# POROSITY AND HYDRAULIC CONDUCTIVITY OF MSW USING LABORATORY-SCALE TESTS

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Summary: Municipal solid waste (MSW) hydraulic properties are key factors that influence flows within landfills. The objective of this study is to investigate the saturated hydraulic conductivity and porosity of different wastes and to assess the influence of waste density and maximum particle size on these parameters. Different series of tests are carried out in a 9.4L laboratory-scale cell on two distinct types of shredded MSW. The open porosity and the effective porosity of shredded waste samples are inferred from upward saturation and downward drainage tests. In addition, the saturated vertical hydraulic conductivity is quantified using a falling head test. A clear trend of decreasing effective porosities and permeabilities with density and a good correlation between effective porosity and hydraulic conductivity are highlighted. The average particle size and the structure of the waste influence the values of the porosities and the hydraulic conductivity significantly. The double porosity behavior, or at least two major levels of water retention exist in MSW, a highly heterogeneous material. Research is undertaken to investigate this aspect more thoroughly. The perspectives offered by this research are especially promising for hydraulic modeling purposes.

## 1. INTRODUCTION

Landfilling is still the most common municipal solid waste (MSW) disposal method used worldwide. The operation of landfills as bioreactors presents a promising alternative to conventional landfills because bioreactors are designed to enhance the waste stabilization process (Jain et al. 2006). They mainly involve increasing moisture content by the injection or recirculation of fluids in order to stimulate bioactivity. MSW is a very heterogeneous mixture of varied materials, and the quantification of waste materials' mechanical and hydraulic properties is challenging (Durmusoglu et al. 2006). MSW hydraulic conductivity and porosity influence the design and operation of bioreactor landfills. The relatively low hydraulic conductivity of heavily compacted wastes or waste experiencing relatively high vertical effective stress might hinder the recirculation process in bioreactors (Khire and Mukherjee 2007; Reddy et al. 2009). Besides, the knowledge of hydraulic conductivity is essential to ensure slope stability and leachate or gas well reliability and efficiency (Dixon and Jones 2005; Mukherjee 2008). Porosity also influences the mechanical behavior of waste (Olivier and Gourc 2007). The objective of this study is to investigate the hydraulic conductivity as well as the open and effective porosities of two compositions of shredded waste in two series of tests.

## 2. LITERATURE REVIEW

### 2.1 Hydraulic Conductivity

Waste permeability is classically considered to be anisotropic due to the composition and placement of MSW and to the use of daily cover soil (Bendz et al. 1997; Dixon and Jones 2005). The flow regime is therefore at least bi-dimensional. A structure with sub-horizontal layers is used to describe this anisotropy, leading to higher permeability values for the horizontal direction (e.g. Mukherjee 2008). Most research is focused on the vertical conductivity of waste, as it is decisive for water injection or leachate recirculation, being generally the limiting factor to recirculation rates. The saturated hydraulic conductivity can be determined at laboratory scale by performing constant head or falling head tests. Field scale hydraulic conductivities can be determined from pumping tests (Theis or Jacob method), borehole tests or even inverse modeling of liquid addition using permeable blankets (Mukherjee 2008). Table 1 presents selective published values of hydraulic conductivities that can be found in published literature:

Table 1. Literature review of saturated hydraulic conductivity values.

| Authors | Hydraulic Conductivity (m/s) | Conditions of the test |
|---|---|---|
| *Laboratory-scale* | | |
| Beaven and Powrie (1995) | $1.7 \times 10^{-4}$ to $2.0 \times 10^{-4}$ | Constant head test |
| Chen and Chynoweth (1995) | $4.7 \times 10^{-7}$ to $9.6 \times 10^{-4}$ | Constant head test |
| Durmusoglu et al. (2006) | $4.7 \times 10^{-6}$ to $1.2 \times 10^{-4}$ | Falling head test |
| Olivier and Gourc (2007) | $1.0 \times 10^{-6}$ to $1.0 \times 10^{-4}$ | Falling head test |
| Reddy et al. (2009) | $1.0 \times 10^{-8}$ to $1.0 \times 10^{-4}$ | Constant head test |
| *Field scale* | | |
| Oweis et al. (1990) | $1.0 \times 10^{-5}$ to $2.5 \times 10^{-5}$ | Pumping test |
| Burrows et al. (1997) | $3.9 \times 10^{-7}$ to $6.7 \times 10^{-5}$ | Pumping test |
| Gawande et al. (2005) | $1.2 \times 10^{-5}$ to $2.5 \times 10^{-5}$ | Inverse flow modeling |
| Jain et al. (2006) | $5.7 \times 10^{-8}$ to $1.9 \times 10^{-7}$ | Borehole permeameter test |

