	0.0482	0.54	0.52
Pore size distribution index, λ	0.651	0.076	0.67	0.211
Bubbling pressure (cm)	30.3	17.1	15	20.76
K_{us} initial (cm/s)	6.14×10^{-5}	3.54×10^{-5}	2.14×10^{-2}	
K_{us}-ultimate (cm/s)	6.08×10^{-6}	5.65×10^{-7}	1.12×10^{-3}	1.20×10^{-7}[b]

[a]Moisture content at wilting point.
[b]Unsaturated hydraulic conductivity at field capacity.
*From Hasselriis, 1984.

during the tests, porosity, field capacities and resulting pore size distribution indices were determined with Brooks-Corey [3] and Campbell [4] equations. Finally, the bulk hydraulic conductivities were determined from the measured breakthrough times and ultimate discharge rates.

Rosin-Rammler characteristic particle sizes Xo and distribution slopes n were determined from 5 kg samples taken from the waste loads during charging of the cells (see Table 3).

The sizes range from 8 to 22 cm (3 to 9 inches). These are typical values for opened solid waste streams (see e.g. [13]) and may therefore be considered representative of the range of sizes, albeit without bulk items. The packed densities in the cells were slightly low at 150 to 200 kg/m3, compared with reported values of 500 to 600 kg/m3 in landfills. However, Zeiss and Major caution about the interpretation of density for predicting flows as it is virtually meaningless [1]. The compaction ratios of 1.2 to 1.4, however, are in the lower range of those estimated in a previous study [1] and, presumably, of the compaction found in landfills [9].

Initial and air-dried moisture contents were measured as 0.029 and 0.049 and 0.003 to 0.013, respectively, which show good agreement with values found in Bagchi [9] (initial moisture content range from 0.021 to 0.067). Similarly, porosity of the waste in cells ranged from 0.49 to 0.55, which are equivalent to the HELP default value (0.52) and previously reported measured values of 0.53 over a range of compaction ratios [1].

The practical field capacities, the moisture volume at which drainage begins, were measured between 0.07 and 0.15; despite the lower loading rates of 0.017 to 0.034 mm/hr in this test, these values straddle the average value of 0.135 measured in at loading rates of 95 mm/hr [1]. Thus, the practical field capacity value seems to remain relatively constant at 0.07 to 0.14. HELP field capacities, that is, the moisture remaining after drainage from saturation, too, at 0.23 to 0.36, remained equal to the previously determined range of 0.26 to 0.37. The differences between the practical and HELP values, therefore, are confirmed in this test with lower loading rates.

The effect of moisture redistribution with low loading rates is tested by measuring the increase in moisture content during the test period of 80 days (see Figure 3a, b, and c).

Approximately 35 L to 40 L are added after initial breakthrough (practical field capacity) before steady-state conditions of in- and outflow are reached after day sixty. The total cumulative moisture storage flattens out at about 37 to 55 L per cell. Thus, the moisture content after redistribution reaches an average of 0.294, above the initial practical field capacity of 0.0996, an increase of nearly three times. Clearly, this constitutes a significant increase in storage volume in the waste.

The air-dried moisture content and the practical field capacity were used to graph the pore size distribution curves with slope, λ, the pore size distribution index. Figure 6 shows the average curve for the three test cells (see Table 3 for average value). The slope is steeper, but the resulting bubbling pressure is similar (at 30.3 cm) and is close the HELP value of 20 cm.

The apparent hydraulic conductivities were calculated as initial values from the breakthrough time, and as ultimate conductivities from the final steady-state discharge rates. The initial hydraulic conductivity values averaged 6.14×10^{-5} cm/s, slightly lower than the values found by Korfiatis et al. [8], while the ultimate hydraulic conductivity values averaged 6.08×10^{-6} cm/s. These values are two and one order of magnitude greater than the HELP default value for unsaturated hydraulic conductivity at field capacity of 1.20×10^{-7} cm/s. However, they are three orders of magnitude less than those found in a previous study [1]. This may be due to the difference in loading rate, as the loading rate for [1] was approximately 500 times greater than that used in this experiment (0.095 m/s to 1.7×10^{-4} m/s as previously noted). At such extremely low loading rates, channeled flow may be more readily redistributed through the waste matrix ($I_2(t)$ would be larger [7]). However, the results show that channeling is still a significant flow mechanism, even at low loading rates.

