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# MSW characteristics and landfill performance in tropical regions

**S. L. Machado[1,]*, M. Karimpour-Fard[2], M. F. Carvalho[3], O. Monjer Vilar[4], Á. Caldas Santos[5]**

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**Abstract**

*Municipal Solid Waste (MSW) materials are among the most complicated materials for geotechnical engineering as their composition includes an organic fraction, which suffers loss of mass over time, and a fibrous part, which acts as reinforcement, governing the MSW shear behavior. Because of these characteristics MSW can be described as a viscous material which shows time dependent behavior. Since the decomposition of MSW leads to gas and leachate generation, the changes in the mechanical behavior of MSW could be linked to gas emission and leachate production from landfills. This paper deals with the characteristics of MSW materials to provide the necessary data for efficient and safe landfill design, construction and operation. Physical characteristics such as composition, water content and organic content at varying ages, field and laboratory measurements of methane generation and leachate production, MSW compressibility behavior and its shear strength are covered. By presenting these data the authors hope to promote a better understanding of the mechanical behavior of MSW and provide useful data for use in landfill management tasks.*

**Keywords:** *Municipal solid waste, Landfill, Mechanical and physical properties, Methane emission, Leachate production.*

## 1. Introduction

The environmental impact of disposing of all kinds of solid waste has long been recognized. Despite the fact that many strategies, such as “3Rs” (reduce production, recycle and re-use waste), have been introduced in recent years, large amounts of waste must still be disposed of.

Landfilling is the most common method of disposing of Municipal Solid Waste, MSW. However, uncontrolled population increase in urban regions, mainly in developing countries, has put pressure on municipal authorities and geo-environmental designers to design and construct new dump sites. The difficulties of finding new locations for waste disposal due to social reaction and resistance is a further challenge.

An engineer designed landfill is usually conceptualized as a biochemical reactor. In this giant reactor, waste and water are the main inputs, while gas and leachate are the major outputs. Landfill gas is the result of biological anaerobic decomposition of organic materials in landfills.

The principal constituents present in landfill gas are methane ($CH_4$) and carbon dioxide ($CO_2$), but landfill gas is commonly saturated with water vapor and presents small quantities of other organic components. In modern landfills, this gas is usually collected to prevent its undesirable release into the atmosphere or its movement through the surrounding soil. Sometimes the recovered gas is flared and nowadays there is an increasing interest in using landfill gas to produce energy. Therefore potential gas generation and its production rate is crucial as these are the most important parameters in designing gas collection and flaring systems or an electric power plant, for example.

As gas emissions in a landfill are the result of the bio-degradation of the MSW and the loss of mass can be related to the rate of biogas or methane production. Researchers such as Liu et al. [1], Machado et al. [2], Sivakumar et al. [3], Gourc et al. [4] and others have suggested different models to estimate the bio-degradation induced settlement in waste fills. Prediction of the extent of settlement occurring in a landfill cell can help the operators to make more optimized use of the dump site capacity as well as the execution of final covers at the right time.

The leachate in a landfill produced from the decomposition process should also be accurately estimated because the volume of collected leachate is a key parameter in the design of the leachate treatment and drainage facilities and obviously stability issues arising with the flow of liquids inside geomaterials.

The catastrophic effects of instabilities in a landfill body have been reported, analyzed and discussed by geo-

* Corresponding author: smachado@ufba.br
1 Department of Materials Science and Technology, Federal University of Bahia, 02 Aristides Novis St, Salvador, BA, Brazil
2 Faculty of Engineering, University of Guilan, Rasht, Iran
3 School of Engineering, Catholic University of Salvador, 2589 Pinto de Aquiar Av, Salvador, BA, Brazil
4 Geotechnical Department, University of São Paulo, 1465 Dr. Carlos Botelho Av, São Carlos, SP, Brazil
5 Interdisciplinary Center for Energy and Environment, Federal University of Bahia, 02 Aristides Novis St, Salvador, BA, Brazil

environmental researchers. Koerner & Soong [5] analyzed failures which occurred in ten large landfills. They stated that all the triggering mechanisms in the studied cases are liquid related, i.e. leachate buildup within the waste mass, wet clay beneath the geomembrane, or excessively wet foundation soil. They proposed five different scenarios, the third scenario of which, regarding the presence of leachate head acting on the liners, is probably the most common cause of landfill ruptures. However, the fifth scenario, which considers the effect of excess pore pressure in the MSW mass stability, is becoming much more important due to the tendency to construct bio-reactor landfills in which leachate is re-circulated inside the landfill body. This must be considered both in the design and performance issues. Clearly the number of catastrophic failures in landfills over the last decade is an indication that the mechanical behavior of MSW materials as a geo-material has not been investigated completely, despite the fact that much valuable work has been carried out in this field.

In this paper, after introducing the Metropolitan Center Landfill (MCL), located in Salvador, Brazil, a review of the achieved results of research performed on the characteristics of MSW collected in this landfill will be presented. These characteristics are the composition, water content and organic content at different ages, field and laboratory measurements of methane generation and leachate production, The MSW compressibility behavior and its shear strength are also among these characteristics. The authors believe the results reported in this paper could be used as a reliable source of information for the design, construction and operation of landfills in tropical regions.

## 2. Landfill Site

The Metropolitan Center Landfill, MCL, is located around 20 Km from the city center of Salvador, capital of the state of Bahia, Brazil. The daily input of MSW is about 2500 Mg. The total landfill area available is about 25 hectares and the filling process started in October 1997. The initial estimated lifespan of the facility was 20 years but it is now estimated to be more than 30 years as a consequence of several design modifications and improvements. In Fig.1 an aerial photograph of the MCL is presented.

Incoming waste rates are subject to seasonal oscillations (Fig. 2). There are peak values in the period December to March. This is probably associated to the influx of tourists in the summer season. If seasonal variations are taken into account, it can be said that after March 1999 the rate of incoming waste has remained almost constant over time.

The bottom of the MCL cells is located 6-12m below the soil surface and the thickness of the waste column at the end of the disposal process reaches about 45m. A double liner system is used at the bottom and on the lateral slopes of the cells (1m clay liner, $k < 1x10^{-7}$ cm/s plus 2mm HDPE membrane). Temporary top covers are made using a single layer of soil $k < 1x10^{-5}$ cm/s, 60cm thick. These layers are removed in case of additional disposal. Final covers use a PVC-Geotextile membrane (PVC-GM) over the soil layer (60cm thick) and about 20cm of organic soil for grass support, which is spread over the PVC-GM.