### 2.2 Porosity

The concept of porosity is complex and requires clear terminology (Olivier and Gourc 2007). The total porosity is the ratio between the volume of voids, $V_v$, and the overall volume of material, $V$ (Hudson et al. 2004):

$$n = \frac{V_v}{V} = 1 - \frac{V_s + V_{gs}}{V} \tag{1}$$

where $V_{gs}$ is the volume of gas trapped in the solids and $V_s$ is the volume of solids. However, the knowledge of total porosity has a limited significance, as unconnected voids are included, which do not contribute to the hydraulic behavior of the material. Therefore, two other porosities usable for practical engineering applications can be defined: the open porosity $n_o$ and the effective porosity $n_e$. The open porosity is defined by (Olivier and Gourc 2007):

$$n_o = 1 - \frac{V_s}{V} \tag{2}$$

The effective porosity can be in turn defined by (Hudson et al. 2004):

$$n_e = n - \frac{V_g^{'} + V_w^{'}}{V} \tag{3}$$

where $V_g$’ is the remaining volume of gas in the pore space, and $V_w$’ is the volume of liquid in the pore space which cannot be drained by gravity. However, there is no mathematical method to predict the effective porosity; it can only be back-calculated from experimental results. Similarly, Beaven and Powrie (1995) define the effective porosity of the refuse as the volumetric water content at field capacity. However, the true effective porosity may be higher than predicted by Equation 3, which considers gravimetric drainage. Table 2 presents published values of porosities for MSW:

Table 2. Literature review of porosity values (Eff. = Effective).

| Authors | Porosity (%) | Type of porosity |
|---|---|---|
| *Laboratory-scale* | | |
| Beaven and Powrie (1995) | 28% to 33.5% | Initial effective porosity |
| | 1.6% to 22.7% | Eff. porosity under stress |
| Zeiss (1997) | 47% to 57% | Initial effective porosity |
| Hudson et al. (2004) | 45.5% to 55.5% | Total porosity under stress |
| | 1.5% to 14.4% | Eff. porosity under stress |
| Olivier and Gourc (2007) | 48% to 51% | Initial open porosity |
| Stoltz and Gourc (2007) | 45% to 62% | Total porosity under stress |

## 3. MATERIALS & METHODS

### 3.1 Waste Characteristics

Two mixtures of shredded MSW samples ‘A’ and ‘B’, obtained from two French landfill sites, are used. The samples’ composition and characteristics are given in Table 3 and Table 4. To compare the different waste samples, the dry density, $\gamma_d$, is used. It is defined as:

$$\gamma_d = \frac{M_d}{V} \tag{4}$$

where $M_d$ is the dry mass. The Moisture Contents (MC) of the samples are determined at the end of each trial by oven-drying at 105°C for 72 hours.

Table 3. Composition of the MSW samples.

| *Waste component* | *Percentage by wet weight (%)* | |
|---|---|---|
| | Waste of type A | Waste of type B |
| Putrescible waste | 36.6% | 58.1% |
| Paper/Cardboard | 26.1% | 13.3% |
| Plastic | 14.0% | 9.5% |
| Glass | 6.1% | 5.4% |
| Metal | 5.7% | 0.4% |
| Textiles/Medical textiles | 5.5% | 2.1% |
| Miscellaneous | 6.0% | 11.2% |

Table 4. Physical characteristics of the MSW samples.

| *Characteristics* | Waste of type A | Waste of type B |
|---|---|---|
| Maximum particle size (mm) | 70 | 40 |
| Average bulk density ($kg.m^{-3}$) | 0.70 | 0.78 |
| Initial gravimetric MC (m/m) | 36.6% ± 2.0% | 48.1 % ± 2.0% |
| Initial volumetric MC (v/v) | 21.5% ± 1.5% | 39.2% ± 1.5% |

The major difference between the two samples is that sample 'A' is very close to typical French domestic waste, whereas sample 'B' is finely-graded and has a high proportion of organic material.

