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Measuring transient water flow in unsaturated municipal solid waste – A new experimental approach

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Abstract

This research investigated transient water flow in unsaturated municipal solid waste (MSW) packed in columns using neutron scattering. The method developed was able to measure absolute moisture content and moisture variation in a sample of MSW produced in the city of Fortaleza (Brazil) during a simulated tropical rain event. The technique was proven to be efficient, showing that channeling flow accounts for most of the unsaturated flow conditions. The most important effect of micro-porous flow was on water accumulation and small long-term outflow. Furthermore, the definition of *field capacity* used in soil sciences does not seem to apply to flow in unsaturated MSW; the MSW layers kept increasing in moisture content long after water was allowed through. Finally, the long-term draining experiment demonstrated that the macro-porous matrix may not be a continuous medium, which makes experimental procedures that rely on matrix potential in specific points of the solid waste mass inaccurate.

1. Introduction

Landfills are the dominant means of disposing of MSW in Brazil. Because of the relative simplicity of landfilling, it offers low cost, easy management, and therefore is a sited alternative for almost all developing countries. Approximately 73% of the 130,000 metric tons/day of municipal solid waste generated in Brazil in 2000 was placed in municipal landfills (PNSB, 2000). Recycling may play an increasingly important role in MSW management; however, landfilling will still account for a significant portion of MSW disposal long into the future.

One of the greatest concerns on the impacts of an existing or a proposed landfill is the groundwater pollution caused by landfill leachate. Leachate may be composed of liquids that originate from a number of sources, including precipitation, groundwater, consolidation, initial moisture storage, and reactions associated with decomposition of waste materials. The chemical quality of leachate varies as a function of a number of factors, including the quantity produced, the original nature of the buried waste materials, and the various chemical and biochemical reactions that may occur as the waste materials decompose. Even small amounts of landfill leachate can pollute large amounts of groundwater, rendering it unusable for domestic and many other purposes. Municipal solid waste contains a variety of potentially significant chemical constituents and pathogenic organisms that could be adverse to public health, groundwater quality, and the environment within the area of influence of the landfill. Those chemical constituents include regulated hazardous chemicals such as heavy metals, VOCs, and chlorinated solvents; conventional pollutants, chemicals that cause taste and odors such as H_2S, Fe, Mn, Cl, and ammonia.

Landfills should be designed to prevent any waste or leachate from moving into adjacent areas. Thus, a first step in controlling leachate migration is to limit leachate production by preventing, to the maximum extent feasible, the entry of external water into the MSW layers. A second step is to collect any leachate that is produced for subsequent treatment and disposal. Techniques are currently

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available to limit the amount of leachate that migrates into adjoining areas. In order to correctly design a leachate collection system, one should understand MSW hydraulic properties and leachate flow characteristics.

Many authors have attempted to model flow through MSW (Noble and Arnold, 1991; Al-Yousfi et al., 1992; Ahmed et al., 1992; Khanbilvardi et al., 1995). However, they basically tried to apply the same laws and theories used to model water flow in soils, which proved to be an ineffective approach. Capelo (1999) applied two frequently used models, HELP (Schroeder et al., 1984) and Water Balance Model, to simulate leachate productions in northeastern Brazil, where a semi-arid tropical climate predominates, and compared them to the measured values for leachate generation. The results showed that none of the models simulated accurately either the short-term (rain event or day) or the long-term (month or year) leachate generation.

Therefore, the objectives of this research were to study the transient vertical leachate flow characteristics in unsaturated MSW using a different experimental approach and to determine the solid waste hydraulic properties in a semi-arid tropical region. The results should provide data essential in developing new mathematical modeling efforts and explain the phenomenon in a more realistic way.

2. Literature review

Many authors have studied water flow in MSW packed columns in order to develop or to verify the accuracy of mathematical models. Korfiatis et al. (1984) used a 56 cm diameter laboratory column packed with a heterogeneous mixture of approximately 6-mo old waste obtained from a MSW landfill to simulate the vertical movement of leachate within a landfill. The column was equipped with in situ pressure transducers to determine the relationship between suction pressure and saturation.