**Fig. 1** Aerial photograph of the Metropolitan Center Sanitary Landfill

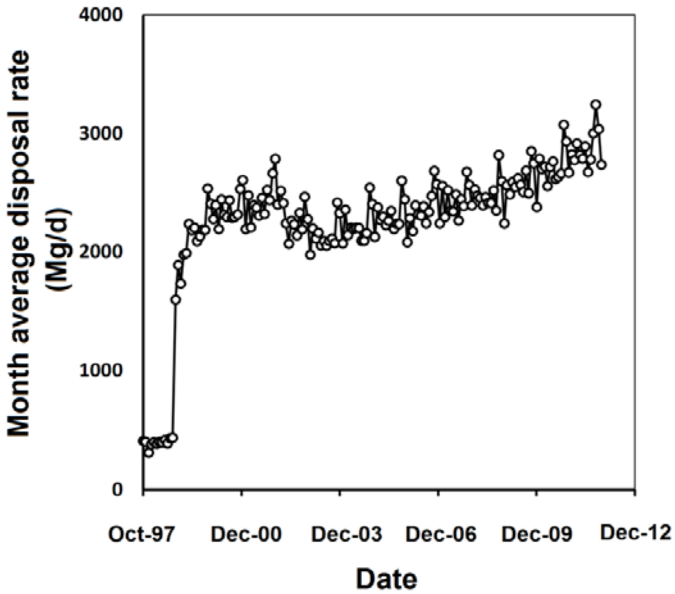



**Fig. 2** MSW disposal rate at the Metropolitan Center Landfill

A biogas recovery system was installed at the end of 2003 as part of the landfill's clean development mechanism. To date, this system is composed of almost 200 superficial and deep gas drains. Deep gas drain construction normally follows the landfilling process and they connect the bottom to the cover layers of the landfill. There are however, additional deep drains which are installed after the final cover using boring machines. In this case the depths are about 20 meters.

Superficial drains are located above the soil layer of the final cover and beneath the PVC-GM (Fig. 3) and serve to collect the bio-gas accumulated in this region and to minimize possible fugitive emissions due to PVC-GM non-conformities. Individual measurements of gas flow rate, temperature and composition are made monthly of all the drains of the landfill. The gas recovery system is composed of a control center, where measurements of temperature, composition and recovery rates are made considering the system as a whole, three flares, gas humidity removers and a set of pumps responsible for applying suction to all the installed drains for gas extraction. All the produced biogas is directed to a thermal power plant with a nominal capacity of 20 MW of energy.

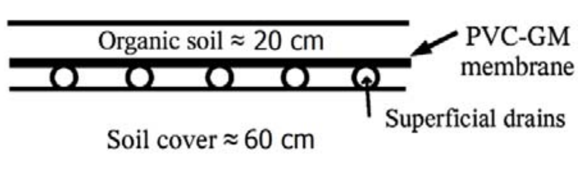



**Fig. 3** Schematic view of the final cover adopted in the MCL

## 3. Physical Characterization of MSW

Since 2004, every 6 months samples of MSW have been collected from MCL. The samples were generally fresh and were collected before landfilling. However, to address the effect of aging on the key MSW parameters such as water and organic content, some complementary sampling campaigns were performed in waste fills of different ages. To collect samples from shallow depths an excavator was used and for samples located in deeper parts a drilling machine. In the following sections the results obtained from these sampling campaigns are briefly presented.

### *3.1. Water content*

MSW water content was determined using representative samples obtained after manual and machine assisted homogenization and quartering. The waste composition, wet basis, was measured immediately after sampling in a field laboratory using some basic tools (oven, balance, trays, masks, gloves, plastic sacks, etc.). The waste was separated into the following component groups: paper/cardboard, plastic, rubber, metal, wood, glass, ceramic materials/stone, textiles and paste fraction. The paste fraction includes organic materials that are easily degradable (food waste), moderately degradable (e.g. leaves) and other soil like materials which could not be easily separated.

After weighing each component the samples were placed in an oven at a temperature of 70°C. The samples were kept in the oven until weight stabilization. Using this approach not only could the moisture content of each component be calculated but also the average waste water content could be ascertained and compared to that obtained using the waste with no segregation (sample of 20kg).

Fig. 4(a) compares the water content values achieved in this research with values reported in literature. As can be observed the average moisture content of the MCL samples is higher than results presented by others. The MCL samples presented less variation in the moisture content compared to the values reported by Landva & Clark [6], Blight et al. [7], Coumoulos et al. [8] and Gabr & Valero [9]. Jucá et al. [9] presented relatively low moisture content values, but in this case the waste samples were collected from a 17 year old waste fill with a very high level of bio-degradation. Fig. 4(b) shows the variation in the water content with age in these landfills. A clear decrease in the water content of MSW samples over time can be observed which is in agreement with the concept of MSW decomposition, although sampling depth and the performance of the leachate drainage and collection system could affect this.

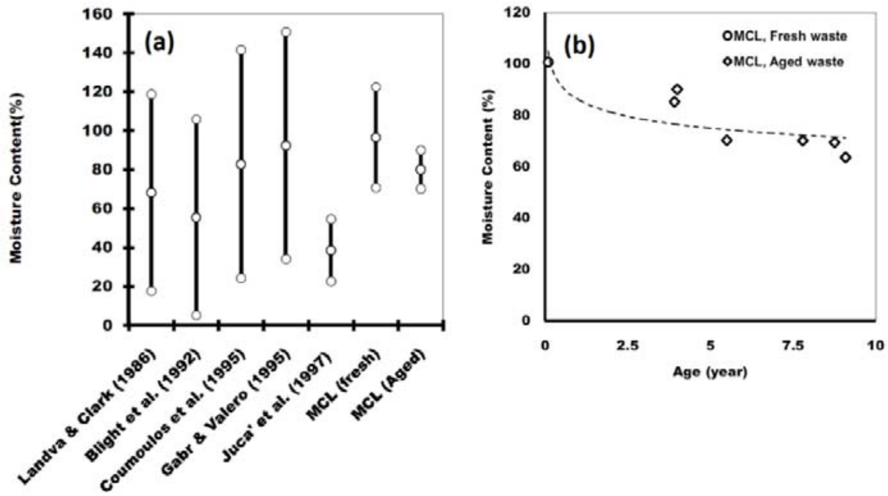



**Fig. 4** MSW moisture content values (a) comparison with reported values in literature (b) variation with age

### *3.2. Waste composition*

After the separation and measuring the water content of the waste components, the composition of dry waste was determined. Fig. 5 shows the average waste composition. The average percentage of plastics, which are referred to as the fibrous elements in the MSW samples, was about 20%. This can be considered high compared to the amounts reported in the literature. If textiles and rubber are also taken as reinforcement elements, the fiber content of the waste reaches about 25%. Furthermore, paper and cardboard can act as reinforcement elements (at least in a short term analysis) but because of the high moisture content of MSW samples in MCL and the loss of tensile strength of these materials due to wetting, these components are not considered to be reinforcement elements in the MCL.