Trials are run at various dry densities approximately ranging from 0.3 to 0.5 $Mg/m^3$. These values are slightly lower than reported values for field waste. Based on a gravimetric Moisture Content of 30%, Oweis et al. (1990) have found $\gamma_d$ values ranging from 0.34 to 0.77 $Mg/m^3$. Zhan et al. (2008) have found in-situ values of $\gamma_d$ ranging from 0.3 to 1.2 $Mg/m^3$. However, the experimental cell used in this study does not enable to test samples with dry densities higher than 0.5 $Mg/m^3$, which correspond, according to some field investigations (Zhan et al. 2008), to an approximate depth of 10 meters maximum.

### 3.2 Experimental Setup

The experiments are performed in a custom-made cell called the "alpha cell". The alpha cell is a rigid 20 cm diameter, 30 cm long, Polymethyl Methacrylate (PMMA) watertight cylindrical tube whose upper and lower ends are closed with PVC plates. The container is used to saturate, drain, and run falling head tests on waste samples. All tests are performed using de-aired water to ensure no air is added to the waste. Waste is placed in the cell in four lifts and compacted after each lift to ensure uniform density throughout the cell. A diffusion disk is placed at the bottom of the cell to equally distribute the water being introduced to the waste. After being sealed, the cell is placed on a scale and the initial mass is recorded. Two scales are used in this experiment, the Soehnle 7745 professional scale for mass readings during the imbibition of the sample, precise to five grams (Soehnle Leifheit, Nassau, Germany), and the Baxtran BAT 1500 precision scale for the determination of the drained leachate quantities to determine the effective drainage porosity, precise to 0.02 grams (Baxtran Scales S.L., Vilamalla, Spain). A constant head tank, shown with the alpha cell in Figure 1, is then placed at a height of 12.0 cm ± 0.5 cm above the top of the MSW sample to allow for a sufficient head $h_0$ for saturation. The head is maintained constant in the tank using a ball cock valve.

All experiments to determine both open and drainage porosities are run twice to ensure consistency of the results. The results shown in the following are the average values of the series of two trials.

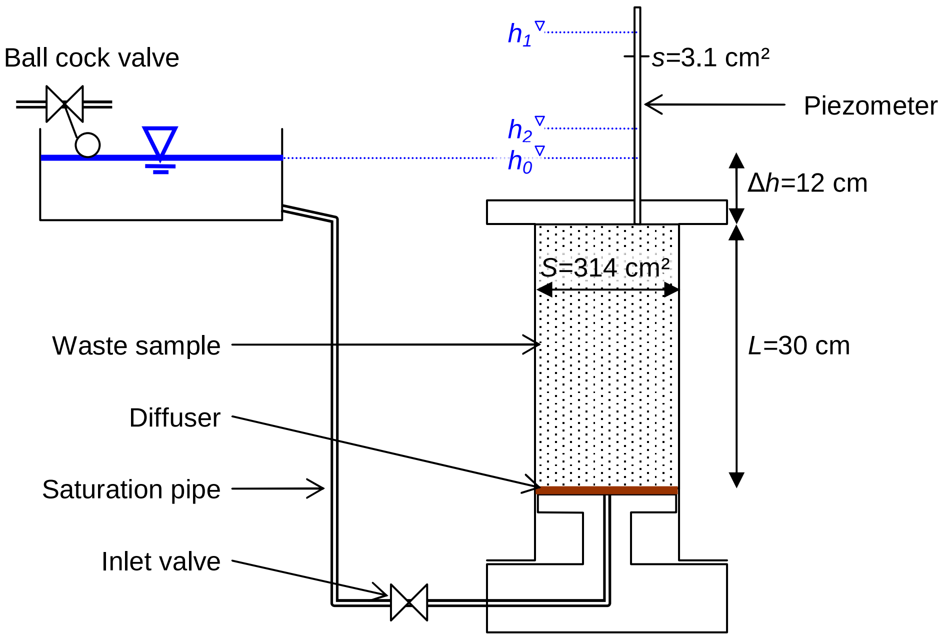


Figure 1. Schematic of the alpha cell and of the experimental setup during the sample's saturation phase. *S* and *s* are the diameters of the cell and the standpipe, respectively.