Noble and Arnold (1991) evaluated the use of Richards' equation in the moisture transport within a landfill. One-dimensional water vertical infiltration in landfills was simulated by studying water flux in experimental glass columns (40.7 cm length and 4.7 cm internal diameter) packed with 1.27 cm^2 of shredded dry newspaper with an overall density of 334.8 kg/m^3. They found that Richards' equation provided a reasonable description of moisture transport and that capillary effects should not be neglected in landfill water transport modeling. However, by using small pieces of newspaper as the simulated MSW, the authors practically eliminated one of the most important flow mechanisms in this medium, channeling flow; therefore, their experiment may not represent the actual behavior of water in a real landfill.

Zeiss and Major (1992) used a column study to measure patterns of moisture flow in MSW. Each column consisted of two 200 L drums welded together to give a total column height of 1.8 m and an internal diameter of 0.57 m. The columns were filled with hand-picked MSW with particle sizes ranging from 2.9 to 15.3 cm and an average diameter of 9.05 cm. Waste density, porosity, field capacity, apparent hydraulic conductivity, and flow channeling were analyzed as a function of compaction. Flow was detected by sensor plates, which consisted of a circular frame grid holding twenty 1.5 cm diameter and 1.5 cm high cups disposed along the whole column cross section area. Two wires, separated by a small distance, ran into each cup. Leachate flow was detected when it filled the cups and closed the circuit, activating a light emitting diode (LED) control panel. Their experiment was successful in confirming that channeling flow was predominant in MSW; however, the apparatus was not able to measure solid waste moisture content along the experimental run, making the hydraulic characteristics found, such as conductivity and field capacity, questionable.

Zeiss and Uguccioni (1994) used the same columns as the Zeiss and Major (1992) study described above to evaluate mechanisms and patterns of leachate flow, with special attention to macro-pore effects (channeling). The columns were filled with hand-picked MSW with particle sizes ranging from 8 to 22 cm. Moisture flow sensor plates and tensiometers were installed at three levels within the waste mass.

Zeiss and Uguccioni (1997) attempted to confirm channeling, characterize flow regimes, and determine the effects of infiltration rate and waste density on flow parameters. Additionally, the key flow parameters of practical field capacity, pore-size distribution index, effective storage, hydraulic conductivity, breakthrough times, and discharge rate were measured. Eight rectangular-steel containers (1.8 m × 1.6 m × 1.5 m) filled with residential MSW and equipped with tensiometers and a grid of flow sensor cups (as described by Zeiss and Uguccioni, 1994) were used in this study. Breakthrough times at 15–30 min (with two outliers of 25 and 40 h) occurred at times similar to previous studies while the apparent initial unsaturated hydraulic conductivity was slightly higher than in previous studies.

The experimental apparatus used by Zeiss and Uguccioni in 1994 and 1997 (moisture flow sensor plates and tensiometers) measured water content in a particular point of the MSW and did not reflect a representative measurement of the layer moisture content. Moreover, tensiometers may not be an effective instrument to indicate water content in real MSW due to the restricted area that may occur between the tensiometers porous cup and the coarse MSW particles (Yuen et al., 2000).

Gawande et al. (2003) studied MSW moisture content using electrical resistance sensors. They briefly described a number of *in situ* moisture content sensors (time domain reflectometry, neutron probe, capacitance probe, and electrical resistance), which were developed and used mainly for agricultural purposes. The electrical resistance method was chosen because of its precise correlation between moisture content and electrical resistance, its low cost, and its easiness to obtain measurements. They encountered two fundamental limitations: the sensors were not able to detect moisture content below 35% (w/w) and their readings were highly dependent on leachate composition, which can vary substantially in time and space within the same landfill. Those limitations compromise the practical validity of this experimental procedure.

A neutron probe has been widely used for estimating volumetric water content in soils. The probe emits fast neutrons from a radioactive source, which are thermalized or slowed down by successive elastic collisions with hydrogen atoms in the medium. Since hydrogen atoms in soils are generally components of water molecules, the proportion of thermalized neutrons is related to the water content. This method has the advantage of measuring a large sample volume and the possibility of scanning at several depths to obtain a profile of moisture distribution.

