MSW Characteristics and Landfill Gas Generation Performance in Tropical Regions

Átila Caldas
Dept. of Materials science and technology, Federal University of Bahia, Salvador-BA, Brazil; e-mail: atila.caldas@ufba.br

Sandro Machado
Associate Professor, Polytechnic School, Federal University of Bahia, Salvador-BA, Brazil; e-mail: smachado@ufba.br

Mehran Karimpour-Fard
Assistant Professor, Faculty of Engineering, University of Guilan, Rasht, Iran; e-mail: mehran.karimpour@guilan.ac.ir

Miriam Carvalho
Assistant Professor, School of Engineering, Catholic University of Salvador, Salvador-BA, Brazil; e-mail: miriam@ucsal.br

ABSTRACT

This paper presents the results of research carried out into waste characterization and methane generation at the Metropolitan Center Landfill, Salvador, Brazil. The physical characteristics of the waste, such as composition, water and organic content, were studied over time, as well as the results obtained in field and laboratory measurements of methane generation. It is shown that values of Lo obtained using waste composition and BMP tests presented compatible results and that most of the decomposition process occurs in the first 4 years in field. The methane recovery rate appears to be largely dependent on landfill operation conditions. Although waste properties are site specific, the authors believe that the presented data can be a useful source for both the design and performance analysis of methane generation in tropical regions.

KEYWORDS: Municipal Solid Waste; Landfill; Methane emission.

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.

An engineer designed landfill is usually regarded as a biochemical reactor in which 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.

Machado *et al*. (2009) presented a simplified procedure based on the approaches adopted by USEPA (1998; 2005) and IPCC (2006) to estimate the MCL gas generation rate. In this method, the theoretical potential of gas production obtained using stoichiometric equations, which assume a complete conversion of organic matter to gaseous products (C_m, m^3 CH_4 /dry-Mg), is adjusted by biodegradability factors in order to take into account field conditions.

The rate of produced gas due to biodegradation process is modeled by first order decay model (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 time since waste disposal (yr) and L_0 is methane generation potential (m^3 CH_4 /·Mg).

$$q = L_0 . k . e^{-kt} \tag{1}$$

The value of L_0 is estimated (Eq. 2) using the value of C_m, the biodegradable fraction of the waste as a whole, BFw and water content of MSW, w. The water content is used in Eq. 2 to consider only the dry mass of potentially degradable organic matter.

Eq. 3 is 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. BF values adopted by Machado *et al*. (2009) follow Lobo's (2003) suggestion: paper (BF = 0.4), Cardboard (BF = 0.41), Food waste (BF = 0.64), Garden waste (BF = 0.4), wood (BF = 0.17) and textile (BF = 0.32).

The waste average value of C_m can be calculated using Eq. 4. Table 1 shows the values of C_m and water consumption for complete decomposition of different waste components (Tchobanoglous *et al*., 1993).

$$L_0 = \frac{BF_W \cdot C_m}{1 + w} \tag{2}$$

$$BF_W = \sum_{i=1}^{n} BF_i \cdot FR_i \tag{3}$$

$$C_m = \frac{\sum_{i=1}^{n} BF_i \cdot FR_i \cdot C_{mi}}{BF_w} \tag{4}$$

Table 1: Methane generation (C_m) and water consumption for complete organic matter depletion

Waste organic component	C_m	H_2O consumption
	m^3 CH_4/dry-Mg	H_2O 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

In order to obtain field values of k, Machado *et al.* (2009) suggest the use of samples of different ages obtained from different points in the landfill mass. The values of the remaining methane generation potential, $L_0(t)$ are obtained using the same Eq. 2, replacing BF_W with $BF_W(t)$ (Eq. 5). Eq. 6 is then used to obtain the value of k in field conditions.

$$BF_w(t) = \sum_{i=1}^{n} BF_i \cdot FR_i \cdot \left[\frac{TVS(t)}{TVS_o}\right]_i \tag{5}$$

where TVS(t) is the volatile solid content at elapsed time t and TVS_0 is the initial value of TVS.

$$L_0(t) = L_0 \cdot e^{-kt} \tag{6}$$

Once the values of L_0 and k are obtained, Eq. 7 can be used to predict the methane generation rate in the landfill. In Eq. 7, t is the average time since waste disposal (yr) and Δm is the amount of waste disposed of each month (Mg). Q is the total methane generation rate estimated (m^3 CH_4 /yr) for the landfill.

$$Q = \sum_{i=1}^{n} L_o \cdot k \cdot e^{-k \cdot t_i} \cdot \Delta m_i \tag{7}$$

This paper summarizes, discusses and reviews the results of research into methane gas generation in the Metropolitan Center Landfill, MCL (Salvador-BA, Brazil). The research has been performed on both a laboratory and field scale over the last few years by a research group in Environmental Geotechnics from the Federal University of Bahia.