### 3.3 Determination of the Open Porosity

The open porosity discussed in this paper refers to the open porosity for water at a head of 12.0 ± 0.5 cm. At the start of the experiment, the inlet valve is opened and the mass is then recorded at frequent time intervals. As water enters the waste sample, the air in the pores of the waste is displaced as it escapes, thus once the cell reaches its equilibrium at saturated state, the open porosity is known. The final mass is the number used to calculate the total open porosity of the sample. Every trial lasts for a time of 6 to 8 hours. Due to the relatively short-term length of the experiment and small hydraulic gradient, the "final porosity" determined by this test is actually the open porosity to water as defined above, and is different from the total porosity using back-pressure. This is why the results yielded here may differ from experiments conducted by Stoltz and Gourc (2007) with gas back-pressure and under. However, the difference between these two porosity values is assumed to be small, and the sample can be considered saturated by water as the remaining unsaturated pores do not impact the porosity that affects saturated the hydraulic conductivity.

### 3.4 Determination of Hydraulic Conductivity

The saturated vertical hydraulic conductivity of each sample is determined using a falling head test. The falling head test is run after the sample is saturated as described above. Water is placed in the vertical tube until it stabilizes at the level $h_1$. The valve at the base of the cell is opened until the water surface reaches the half-way point in the tube. The time it takes for the water to stabilize ($\Delta t$) and the distance the water surface drops ($h_2$) are recorded. The saturated vertical hydraulic conductivity $K_{sat}$ of the waste is then obtained from the falling head permeameter formula:

$$K_{sat} = \frac{s}{S} \cdot \frac{L}{\Delta t} \cdot \ln\left(\frac{h_1}{h_2}\right) \qquad (5)$$

where $s$ and $S$ are the sections of the stand pipe (piezometer) and of the sample respectively ($m^2$), $L$ is the sample length (m), $\Delta t$ is the time to go from $h_1$ to $h_2$ (s). This procedure is run five times on each sample to ensure consistency, and the average is taken.

### 3.5 Determination of the Effective Porosity

After saturation and permeability tests are completed, a drainage procedure is performed on the cell for several hours. The mass of water collected from the cell is continuously recorded at frequent time intervals. To neglect biodegradation and to ensure gas production may be ignored, the tests are performed within the same day as the saturation and the hydraulic conductivity tests (maximum drainage time is 6 to 8 hours).

The effective porosity may be determined more accurately during drainage than during saturation of the sample, as during saturation it is not only the macropores being filled, but also some micropores. The values obtained for open porosity and effective porosity are compared.

## 4. RESULTS & DISCUSSION

### 4.1 Hydraulic Conductivities of the MSW Samples

The saturated vertical hydraulic conductivity data is shown below in Figure 2. As displayed in the graph, when dry density increases, hydraulic conductivity decreases. This trend is observed for both waste samples 'A' and 'B'. On the whole, as density increases, the volume of voids decreases, therefore restricting the ability of fluid to flow through the medium. The overall average value of the saturated vertical hydraulic conductivity of 'A' waste is $5.61 \times 10^{-5}$ m/s, that of 'B' waste is $3.34 \times 10^{-5}$ m/s. These values fall within the range of previously published data shown in Table 1. As the data indicates, $K_{sat}$ of both fall in the same order of magnitude. The 'A' trials show a slighlty lower dependance of conductivity on the dry density, probably because the maximum particle size of this sample is larger than that of 'B' waste, hence allowing large voids to remain even at higher compaction. This assumption will be confirmed later on by the higher effective porosity values found for 'A' waste. The range of dry densities covered by the tests is not wide enough to see a major role played by the compaction of the samples, but indicates a clear decreasing trend.