The use of neutron probe to measure moisture content in soils has been widely studied and is a common practice in agricultural, engineering, and hydrological applications. However, little reliable information on the application of this method when it comes to a different media, such as MSW, is available.

Recently, Yuen et al. (2000) developed an extensive investigation on the use of a neutron probe in measuring MSW moisture. First, a feasibility assessment was developed in order to identify if the technique was viable for this purpose; then, the method limitations were identified in a laboratory scale, and finally a field application was carried out. Two major error sources were observed in the field trial: bound hydrogen effect and errors incurred during the gravimetric-to-volumetric moisture content conversion.

They concluded, however, that neutron probe could be considered useful and practical in measuring the absolute moisture of municipal solid waste, provided the proper calibration curves are available and neutron capture elements are not excessively present. These limitations are not significant if moisture variation is to be measured.

3. Methodology

3.1. Column preparation

Three leaching columns were constructed using concrete cylinders (60 cm internal diameter × 3 m high) to simulate vertical water movement (Fig. 1). At the bottom of each column, a draining system consisting of a perforated 5 cm PVC pipe buried in a 10 cm thick layer of crushed brick was built to allow water removal. In the center of each column, an aluminum pipe 5 cm in diameter and 3 m long was installed before solid waste was packed. Fig. 1 shows a simplified sketch of the experimental columns.

A representative sample of new MSW was collected in the sanitary landfill of Fortaleza, Ceara (Brazil). Objects larger than 20 cm were manually removed from the sample. The sample was manually homogenized, weighed and packed in successive layers of 20 cm until reaching a density of 550 kg/m^3, the same density used to pack MSW in the Fortaleza sanitary landfill. Effects of MSW biodegradation were not considered because of the relatively short duration of the experiment (≈2 mo). Some indication of the composition of the MSW used in the experiment can be made from a previous study as shown in Table 1 (EMLURB, 1996).

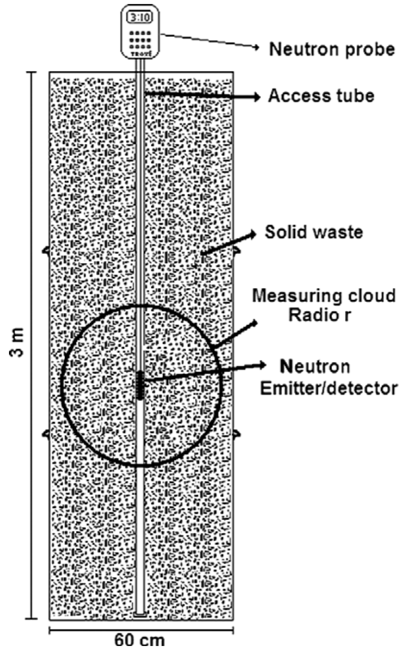

Fig. 1. Simplified sketch of the experimental column.

3.2. Neutron probe calibration

The solid waste sample collected was relatively dry due to the region's weather characteristics at the time of the experiment. Its initial volumetric water content, referred to as residual volumetric water content (θ_r), was determined gravimetrically. Residual volumetric water content is defined in this study as the lowest moisture that MSW can achieve in a natural condition. The gravimetric determination was done by placing samples into an oven at 105 °C for 24 h and calculating the weight difference before and

Table 1
Fortaleza city, Brazil, MSW characterization

Waste category	Composition (% v/v)
Food and yard waste	38.14
Paper	6.98
Cardboard	7.58
Plastics	10.69
Rubber	0.83
Ferrous metals	3.03
Non-ferrous metals	0.89
Glass	2.15
Wood	2.33
Textiles	3.45
Leather	0.39
Construction waste	3.84
Coconut shells	8.68
Dirt, ash, etc.	11.02

after the drying process. The samples were collected from the MSW used to pack the columns. An average residual volumetric water content of $\theta_r = 0.13$ (v/v) with a variation coefficient of 17.41% was detected. The determined residual volumetric water content seems to agree with values (7–18% v/v) found by Benson and Wang (1998).