LANDFILL SITE

The MCL is located around 20 km from the city center of Salvador, capital of Bahia state, Brazil. The daily input of MSW is about 2500 tons. 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 MCL is presented.

Figure 1: Metropolitan Center Sanitary Landfill

Fig. 2 shows monthly averages incoming waste. As can be observed these values are subject to seasonal oscillations. There are peak values in the period from December to March associated to the influx of tourists in the summer season. Since 2002 there has been a steady increase in the amount of waste coming to the landfill.

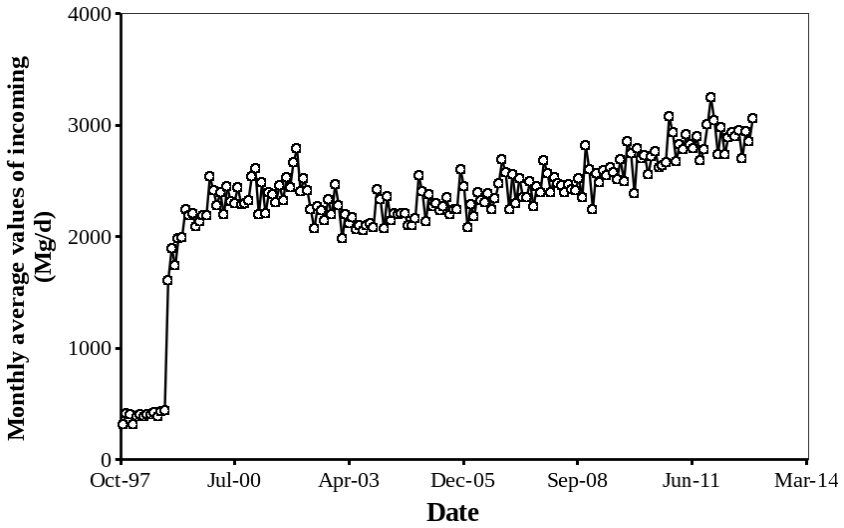

Figure 2: Monthly average values of incoming waste in the MCL

The bottoms of the MCL cells are located 6-12 m below the soil surface and the thickness of the waste column at the end of the disposal process reaches about 55 m. A double liner system is used at the bottom and on the lateral slopes of the cells (1 m clay liner, $k < 1x10^{-7}$ cm/s plus 2 mm HDPE membrane). After the middle of 2012 a GCL layer was adopted replacing the clay liner on the lateral slopes. Temporary top covers are made using a single layer of soil $k < 1x10^{-5}$ cm/s, 60 cm thick. These layers are removed in the case of additional disposal. Final covers use a PVC-Geotextile membrane (PVC-GM) over the soil layer (60 cm thick) and about 40 cm of organic soil for grass support, which is located over the PVC-GM.

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 usual depths are of about 20 meters.

Superficial drains are located above the soil layer of the final cover and beneath the PVC-GM (Fig. 3) and they serve to collect the biogas accumulated in this region and to minimize possible fugitive emissions due to PVC-GM non-conformities. Recently, drainage trenches are used replacing the superficial drains. The trenches are excavated in the MSW surface and are located just below the cover layer and they are connected to the deep drains for gas extraction.

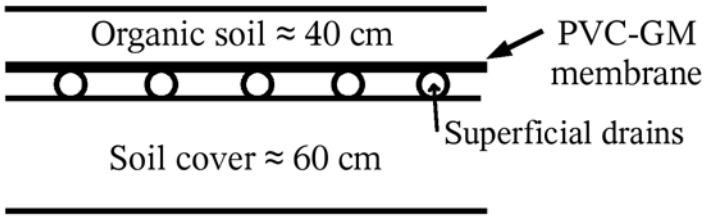

Figure 3: Schematic view of the final cover adopted in the MCL

Individual measurements of gas flow rate, temperature and composition are taken on a monthly basic at 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 are 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 and the flares are used only occasionally.

MATERIALS

Since 2004, MSW samples have been collected from MCL every 6 months. The samples are normally collected just before landfilling, in the disposal front of the landfill. However, to address the effect of aging on the key MSW parameters, such as water and organic content, some complementary campaigns were performed in order to collect samples 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.

Water content

The 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 materials not easily separated. More sampling details are provided in Machado *et al*. (2009).

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 (samples of about 20 kg).

Fig. 4(a) shows the variation in moisture content with depth reported by different authors (Knochenmus *et al*., 1998). Fig. 4 (b) compares the water content found in this research with those reported in literature. As can be observed, the average moisture content for MCL samples is higher than the results presented by other authors and there is a decrease in water content over time (MCL fresh x aged samples). The MCL samples presented less variation in moisture content compared to the values reported by Landva & Clark (1986), Blight *et al*. (1992), Coumoulos *et al*. (1995) and Gabr & Valero (1995). Jucá *et al*. (1997) 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 biodegradation. Fig. 4(c) shows the variation in the water content with age in MCL.