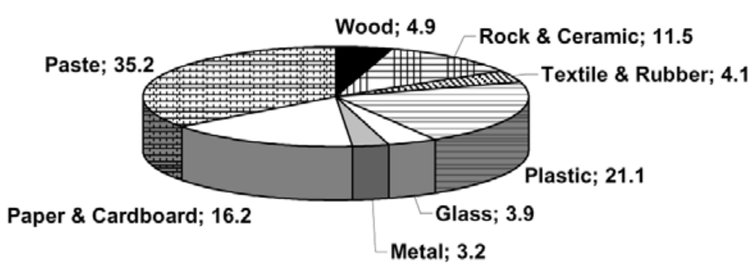



**Fig. 5** Average fresh waste composition in MCL (in percent)

### *3.3. Particle size distribution of MSW*

Sieve analysis was performed with opening sizes from 0.075 mm to 101 mm using the waste components after drying. For components of sizes between 101 and 400 mm the average dimensions were measured manually. Fig. 6 presents the size distribution of different waste samples. As can be observed, the older the waste, the more biodegraded it is and this is reflected in a reduction in the particle size of waste elements. In fresh waste samples, 50% of the material is smaller than 30 mm. This percentage increases to 65 and 73 for 1 and 4 year old samples respectively. This figure also shows the boundary limit for the size distribution of MSW materials suggested by Jessberger [11]. As can be seen, although the size distribution curve of fresh waste falls inside this range, old samples tend to have grain size distribution curves located to the left of the suggested boundaries.

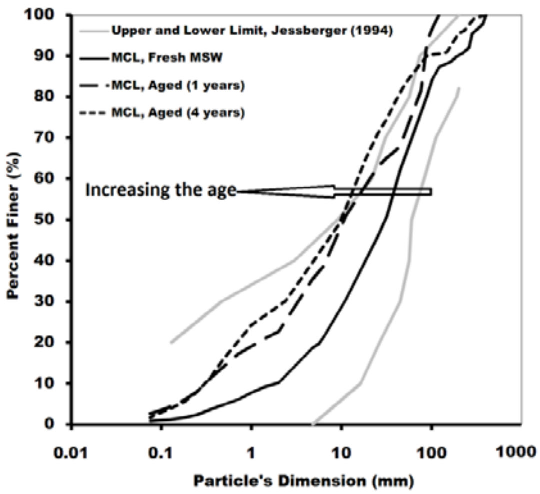



**Fig. 6** Particle size distribution of waste samples

*3.4. Total volatile solids*

Total Volatile Solids of the MSW's paste part (TVS, or ignition lost) was obtained after waste sieving. The paste fraction was quartered to a mass of about 1000g and ground for size reduction and to increase the specific surface. For each sampling campaign, about 36 paste samples of 20g were placed into crucibles and dried in an oven at 70°C for 1 hour. The samples were then combusted in muffle at 600°C for 2 hours. The volatile content was computed using the ratio between the loss of mass and the dry mass before combustion. Fig. 7 presents the variation in TVS with age of the MSW materials.

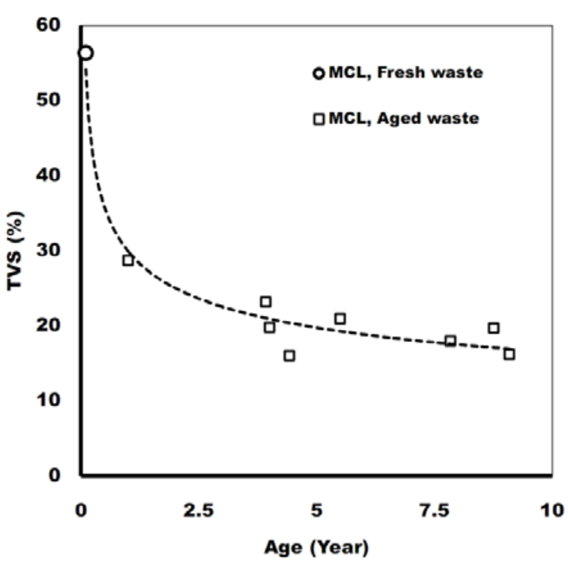



**Fig. 7** Variation in organic content with age

As can be observed in the first year a sharp decrease in the TVS occurs (around 50%) and after that the decomposition rate decreases considerably. During a 10 year period the decrease in TVS is about 75%.

## 4. Methane Gas Generation

Determining the gas generation potential and rate for MSW materials is crucial as these are the most important parameters for the design of the gas collection and flaring systems or the electric power plant. Some models have been drawn up to estimate the methane and biogas generation rate of landfills, such as the first order decay model recommended by the Environmental Protection Agency, USEPA [12, 13 and 14] and Intergovernmental Panel on Climate Change IPCC [15].

The gas generation parameters can be obtained in various ways such as theoretical prediction, laboratory experiments and from best fit analysis of gas recovery in real landfills. Theoretical predictions based on the chemical composition of the waste would give the absolute maximum methane potential. However, in practice this potential is never reached due to the inability of all the organic waste to decompose. Therefore the theoretical methane potential must be adjusted by a biodegradability factor, also based on various assumptions [14].

Both USEPA [12] and IPCC [15] consider that the methane generation rate decays exponentially with time (Eq. 1). In this equation, q is the specific methane generation rate ($m^3$ $CH_4$ /yr·Mg of MSW), k is the methane generation rate constant ($yr^{-1}$), t is the average age of the waste layer (yr) and $L_0$ is the methane generation potential ($m^3$ $CH_4$ /·Mg). Because each layer in a landfill will have its own t value, the total landfill gas production will be the sum of the product of Eq. 1 by the layer MSW mass.

$$q = L_0 . k . e^{-kt} \quad (1)$$

According to Machado et al. [2], the value of $L_0$ can be estimated using the value of $C_m$ (value predicted by stoichiometric equations, which assumes the complete conversion of organic matter to gaseous products, $m^3$ $CH_4$ /dry-Mg), the biodegradable fraction of the waste, BFw ( - ) and water content of MSW ( - ). Eq. 2 can be used to calculate $BF_W$. The fraction (dry basis) of each component in the waste composition, FR, is multiplied by its BF value and the value of $BF_W$ is calculated by adding the components considered. The waste average value of $C_m$ can be calculated using Eq. 3. Table 1 shows the values of $C_m$ and water consumption for the complete decomposition of various waste components. These values are based on the Tchobanoglous et al. (1993) equation for organic matter depletion. More details are provided in Machado et al. (2009).

$$BF_W = \sum_{i=1}^{n} BF_i \cdot \%FR_i \quad (2)$$

$$C_m = \frac{\sum_{i=1}^{n} BF_i \cdot \%FR_i \cdot C_{mi}}{BF_w} \tag{3}$$

Once the $BF_W$ and $C_m$ values are known, Eq. 4 can be used to calculate $L_o$. The water content, w, is used to consider only the dry mass of potentially degradable organic matter.

$$L_o = \frac{BF_W \cdot C_m}{1 + w} \tag{4}$$

Table 1:

| $H_20$ kg/dry-kg | | |
|---|---|---|
| food wastes | 505.01 | 0.26 |
| Paper | 418.51 | 0.20 |
| Cardboard | 438.70 | 0.16 |
| Textiles | 573.87 | 0.41 |
| Leather | 759.58 | 0.64 |
| Yard wastes | 481.72 | 0.28 |
| Wood | 484.94 | 0.24 |

More details regarding this procedure can be found in Machado et al. [2].