A TROXLER® Neutron Probe series 3300 was used to indirectly measure, in a non-destructive form, the MSW moisture during a simulated precipitation event. The neutron probe was mounted on the superior extremity of the aluminum pipe installed previously. Readings were carried out at the depths of 30, 60, 90, 120, 150, 180, 210, and 240 cm from MSW superior surface.

After the MSW was packed, the experimental columns were exposed to heat from the sun, and therefore to high temperatures (±40 °C), for about five weeks to verify if the residual water content could still be reduced. No precipitation was registered in that period. Very little variation in the MSW water content (average of 4%) was observed. Therefore, the residual volumetric water content found in the gravimetric experiment was considered to be a consistent value. To derive the calibration curve, count ratio was used instead of standard count. This procedure was used so that possible changes in the counting time would not invalidate the calibration curve. The use of count ratio also minimizes errors due to equipment electronic and radiation instabilities (Stone, 1990).

The spherical cloud radius (radius through which 98% of the slow neutrons pass before reaching the detector) is a function of volumetric water content and decreases with the increase in the moisture (Fig. 1). The following equation expresses the relation between the cloud radius and water content for soils, as specified by the neutron probe manufacturer:

$$R = 280 - 0.27M,$$

where R is the radius of measurement in mm and M is the water content in kg/m^3.

This equation covers 98% of the sample volume measured and is valid for water contents between 0 and 640 kg/m^3. Because of the MSW composition, this radius should be substantially smaller than in soils but no data is available in the scientific literature.

In the initial measurements, the count ratio (CR) varied from one layer to another, although the MSW was assumed to be at the same residual volumetric water content. These variations were attributed to the different types of materials present such as plastics and organic matter that also would be detectable by the neutron probe. This phenomenon was also observed by Yuen et al. (2000). Therefore, to overcome this characteristic, it was necessary to develop a calibration equation for each 30 cm layer of the three columns.

A linear relationship between water content and neutron probe reading (count ratio – CR) was assumed, as suggested by Stone (1990). The calibration curves were found in the following manner:

1. A measured *count ratio* value was attributed to the residual volumetric water content ($\theta_r = 0.13$ v/v) for each column and depth.
2. The moisture at full saturation was found by flooding the MSW columns and measuring the amount of water that each one held at the end of the experiment. It was made sure that no air was trapped inside the three columns. The average measured value was $\theta_s = 0.41$ v/v.
3. A measured *count ratio* value was attributed to full saturation (θ_s) for each column and depth.
4. A straight line intercepting both points (CR at θ_r and CR at θ_s) was plotted defining the calibration equation for each depth. The curve coefficients are presented in Table 2.

3.3. Rain simulation

An aspersion system was installed with the objective of simulating precipitation over the MSW, adding water in a controlled and distributed form. This system was composed of a submerged pump, tanks for water storage, tubing, flow meter and control valves. During the rain simulation, the draining system at the column bottom was maintained closed so water would accumulate from the bottom up.

Only one rain simulation run was possible in each column. The simulated rainfall was applied continuously until the end of the experiment. Once fully saturated, the MSW could only be dried out to the residual moisture values (θ_r) if removed from the column. The simulated rain intensities applied were controlled through a valve and measured with a flow meter. The effects of rain simulation in the MSW were registered by the neutron probe during 390 min in column one and 160 min in columns two and three. Neutron probe readings were taken approximately every 25 min; each reading took an average time of 30 s for every layer.

The applied flow density was 9.50 cm/h in column one and 14.25 cm/h in columns two and three. Those flow densities were chosen in order to mimic the average precipitation intensity present in the studied sanitary landfill area. Fig. 2 shows the experimental apparatus used for the rain simulation. After the rain simulation ended, the columns were flooded in order to find the moisture at saturation (θ_s) and the saturated hydraulic conductivity, and to initiate the free draining experiments.