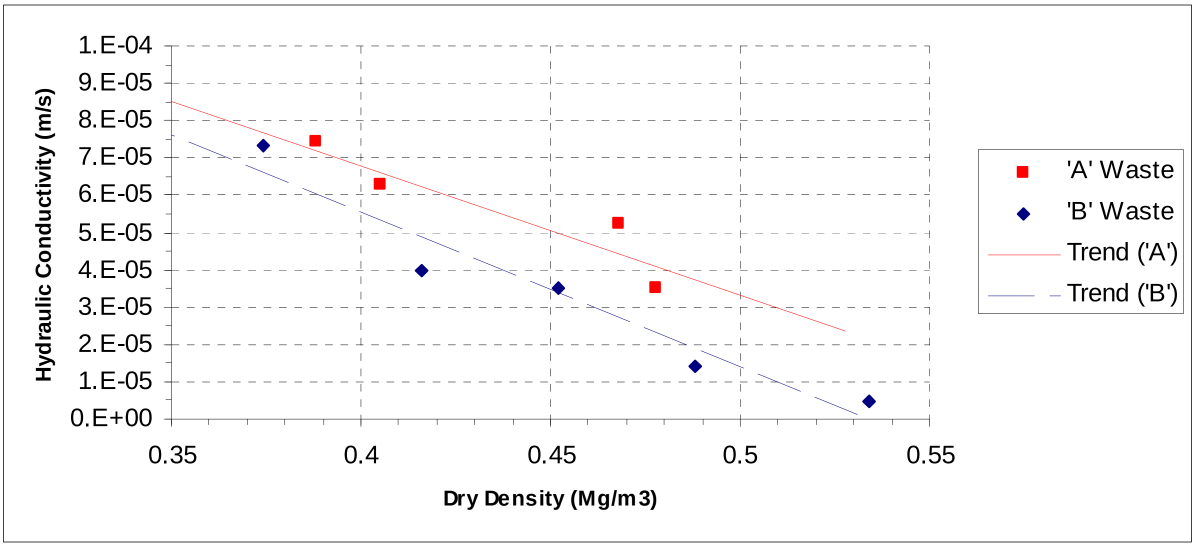


Figure 2. Saturated hydraulic conductivity of the MSW samples.

### 4.2 Porosities of the MSW Samples

Figure 3 displays the results of the porosity tests. The open porosities of both materials remain almost constant as dry density increases. The open porosity values are in the range of 60 to 70 which is consistent with published values for MSW,. The values obtained for the two MSW samples are very consistent, 'B' waste samples being slightly more porous. The maximum open porosity is found for the lowest density of sample 'A' and is as high as 72.9%. Effective porosity is decreasing with increasing density, as it is divided by a factor 2 when the dry density is increased from 0.42 kg/L to 0.49 kg/L for the 'B' waste, and from 0.38 to 0.48 for the 'A' waste. For both samples, the loss in effective porosity is greater than the loss in open porosity. The values of total open porosity for both samples are slightly higher than the range of published data shown in Table 2.

Figure 3 shows that both MSW samples have relatively similar open and effective porosities. For both samples, the effect porosity is decreasing as a function of dry density. Hence, the compositional differences and the maximum particle size have relatively small influence on the open porosity and the effective porosity. The density has a greater influence on the effective porosity values.