According to USEPA [13] the values of $L_0$ vary widely; between 6.2 and 270 $m^3$ $CH_4$ /Mg of MSW and developing countries often present higher values of $L_0$. It must be emphasized however, that in tropical developing countries the elevated water content tends to reduce the dry matter content of the waste, counterbalancing the presence of high amounts of organic matter. k values of around 0.2 $yr^{-1}$ are associated to high temperatures and moisture contents and to the presence of large amounts of food waste.

According to our results from the MCL, field values of k higher than 0.2 are common and the waste enters the transitional decomposition phase just a few weeks after disposal (presence of 10% or more methane in biogas decomposition).

Fig. 8 shows the methane gas recovery and fugitive emissions in MCL for a 2.5 year period presented by Machado et al. [2]. Values of specific methane generation rate (L $CH_4/m^2 \cdot h$) obtained using the superficial drains were used to estimate fugitive emissions in the exposed area. As can be seen, the methane recovery rate increases from 3,013 $m^3$ $CH_4$ /h in June 2004 to 5,095 $m^3$ $CH_4$ /h in August 2006. Fugitive emissions decreased from about 21% to 5% of the total generated over the same period.

Fig. 9 shows the estimated parameters of methane production based on the procedure proposed by Machado et al. [2]. Eq. 5 was used to model the decay of the remaining $L_0$ values over time. Values of $k = 0.21$ $yr^{-1}$ and $L_0 = 63.6$ $m^3$ $CH_4$/Mg MSW were obtained fitting Eq. 5 to experimental results.

$$L_{.}(t) = L_0 . e^{-kt} \tag{5}$$

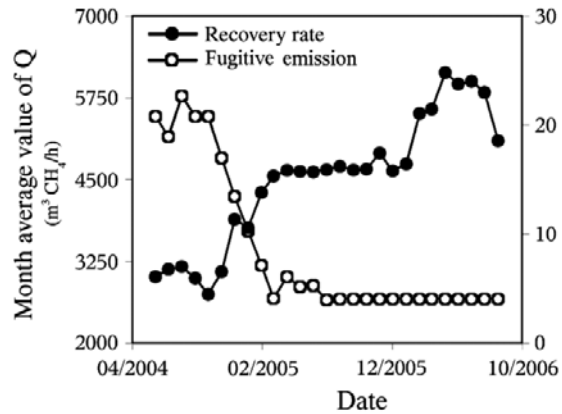



**Fig. 8** Methane recovery rates and fugitive emissions

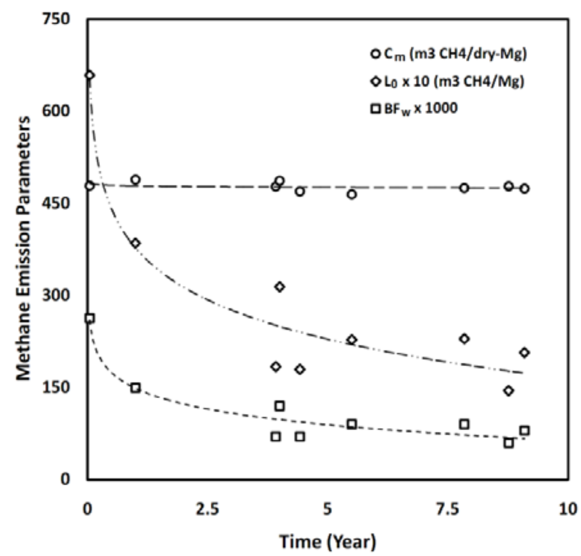



**Fig. 9** Variation of $C_m$, $L_0$ and $BF_w$ with time

Fig. 10 compares the predicted methane production by first order decay model, using the values of k and $L_0$ shown above, and the methane recovery in MCL. As can be observed, from mid 2008 on there was a decrease in the methane recovery rate. In this period, the MCL underwent a series of management problems that resulted in an increase in the exposed area and a reduction in the number of deep and superficial drains. As well as this, there was deposition of new waste on the top of a recently disposed (less than 2 year old) waste layer. This probably mixed micro-organisms of different decomposition phases and changed the values of pH of the waste medium thus affecting the methane production rate. At the beginning of 2011, when most of the problems had been solved, the methane recovery rate started to recover and it is expected that the methane production rate will return to the predicted values The field methane production was estimated as described in Machado et al. [2] using the values obtained in laboratory tests.

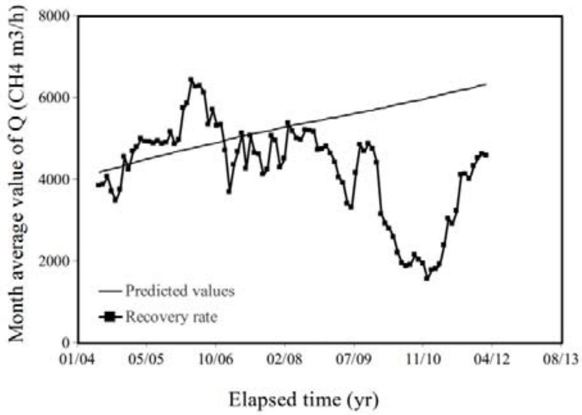



**Fig. 10** A comparison between measured methane recovery rates and predictions of Machado et al. (2009) model

## 5. Leachate Production

As the MSW decomposes, excess water (compared to the water necessary for bio-decomposition) becomes free water or leachate, which is stored in or drained from the landfill cells. The volume of collected leachate is a key parameter in the design of the leachate treatment and drainage facilities. A precise estimate of this is also vital in the operation of a bio-reactor landfill in which leachate re-circulation is used to promote a favorable environment for rapid bio-degradation of the MSW organic content.