Table 2
Calibration curve coefficients

Depth	Column 1		Column 2		Column 3	
	Slope	Intercept	Slope	Intercept	Slope	Intercept
30	0.334	0.077	0.351	0.549	0.358	0.048
60	0.396	0.015	0.42	−0.01	0.345	0.061
90	0.371	0.040	0.362	0.037	0.372	0.033
120	0.404	0.007	0.423	−0.014	0.447	−0.041
150	0.385	0.026	0.385	0.012	0.501	−0.096
180	0.426	−0.015	0.419	−0.002	0.392	0.013
210	0.620	−0.210	0.587	−0.202	0.397	0.083
240	0.663	−0.253	1.006	−0.561	0.585	−0.180

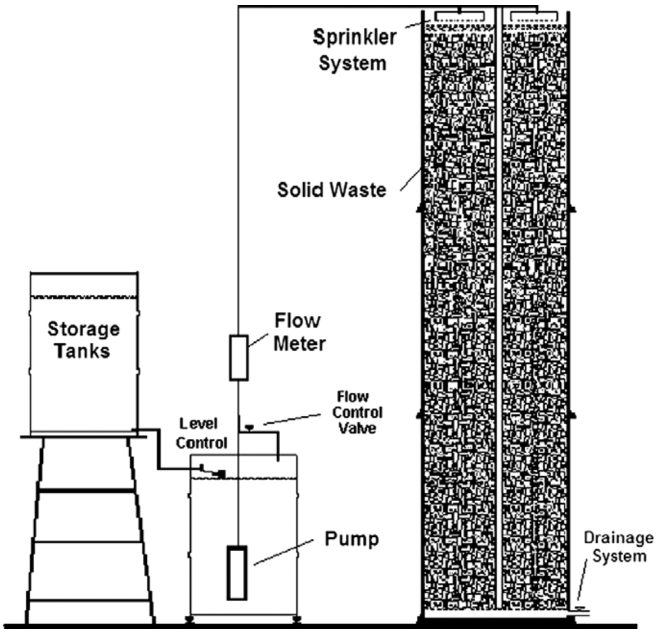

Fig. 2. Experimental apparatus used to simulate rain.

The saturated hydraulic conductivity (K_s) was determined by using the method of unitary profile described by Libardi (2000). This method can be briefly described in this form:

1. The column was flooded up to the solid waste surface.
2. The bottom draining system valve was open and, simultaneously, water was added to the top of the column maintaining an equal flow rate for about 90 min and the same water level in the column.
3. After stabilizing the liquid column height, the inflow rate was divided by the column transversal area resulting in the hydraulic conductivity (K_s).

After the hydraulic conductivity measurements were carried through, the columns were drained by stopping water inflow. During this procedure, neutron probe measurements of solid waste volumetric water content were carried through in columns one and two.

4. Results and discussion

Volumetric water content versus depth is plotted in Fig. 3 for rain simulation in column one. A gradual moisture increase can be observed until the 120 initial min initiating in the superior layer and moving downward to the successive layers, similar to what is called in soil science a *wetting front*. A particular difference observed in this case is that the moisture of the upper layers continues to increase as the wetting front advances. From minute 180 up to the end of the experiment (390 min), the moisture increase follows a different pattern. Water content starts building up between layers 180 and 210 cm instead of accumulating from the bottom up as it would be expected. This accumulation in an intermediary layer was caused by less favorable flow conditions, such as smaller permeability or presence of materials with high water moisture absorption capacity. As mentioned before, in contrast to soil science infiltration theories (Green and Ampt, 1911; Philip, 1957), the upper layers continued to increase in moisture even after infiltrated water was allowed to flow through.

The experimental runs in columns two and three were shorter than in column one (160 min). Volumetric water content versus depth during rain simulation was plotted in Figs. 4 and 5 for columns 2 and 3, respectively. A similar behavior as that observed in column one was experienced in columns two and three. Moisture kept increasing in a determined layer while infiltrated water was allowed to flow through it. Layers with smaller permeability were also encountered at depths of 120 and 210 cm in column two and 180 cm in column three.

The water absorption capacity pattern observed in the MSW columns is in accordance with the conclusions obtained by Korfiatis et al. (1984). The authors demonstrated that solid waste *field capacity* increases with time during the infiltration process.