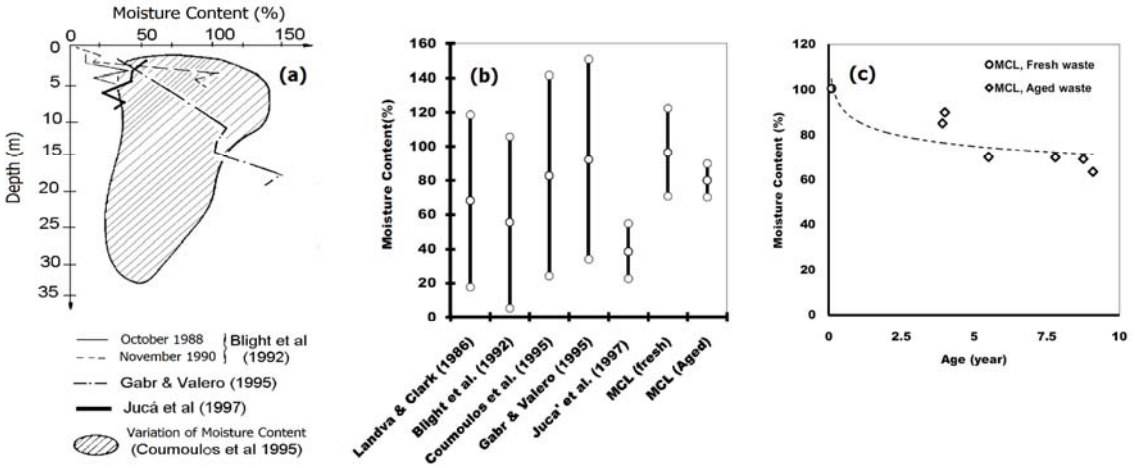

Figure 4: a) Values of moisture content with depth reported by different authors; **b)** MCL MSW water contents compared to values reported in literature; **c)** Variation in the MSW water content with age in MCL

Table 2 shows average water content values, standard deviation and coefficient of variation for each MSW component (20 determinations since 2004). As can be observed, textile, paper and paste have the highest water content.

Table 2: Average water content values for different MSW components

Component	Wood	Rock & ceramic	Textile	Rubber	Plastic	Metals	Glass	Paper cardboard	Paste
Average	89.4	15.8	120.2	32.8	76.6	2.37	24.3	136.4	144.2
Stand. Dev.	36.4	5.40	42.2	24.6	28.4	2.41	8.33	33.7	25.5
Coef. Var.	0.41	0.34	0.35	0.75	0.37	1.02	0.34	0.25	0.18

Composition

After the separation and measurement of the water content of the waste components, the composition of dry waste was determined. Fig. 5 shows the average waste composition. Values in parenthesis mean the coefficient of variation in %. Although not showed here. no clear variation was observed for the MSW components over time. The average percentage of plastics, which are referred to as the fibrous elements in the MSW samples, was about 19%. 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 23%. The paste component, which is responsible for most of the gas generation, represents about 34% of MSW, dry basis. This is lower than the values normally presented in the literature and it is mostly due to the high water content of the paste, which decreases the paste fraction in a dry basis composition.

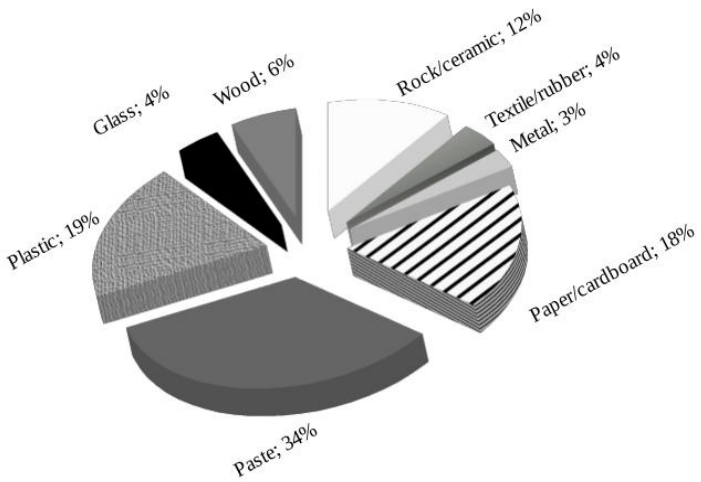

Figure 5: Average waste composition of MSW from MCL

Particle size distribution

Sieve analysis was performed using sieve opening sizes from 0.075 mm to 101 mm with 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 63 and 78 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 (1994). As can be seen, although the size distribution curve of fresh waste falls inside this range, the grain size distribution curves of the old samples are located to the left of the suggested boundaries.