To estimate the volume of drained leachate in a landfill, the standard approach is a water balance. It consists of the calculation of the input and output of liquids in the landfill system. Despite its apparent simplicity, the water balance must take into account a number of variables that can be difficult to evaluate in the field. Climatic aspects, such as the amount of rainfall and evaporation, the hydraulic and mechanical properties of the MSW and the soil cover, as well as specific aspects of the landfill management must be considered in the water balance.

To do this two common pieces of commercial software are used; HELP - Hydrologic Evaluation of Landfill Performance [16] which is the most well known and versions 2 and 3 of the software MODUELO [17] which have the most complete options for water balance modeling. However, the local experiences in the MCL and from similar research in different regions of Brazil, Marques & Vilar [18] and Padilla et al. [19] etc. have demonstrated that the volume of collected leachate is always higher than the values obtained from a water balance using commercial software.

Schueler [20] cited the fact that HELP does not consider the leachate released from the solid waste bio-degradation reactions. Padilla et al. [19], using MODUELO, obtained accumulated leachate production 20% to 30% lower than field measurements in an experimental cell in Belo Horizonte, Brazil. The author attributed most of the observed differences to the fact that the initial water content of the MSW was not included in the simulations due to field experimental problems.

Performing several confined compression tests on MSW samples from the MCL which had 92% (dry basis) of water content, Machado et al. [21] concluded that most of the MSW water content becomes free water under compression and suggest that this factor is one of the main contributors to leachate generation in the landfill.

Sao Mateus [22] and Sao Mateus et al. [23] attempted to model the MCL water balance. The proposed model considers the landfill construction in steps. It is assumed that the landfill cells have horizontal dimensions that are much bigger than height in such a way that une dimentional equations can be used to adequately describe water balance.

The input flows are considered only at the top of the cell (bottom and lateral slopes are considered as impervious). The input components considered in the model are the amount of rainfall and the initial water contents of the MSW and cover layer. The output components considered are evaporation, superficial flow, water consumption by biodegradation processes, leachate collection and the exit of water vapor during biogas extraction.

Fig. 11 presents the accumulated amounts of rainfall water, collected leachate and water that enters the MSW in a research cell in the MCL. The rainfall volume (376,000 $m^3$) was calculated considering the amount of rain in the period (L) times the cell surface at ground level ($L^2$). The volume of water that entered the cell with the MSW until 03/2006 was about 522,000 $m^3$, despite the fact that during the period from June 2004 to August 2005 there was no waste disposal. This was calculated using a mass of disposed waste of 1,055,000 Mg and average water contents of 93%, 83% and 122% for the years of 2003/2004, 2005 and 2006, respectively, and it is greater than the volumes of rainfall and collected leachate (about 349,000 $m^3$).

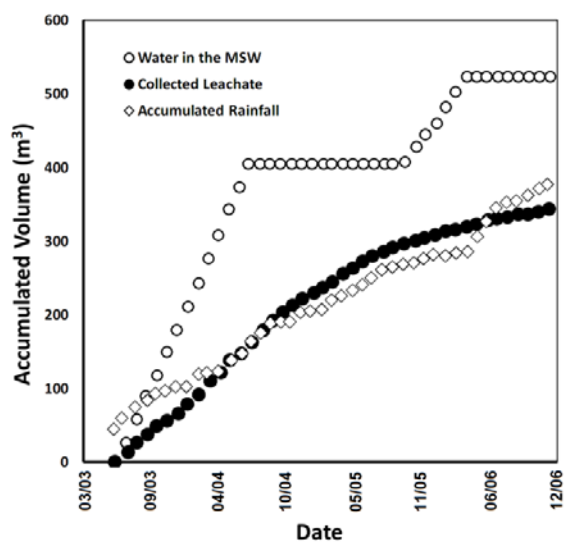



**Fig. 11** Accumulated volumes of water in the cell

Fig. 12 compares the total inputs and outputs of liquid in the cell. According to the obtained data, the total input of water in the system was about 736,000 $m^3$ and the output corresponded to about 425,000 $m^3$ of water/leachate, resulting in a 311,000 $m^3$ net input of water in the system.

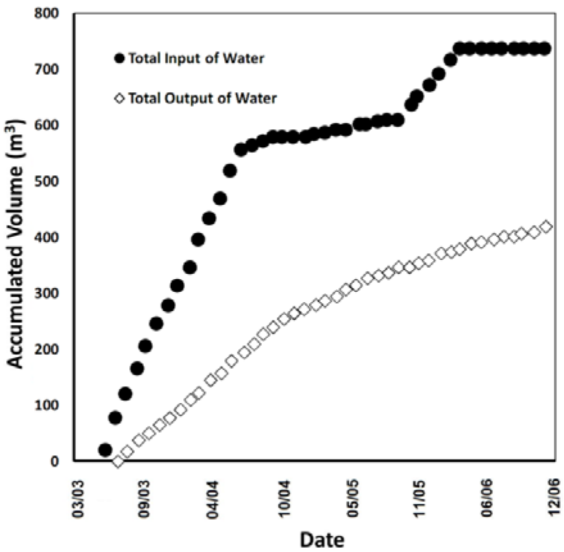



Fig. 12 Total input and output liquids in a pilot cell in MCL

Fig. 13 compares the leachate level measured by two piezometers installed in the research cell with the values predicted by the water balance performed by Sao Mateus et al. [23]. Piezometes construction followed the cell construction process. The piezometers depths are about 26 m. As can be observed, the performed water balance was able of capturing the main trends of the values measured in the field. It must be said, however, that experimental values presented gradual variations over time compared to the predicted results and that the differences in the water table height measured by the two piezometers are significant.

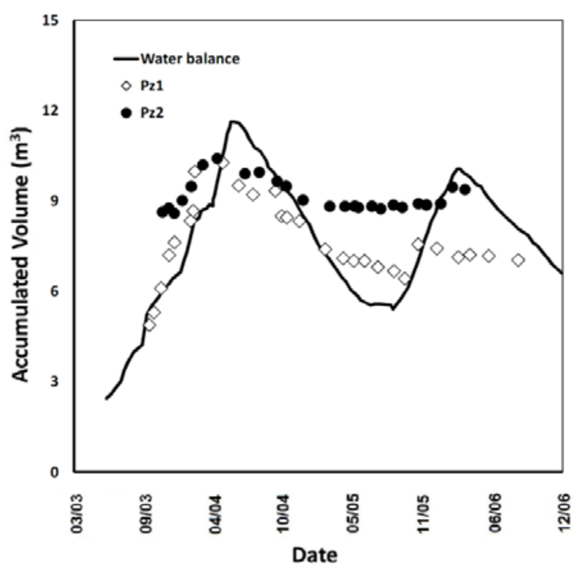



**Fig. 13** Water table height. Predicted and experimental results

This had been expected, at least in part, as the water takes time to flow down to the bottom of the cell. Another aspect worth mentioning is that the movement of water inside the waste mass is influenced by its heterogeneity, gas pressure, the efficiency of the drainage system, etc, all of which help to explain the differences obtained between the experimental and predicted results.