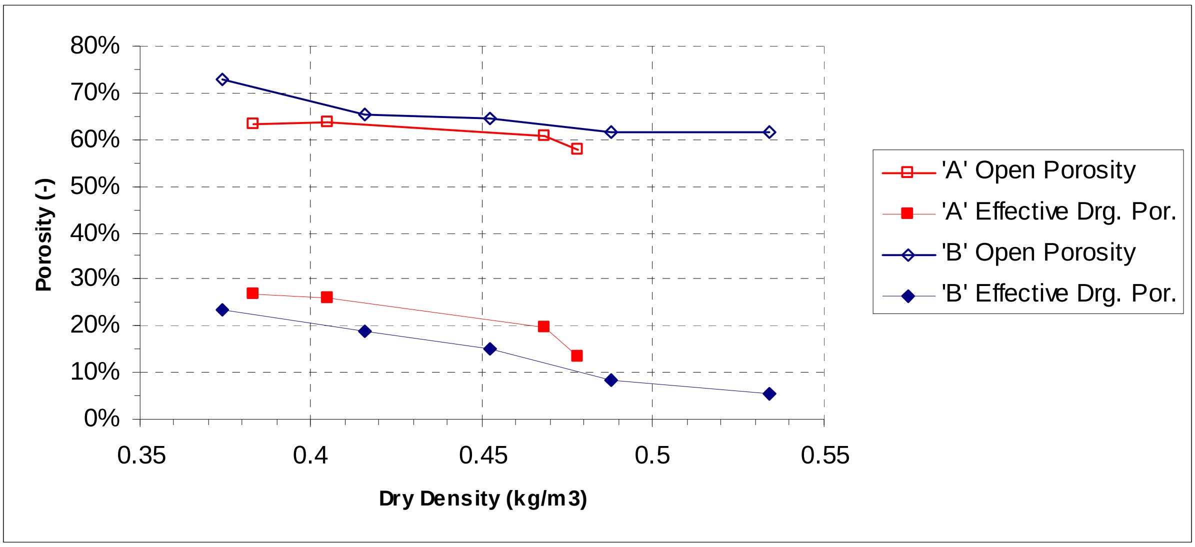


Figure 3. Open porosity and effective porosity of the MSW samples.

### 4.3 Relation between Effective Porosities and Hydraulic Conductivities of the Samples

A connection can be drawn between effective porosity and hydraulic conductivity. As dry density increases, the effective porosity decreases, which causes the vertical saturated hydraulic conductivity to decrease (Figure 4). This behavior is significantly influenced by the pore structure. The compaction tends to reduce the number and the cross-sectional area of these flow paths causing a large decrease of the effective porosity. In the same time, a part of the pores must lose their hydraulic connectivity or reach a higher capillary retention potential since they "disappear" from the effective porosity with an almost constant total open porosity. Nevertheless, the remaining channels provide a better hydraulic conductivity to "A" sample than to "B" sample.

The trend of decreasing hydraulic conductivity with effective drainage porosity is remarkably comparable for both waste samples. This suggests that the major driver for hydraulic conductivity is the effective porosity, which is in accordance with the theory. However, one should note that the covered density range is small and the number of tests carried out is not sufficient to provide for a general assessment of the influence of porosity on permeability. The discrepancy in the various tests carried out to obtain these results may not be negligible and the effect of the waste placement can be significant.

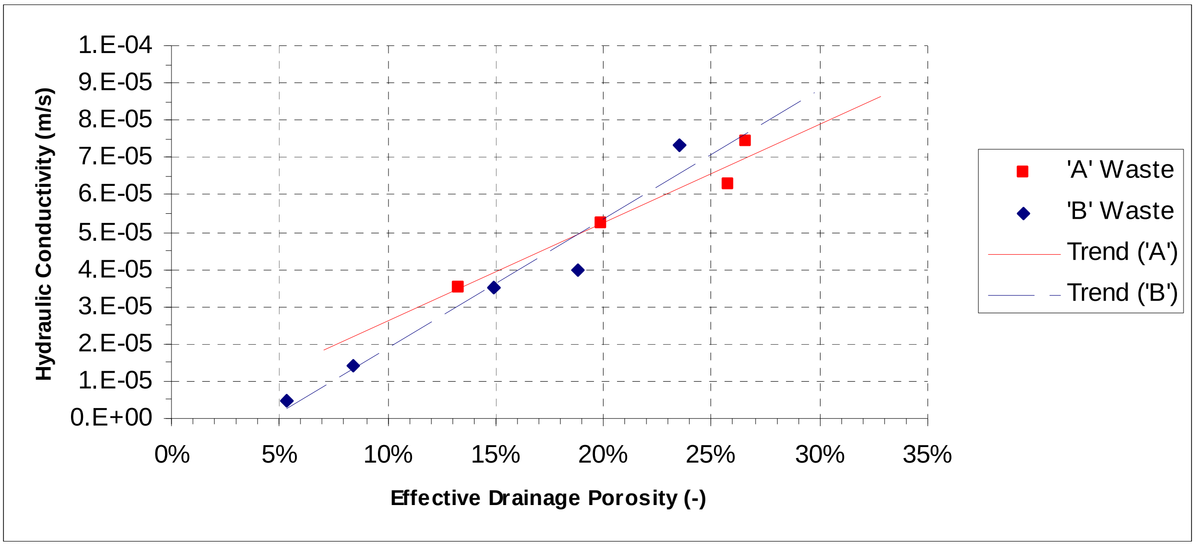


Figure 4. Correlation between effective porosity and hydraulic conductivity

## 5. CONCLUSIONS & PERSPECTIVES

The results of these two series of experiments yield a range of saturated vertical hydraulic conductivities from 4.6 x $10^{-6}$ m/s to 7.4 x $10^{-5}$ m/s for low density shredded waste. The determined open porosity of the samples ranges from 57.7% to 72.9% for the waste samples. A significant influence of the effective porosity of the waste on its hydraulic conductivity is also highlighted, though this aspect should be investigated more thoroughly for a wider range of dry densities.