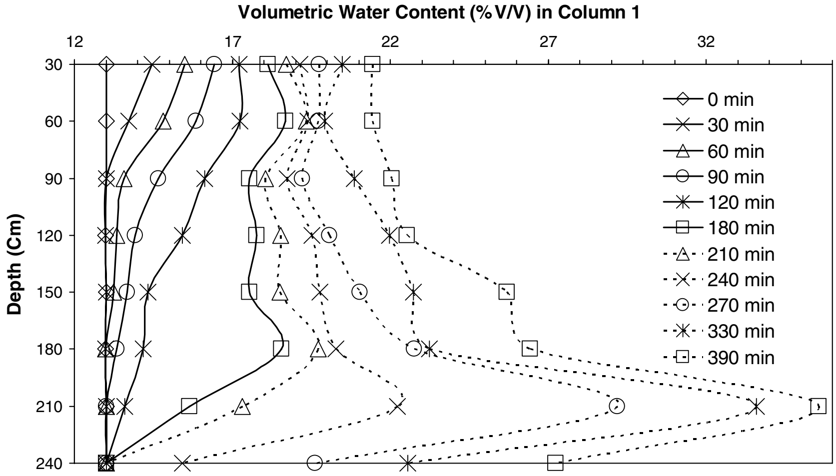

Fig. 3. Change in volumetric water content during rain simulation in column 1.

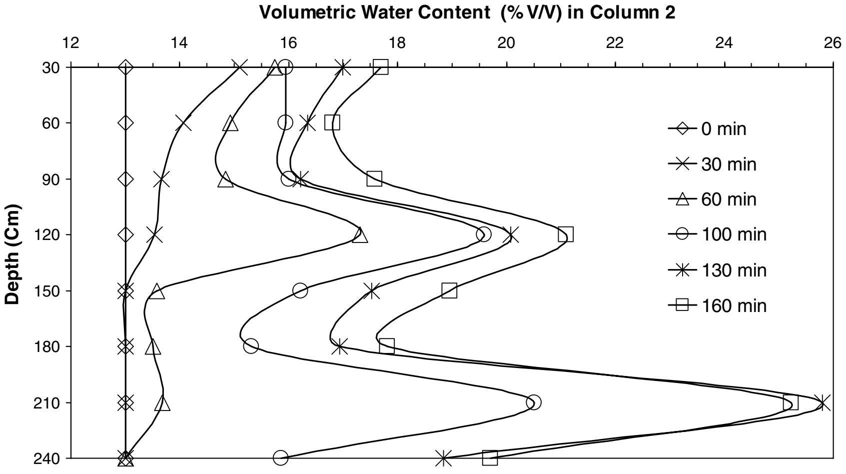

Fig. 4. Change in volumetric water content during rain simulation in column 2.

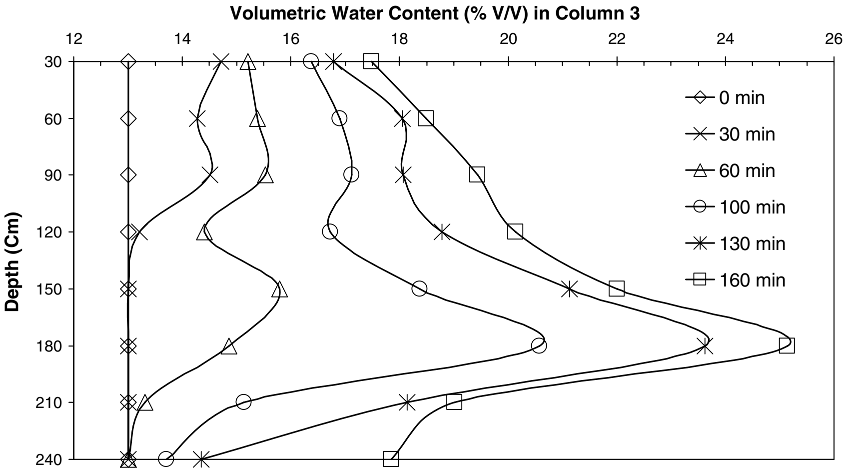

Fig. 5. Change in volumetric water content during rain simulation in column 3.