## 6. Compressibility and Settlement

The compressibility of the MSW was evaluated using field settlement records and laboratory confined compression tests. Field settlements were recorded using benchmarks installed on the top of the cover layer whereas laboratory tests were carried out using a large oedometer apparatus.

### *6.1. Field settlement*

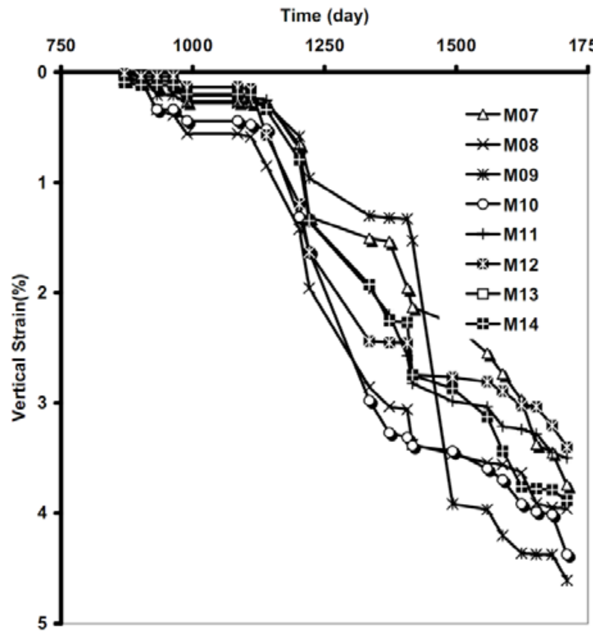
Fig. 14 shows the settlement records of some benchmarks (see Fig. 1 for approximate location). The benchmarks were installed 28 months after the end of the landfilling process. During this period, topography measurements indicated vertical strains varying from 3 to 5% in this region. The landfilling time was about 5 years. The average initial height (after 28 months) of the deposited waste was about 26.5 meters. The measured vertical strain values changed from 3.5 to 4.6%. These values are compatible with the long landfilling time and the fact that the benchmarks were installed more than 2 years after the end of the landfilling process. Thus, most of the settlement probably occurred before the first settlement reading. For the sake of simplicity, the MCL settlements were modeled using the following equations [24]:

$$\varepsilon(t) = \frac{S(t)}{H_o} = C_c' \log\left(\frac{p_o + \Delta p}{p_o}\right) + C_{\alpha 1}' \log\left(\frac{t_2}{t_i}\right) + C_{\alpha 2}' \log\left(\frac{t}{t_2}\right) \quad (6)$$

$$C_c' = \frac{C_c}{1 + e_o} \quad (7)$$

$$C_\alpha' = \frac{C_\alpha}{1 + e_o} \quad (8)$$

where $C_c$ and, $C'_c$ are the compression and normalized compression indices; $p_0$ and $\Delta p$ are the initial effective stress and the load increment, $C_{a1}$ and $C_{a2}$ are the coefficients of intermediate and long-term secondary compression and $C'_{a1}$ and $C'_{a2}$ are the normalized form of the pre-mentioned indices. $t_i$, $t_2$ and t represent the end of the initial settlement period, the time at which the slope of strain-time curve changes and the elapsed time, respectively. $e_0$ is the MSW initial void ratio. The normalized form of the presented coefficients is usually preferred due to the difficulty of determining the MSW void ratio. The values of intermediate and long term secondary compression indices, $C_{a1}$ and $C_{a2}$, are given in Fig 14. The MSW specific density was determined in a similar way to procedures adopted for soils. In this case, however, a larger picnometer (2,000 $cm^3$) was used and both vacuum and temperature increases were applied to the sample to better extract air bubbles. Values of $\rho_s$ of about $\rho_s = 1.7$ g/cm$^3$ were obtained using this method.

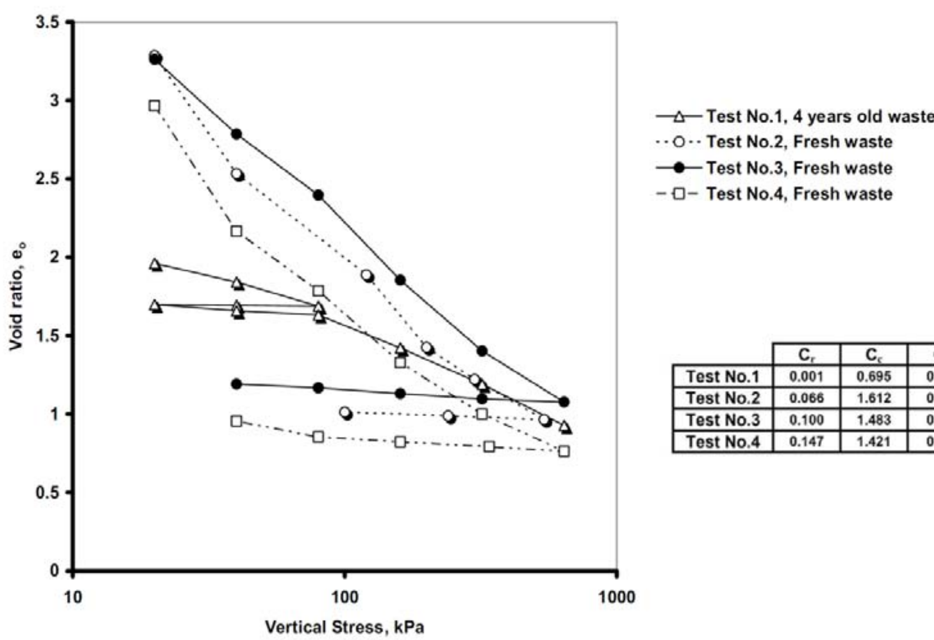



| | | $C'_{\alpha 1}$ | $C'_{\alpha 2}$ |
|---|---|---|---|
| Bench mark | M07 | 0.02 | 0.18 |
| | M08 | 0.05 | 0.17 |
| | M09 | 0.03 | 0.26 |
| | M10 | 0.04 | 0.20 |
| | M11 | 0.02 | 0.18 |
| | M12 | 0.01 | 0.15 |
| | M13 | 0.02 | 0.19 |
| | M14 | 0.02 | 0.20 |
| Ave. | | 0.02 | 0.19 |