The perspectives of this work are to validate these findings by modeling the saturated and unsaturated flows in waste. What is more, distinguishing the effective porosity from the open porosity opens perspectives for double-porosity models. An in depth analysis of the different porosities of MSW has commenced in order to improve the description of liquid exchanges within the waste body.

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**REFERENCES**

Bendz D., Singh V. P., Berndtsson R. (1997). The Flow Regime in Landfills – Implication for Modelling. *Proceedings of Sardinia 97, 6th International Landfill Symposium*, October 13th-17th, S. Margarita di Pula, Italy.

Beaven R., W. Powrie (1995). Hydrogeological and Geotechnical Properties of Refuse Using a Large Compression Cell. *Proceedings of Sardinia 1995, 5th International Landfill Symposium*, October 2nd-6th, Cagliari, Italy.

Burrows M. R., Joseph J. B., Mather J. D. (1997). The hydraulic properties of in-situ landfilled waste. *Proceedings of Sardinia 97, 6th International Landfill Symposium,* October 13th-17th, S. Margarita di Pula, Italy.

Chen T.-H., Chynoweth P. (1995). Hydraulic Conductivity of Compacted Municipal Solid Waste. *Bioresource Technology* 51, 205-212.

Dixon N., Jones D. R. V. (2005). Engineering properties of municipal solid waste. *Geotextiles and Geomembranes* 23, 205-233.

Durmusoglu E., Sanchez I. M., Corapcioglu M. Y. (2006). Permeability and Compression Characteristics of Municipal Solid Waste Samples. *Environmental Geology* 50, 773-786.

Gawande N. A., Reinhart D. R., Cortazar A. L. G. (2005). Landfill MSW Hydraulic Conductivity Estimation Using in situ Moisture Sensors. *Proceedings of Sardinia 2005, 10th International Landfill Symposium,* October 3rd-7th, S. Margarita di Pula, Italy.

Hudson A. P., White J. K., Beaven R. P., Powrie W. (2004). Modelling the compression behaviour of landfilled domestic waste. *Waste Management* 24, 259-269.

Jain P., Powell J. Townsend T. G. (2006). Estimating the Hydraulic Conductivity of Landfilled Municipal Solid Waste Using the Borehole Permeameter Test. *Journal of Environmental Engineering*, 132, 645-652.

Khire M., Mukherjee M. (2007). Leachate Injection using Vertical Wells in Engineered Landfills. *Waste Management* 27, 1233-1247.

Mukherjee M. (2008). Instrumented Permeable Blankets for Estimation of Field-Scale Hydraulic Conductivity of Waste and Confirming Numerical Models. Ph.D. Dissertation, Dept. of Civil and Environmental Engr., Michigan State University, E. Lansing, USA.

Olivier F., Gourc J.-P. (2007). Hydro-mechanical behavior of MSW subject to leachate recirculation in a large-scale compression reactor cell. *Waste Management* 27, 44-58.

Oweis I. S., Smith D. A., Ellwood R. B., Greene D. (1990). Hydraulic characteristic of municipal refuse. *Journal of Geotechnical Engineering*, 116 (4), 539-553.

Reddy K. R., Hettiarachchi H., Parakalla N. S., Gangathulasi J., Bogner J. E. (2009). Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA. *Waste Management* 29, 952-959.

Stoltz G., Gourc J.-P. (2007). Influence of Compressibility of Domestic Waste on Fluid Permeability. *Proceedings of Sardinia 2007, 11th International Landfill Symposium,* October 1st-5th, 2007, S. Margarita di Pula, Italy.

Zeiss C. (1997). A Comparison of Approaches to the Prediction of Landfill Leachate Generation. *Sardinia 1997, 6th International Landfill Symposium*, October 13th-17th, Cagliari, Italy.

Zhan T. L. T., Chen Y. M., Ling W. A. (2008). Shear strength characterization of municipal solid waste at the Suzhou landfill, China. *Engineering Geology* 97, 97-111.