The saturated hydraulic conductivities, determined by the unitary profile method described previously, were $K_s = 1.71 \times 10^{-04}$ cm/s for column one, $K_s = 1.68 \times 10^{-04}$ cm/s for column two, and $K_s = 1.76 \times 10^{-04}$ cm/s for column three. These values are consistently close to data obtained by other authors (Chen and Chynoweth, 1995; Oweis et al., 1990). It is important to point out that, differently from unsaturated flow runs, the experiments in fully saturated media apparently behaved in accordance with Darcy's law, which was also verified by Korfiatis et al. (1984).

Darcy's law is well understood and accepted as valid in the cases of laminar flow, normally observed in micropores. In the cases of larger pores, flow becomes turbulent and the fluid velocity does not have a linear relation with hydraulic gradient. There exists an additional head loss with velocity increase and proportionality of the coefficient decreases with hydraulic gradient. Reynolds number can approximately determine the limit between laminar and turbulent flow. Laminar flow is guaranteed if $R_e < 1$ and turbulent flow if $R_e > 10$ (Bouwer, 1978). Therefore, flow in porous materials can behave as Darcian or Non-Darcian flow depending on the applied water velocity.

With the saturated hydraulic conductivity found, it was possible to calculate the Reynolds number for the saturated flow in the columns. A density of 996.31 kg/m^3 and a viscosity of 0.000833 kg/m.s for water at 28 °C were used. The pore average diameter was obtained from the work of Zeiss and Uguccioni (1997). A linear relation was assumed between MSW density and the average pore diameter in order to calculate the Reynolds number for a variety of diameters (Table 3). It is observed that the Reynolds numbers were well below one, a characteristic of Darcian flow.

After the rainfall and the saturated hydraulic conductivity experiments ceased, free draining of water was conducted by opening the bottom valve in columns one and two. In column one, as it can be observed in Fig. 6, the excessive water drained at a very fast rate up to 160 min. After seven days of free draining, moisture was relatively

Table 3
Reynolds number calculated for different pore diameters, using experimental saturated hydraulic conductivities

MSW densities (kg/m^3)	Pore diameter (cm)	Re
250	1.90	3.89E^{-02}
300	1.58	3.24E^{-02}
350	1.13	2.31E^{-02}
400	0.71	1.45E^{-02}
450	0.39	8.03E^{-03}
500	0.20	4.02E^{-03}

lower, around 23% v/v, between layers 90 and 240 but did not change significantly from the top to layer 90.

In column two, the free draining experiment initiated at full saturation (40.64% v/v) down to an average moisture of about 21% v/v on the 14th day, as shown in Fig. 7. A fast moisture decrease of about 50% (from 40.64% to 23.00%) in layer 30 cm was observed in the first minute of free draining. Moisture decreased very little after this first minute until 40 min. At 2.2 min it was observed that layer 180 cm maintained its initial saturation despite the significant moisture decrease in the upper and lower layers. It is important to observe that the moisture profile format after 40 min remained constant until day 14, a phenomenon also verified in column one.

The observed moisture profiles in the free draining experiments of both columns indicate that water is retained at two major levels of retention. The first one, more subject to gravity, was responsible for the fast water draining at the initial moments suggesting channeling flow through highly interconnected large empty spaces, as reported by Zeiss and Uguccioni (1994). The second one was responsible for most of the long-term moisture accumulation in the solid waste and for the slow draining over longer periods, characterizing the presence of a matrix with small dimension pores. This two-domain behavior was also observed

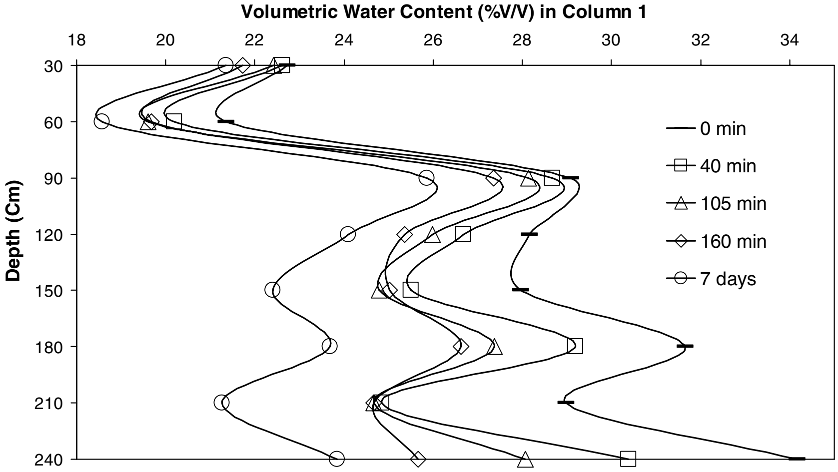

Fig. 6. Change in volumetric water content during the free draining experiment in column 1.