**Fig. 14** Time dependent settlements obtained by benchmarks installed in the MCL

*6.2. Laboratory confined compression tests*

Confined compression tests were performed in an oedometer with nominal dimensions of 497 mm in height and 548 mm in diameter. Fig. 15 presents the results of 4 typical compression tests. Three fresh waste samples and one 4-year old sample were used. It can be noted that not only the primary compression index but also the swelling index seems to decrease with the age of the waste. The compression indexes in the case of the fresh waste samples were similar; however, the rebound indices were significantly different. The achieved values for primary compression index of MSW are in the range suggested by Sowers [25] who stated that the lower and upper limit of this parameter is equal to 0.15 and 0.55 of the initial void ration of the MSW, $e_0$.




| | $C_r$ | $C_c$ | $C'_c$ |
|---|---|---|---|
| Test No.1 | 0.001 | 0.695 | 0.209 |
| Test No.2 | 0.066 | 1.612 | 0.361 |
| Test No.3 | 0.100 | 1.483 | 0.285 |
| Test No.4 | 0.147 | 1.421 | 0.333 |

**Fig. 15** Typical confined compression curves obtained

## 7. Shear Strength

In order to evaluate the MSW shear strength parameters, about 100 triaxial tests have been carried out in the last 5 years. Most of the samples tested had nominal sizes of 200 mm in diameter and 400 mm in height. Various aspects such as confining pressure, density, loading rate, fiber content, over consolidation ratio (OCR), age and stress paths and their influence on the MSW mechanical response, under different drainage conditions have been assessed.

Some typical results of triaxial tests in both drained and undrained conditions conducted on the fresh waste are illustrated in Fig. 16. As the fiber percentage of samples in this figure is different, the effect of fibrous materials on the mechanical behavior of MSW materials can be observed.

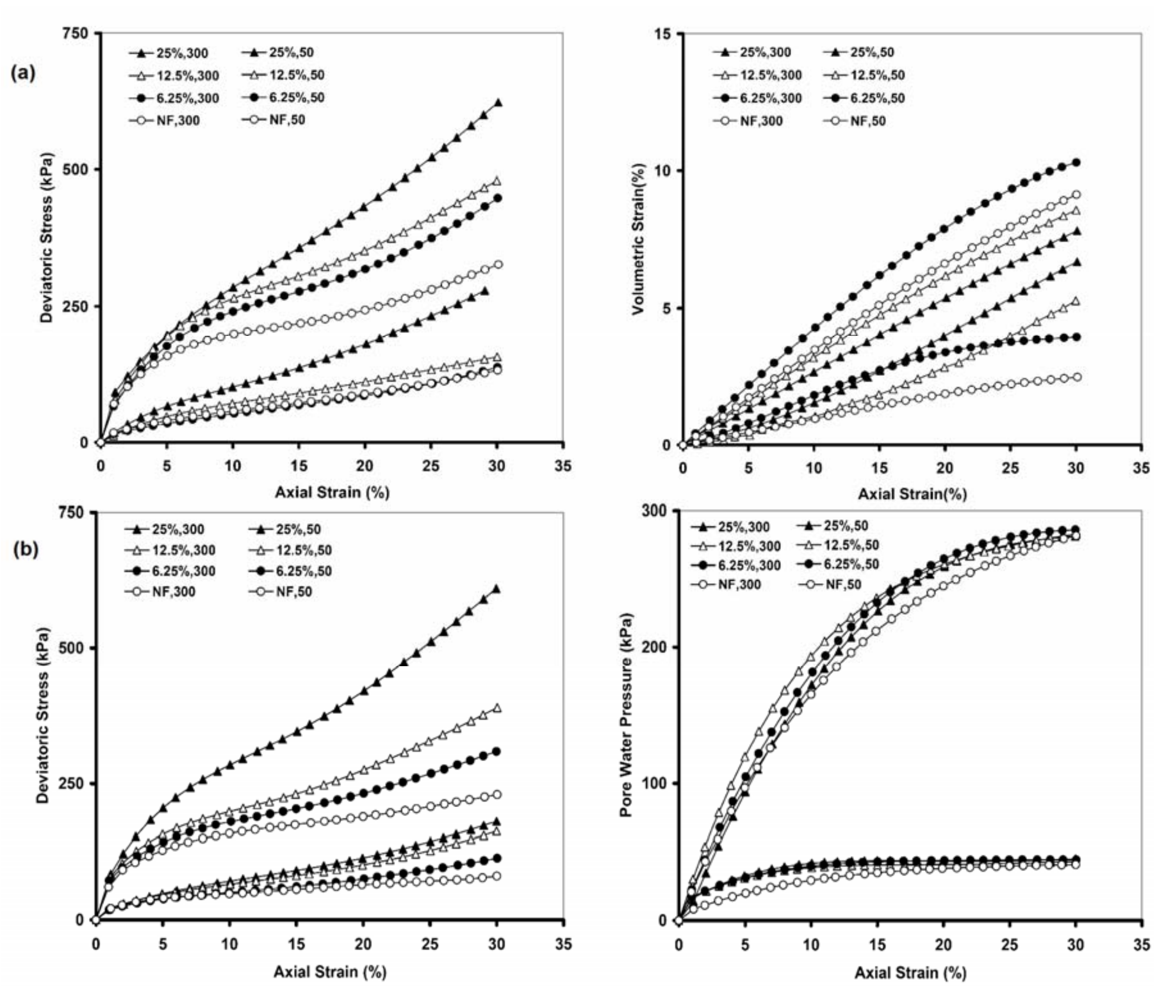



**Fig. 16** Results of triaxial test performed on fresh waste (a) CD (b) CU

As could be observed, the pore water pressure inside the MSW samples increases very quickly during the shearing stage and it stabilizes at a value near the confining pressure. In spite of this, no instability could be observed in the samples and they even exhibited strain hardening in the form of upward concave stress-strain curves. This is one of the most interesting and intriguing aspects of the behavior of undrained MSW and has already been reported by authors such as Carvalho [26], Vilar & Carvalho [27], Nascimento [28], Shariatmadari et al. [29], Karimpour-Fard [30] and Karimpour-Fard et al.[31].

According to Shariatmadari et al. [29] this behavior is due to the compressibility of waste particles which is responsible for maintaining good anchoring conditions for the fibrous material even under very high pore water pressure. Shariatmadari et al. [28] analyzed results obtained from drained and undrained triaxial tests and concluded that compressibility of the MSW particles leads to a contact area that cannot not be neglected compared to the total cross section area of the samples, which is one of basic assumptions of Terzaghi's effective stress equation. According to the authors, instead of the effective stress equation proposed by Terzaghi [32], the following equation, developed by Skempton [33], should be used:

$$\sigma' = \sigma - A \, . \, u_w \tag{9}$$

where, σ', σ are the effective and total normal stresses. "A" is the pore pressure ($u_w$) reduction coefficient which is a function of the ratio between the MSW particle compressibility ($C_s$) and the compressibility of the MSW as a whole (C).

$$A = 1 - \frac{C_s}{C} \tag{10}$$

Fig. 17 shows the variation of A with mean pressure for MSW samples with different fiber contents. Please refer to Shariatmadari et al. [29] for further details about defining the "A" coefficient.