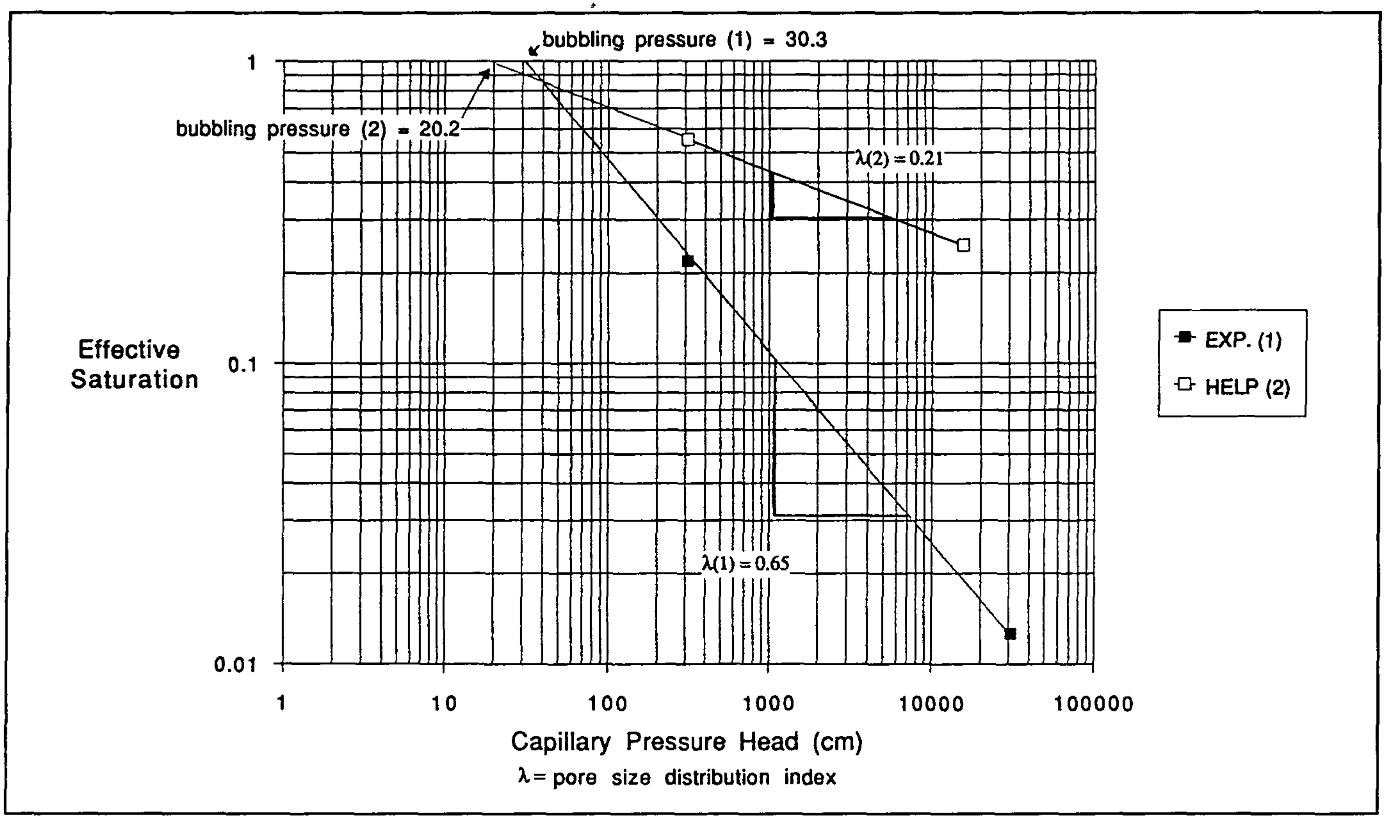

Figure 6. Effective saturation, capillary pressure, and pore size distributions.

SUMMARY AND CONCLUSIONS

Channeled flow through municipal solid waste is a significant flow mechanism at low loading rates as less than 45 percent (maximum) of the cross-sectional area of the solid waste column conveys flow, even at steady-state. Also, the increase in cross-sectional area does not become significantly larger over time indicating that Darcian flow may not be the dominant flow mechanism even at steady-state conditions. However, Darcian flow is experienced through the solid waste, as confirmed by the capillary pressure in many areas of the waste column gradually decreasing over time, as well as storage increasing over time.

Practical field capacity values are significantly lower than the HELP default value or those of measured average drainage field capacity (HELP field capacity). The difference stems from flow channeling and the definition of the default value and drainage field capacity. These parameters are defined as the moisture content at which free drainage of an originally saturated media just stops. However, the practical field capacity is the moisture content at which leachate first appears from the originally unsaturated media.

Initial and ultimate hydraulic conductivity values are higher than the HELP default values but four orders of magnitude lower than those found by [1]. As mentioned, the loading rate used by [1] was approximately three orders of magnitude larger than the loading rate used in this study. Therefore, the values of K_{us}-initial, and K_{us}-ultimate may show the differences in loading rate and may not be valid indications of the permeability of the waste.

In terms of biodegradation of landfilled waste the research results indicate that zones of intense nutrient transport and waste removal may occur around channels resulting in higher biodegradation rates in these areas. Biodegradation in other areas will still occur, albeit at a slower rate, as nutrients and wastes are transported and removed by uniform moisture fronts flowing through the solid waste matrix.

The following are recommended based on the research results:

1. The Darcian flow model should be revised to account for channeling of water through the waste layer. This may be accomplished by use of a two-domain model to describe the flow through channels and the waste matrix.
2. The spatial distribution of channels in the waste, the nature of the flow in channels (laminar or turbulent flow) and their representative length and diameter be investigated, to determine more accurately their effect on moisture movement through solid waste.
3. The changes in the pattern and mechanism of flow due to settlement and biodegradation should be tested and specified. This may be of particular importance in the early stages of landfilling when changes occur rapidly.

APPENDIX

Notation

F.C.	= Field Capacity
$I_1(t)$	= direct infiltration rate into matrix [L^3/T]
$I_2(t)$	= infiltration from macropores into matrix [L^3/T]
K_{us}-initial	= initial apparent unsaturated hydraulic conductivity, effective from the time of first infiltration until breakthrough [cm/s]
K_{us}-ultimate	= ultimate apparent unsaturated hydraulic conductivity after steady-state flow has been established [cm/s]
λ	= pore size distribution index
O(t)	= overland or runoff flow rate [L^3/T]
P	= probability
P(t)	= precipitation rate [L^3/T]
Rosin-Rammler *n*	= particle size distribution index [–]
$S_1(t)$	= seepage from surface into macropores [L^3/T]
$S_2(t)$	= flow through macropores [L^3/T]

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Direct reprint requests to:

Professor Chris Zeiss
Department of Civil Engineering
University of Alberta
Edmonton, Alberta, Canada T6G 2G7