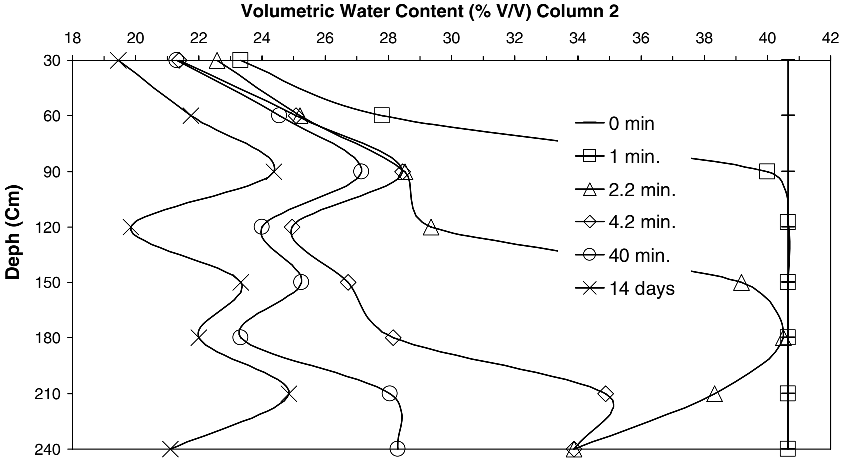

Fig. 7. Change in volumetric water content during the free draining experiment in column 2.

in the work of Rosqvist and Destouni (2000) and Rosqvist et al. (2003).

5. Conclusions

The experiment developed was capable of measuring absolute moisture content and the variation of volumetric water content in MSW samples during a simulated precipitation event in a non-destructive form. This provides a large range of possibilities for future research. Furthermore, this technique could be also applied in large-scale dry cell landfills and bioreactor landfills to measure solid waste moisture content. However, experimental and analytical errors involved in the new method, such as the effect of MSW density and porosity variations along the columns in the residual water content at saturation, influence of the sample size defined by the neutron cloud radius in the residual water content measurements, and validity of the neutron probe calibration curves must be further studied.

The observed water flow behavior does not agree with the physical models borrowed from conventional soil science. A determined layer does not need to reach a definitive saturation, called *field capacity* in the literature, in order to allow water through it. In fact, the definition of *field capacity* seems to be poorly applicable in the case of moisture flow through MSW.

While the MSW was fully saturated, the water flow in all three columns behaved as compatible with Darcy's flow. However, Darcy's law apparently does not physically represent the water flow in non-saturated MSW due to the presence of greatly interconnected macro-pores or preferential pathways (Bordier et al., 1997).

MSW heterogeneity was evident in all experimental runs despite having been subjected to the same compacting procedure. This behavior can be related to larger compacting rates applied in the inferior layers or to the presence of less permeable types of materials. In any case, this phenomenon is also observed in large-scale landfills and should be considered in any modeling effort.

In the free draining experiment, the presence of well interconnected preferential pathways was also verified. Preferential pathways contributed to the total flow to a greater extent than the micro-porous matrix. It is also important to consider that, as observed by Moore et al. (1997), the micro-porous matrix basic role was to store water in the solid waste by absorbing part of the inflow applied at the surface.

After a long period of free draining, uniform water content along the columns was not achieved. MSW-porous matrix discontinuity could be the cause of this pattern. This discontinuity could be caused by a spatially heterogeneous distribution of micro-porous material intercalated by materials with larger pores or even by the empty spaces that formed the channels. If so, experimental procedures that use matrix potential as an indirect way of measuring moisture content, such as tensiometers, may not be appropriate methods.

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