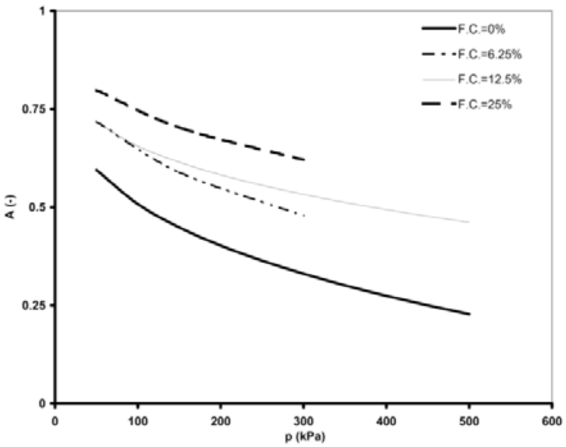



**Fig. 17** Pore water pressure reduction factor, "A", for MSW materials with varying fiber contents [ 28]

For design purposes, all researchers agree that a MSW failure criterion must be strain dependent, but the level of shear strain to be considered remains controversial. Among them, Zekkos [34] suggested a limiting axial strain of 5% departing from the in-situ stress state of the MSW. Stark et al. [35] recommended that a shear displacement greater than 60 mm or an axial strain of greater than 20% might be used in MSW shear testing to mobilize shear resistance that may be representative of the peak shear strength of MSW.

Fig. 18 shows the shear strength envelope of MSW in the MCL based on the results of large triaxial tests on fresh and 4 year old MSW. The average fiber content in the fresh samples is about 25%. The fiber content of the MSW tends to increase over time because plastic and textile components are barely biodegradable. In this graph an axial strain of 20% was chosen to calculate the shear strength of MSW materials. The solid red lines represent the upper and lower limits of the reported shear strength of MSW in literature achieved from direct shear tests and the broken red lines show the boundary limits of shear strength of MSW materials measured based on triaxial tests.

The gray area in the graph shows the range of shear strength of MSW proposed by Kavazanjian et al. [36], Manassero et al. [37], Eid et al. [36], Zekkos [34] and Stark et al. [35]. According to this graph, the shear strength of both fresh and aged MSW samples in MCL are lower than the range of shear strength of MSW proposed for design purposes and are close to the lower limit of values reported in the literature.

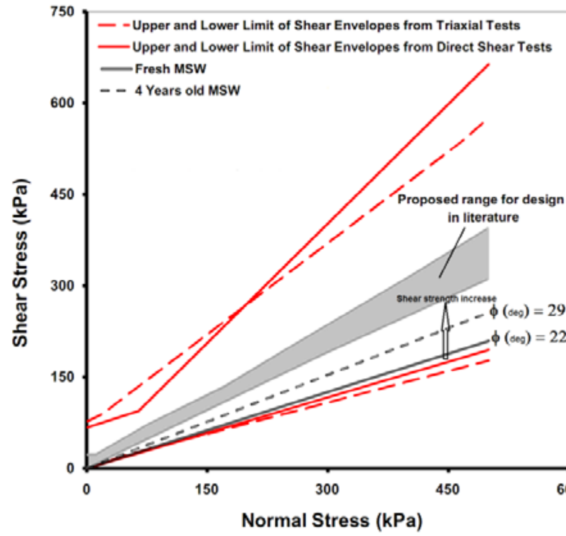



**Fig. 18** Proposed shear strength envelope for MSW materials in MCL

This considerable difference could be due to the high amount of moisture and organic content of the MSW materials in MCL. The average moisture content of fresh MSW in MCL is around 100% which is considerably higher than the moisture content of MSW samples tested for example by Zekkos [34]. The range of moisture content of MSW samples used by Zekkos [34] was between 13 to 23%. Furthermore, these results were obtained from MSW samples from Europe and the USA, places where normally the organic content of MSW is low and there is a considerable amount of soil.

The internal friction angle of MSW in fresh state is equal to 22 degrees which increases to 29 degrees when the MSW is aged for 4 years. As the foil like materials inside the MSW play a key role in the mechanical behavior of these materials [39], increasing the fiber content could promote the shear strength level of the MSW samples. According to Machado et al. [40], in regions where the decomposition rate is high, over a relatively short period the soil like or paste part will be subjected to considerable mass loss leading to an increase in the percentage of foil like or fibrous part (mainly plastic fraction). This causes an increase in the shear strength of MSW samples. However, recent research has indicated the importance of shearing mechanisms on the effect of fibers on the shear strength of MSW [41].

## 8. Conclusions

Although landfilling is one of the most common methods to dispose of MSW materials, the issues related to the design and operation of this engineered structure remain a challenge for geotechnical and environmental engineers.
The stability of landfills can be affected by the physical and mechanical properties of the MSW materials, the presence of produced leachate due to the decomposition

process and the generation of methane gas which could elevate the pore water pressure inside the waste fills. All of these issues make stability analysis of landfills very complex.

This paper presents laboratory and field records collected over almost one decade at the Metropolitan Center Landfill, Salvador, Brazil.

An evaluation of the physical properties of the MSW at this site have shown that the disposed waste presents high levels of moisture and organic content which together with the tropical climate conditions leads to an environment which is favorable for the rapid decomposition of the MSW organic content.

The laboratory and field measurements of methane gas generation were similar to the methane gas generation potential, $L_0$, at around 66 $m^3$ $CH_4$/Mg MSW and a production rate of 0.20 $yr^{-1}$.

A considerable difference between input and output water inside the waste fills in MCL was recorded. According to the data, the total input of water in the system was about 736,000 $m^3$ and the output corresponded to about 425,000 $m^3$ of water/leachate, resulting in a 311,000 $m^3$ net input of water in a specific landfill cell.

The MSW compressibility characteristics in the field showed that after 28 months the rate of settlement is low and that most of the settlements had probably already happened before the first reading. The laboratory results of large scale compression tests showed that the primary compression index was in the range proposed by Sowers [25].

The results of the performed triaxial tests showed that the shear strength envelopes obtained using MCL samples are considerably lower than those cited in the literature and this implies that landfill design projects and their development for further use should be supported by local measurements and evaluations. An internal friction angle of 22 degrees was proposed for fresh MSW whereas in the case of 4 year old waste this parameter  to 29 degrees.

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