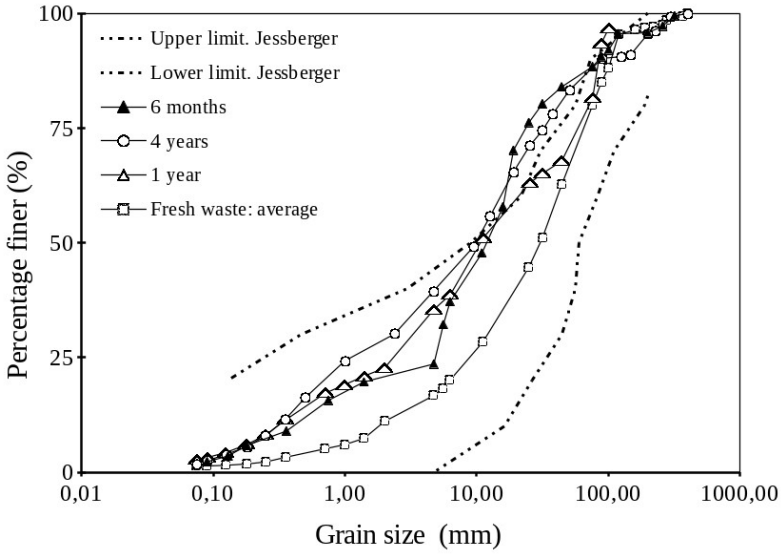

Figure 6: Grain size curve for samples of different ages

Total Volatile Solids

Paste Total Volatile Solids (TVS, or ignition lost) was obtained after waste sieving. The paste fraction after drying was quartered to a mass of about 1000 g and ground for size reduction and to increase the specific surface. For each sampling campaign about 36 paste samples of 20 g 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. An average value of TVS = 60% was obtained for fresh samples, with a standard deviation of 20%. Fig.7 presents the variation in TVS with age in the MCL. As can be observed there is a sharp decrease in TVS (around 50%) in the first year and after that the TVS values decrease smoothly. During a 10 year period the decrease in TVS is about 75%.

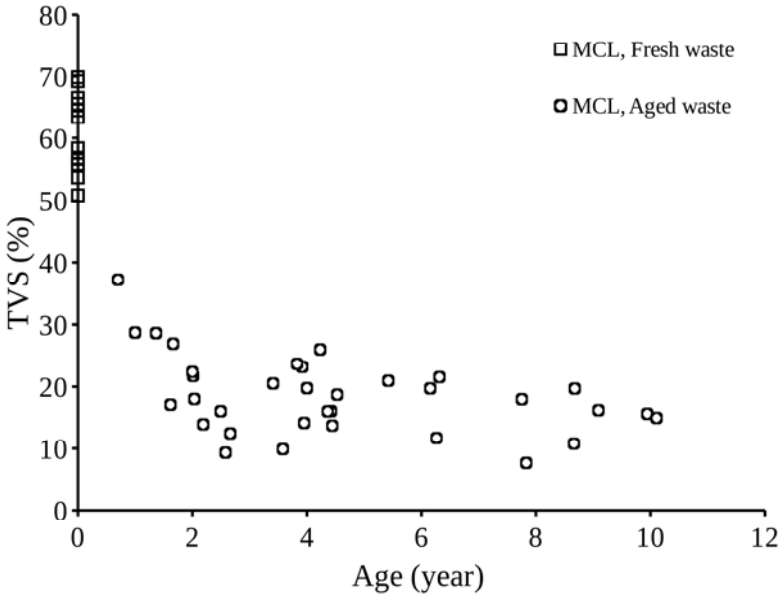

Figure 7: Variation in TVS with age in the MCL

METHODS

Methane production potential

Methane production potential was obtained using two different approaches a) estimating L_0 values from waste composition as described above in this paper and b) performing Biochemical Methane Potential tests (BMP). In order to perform BMP tests MSW samples (field water content) were first shredded and an amount of waste was introduced in the glass vessels used as bio-digestors. The amount of waste used in the tests was calculated based in the expected values of L_0 and the bio-digestors effective volume (about 2 L). MSW samples were collected to calculate the loss of water during the shredding process. MCL leachate (pH = 8.3, Chemical Oxygen Demand, COD = 9,975 mg/L, Total Dissolved Solids, TDS = 14,051 mg/L, Electrical conductivity, EC = 29000 µS/cm) was used to accelerate the biodegradation process. The volume of leachate used in each bio-digestor was about 200 ml. One bio-digestor was used containing only leachate (without waste) in order to correct the obtained values of L_0.

Before the tests began, the inner atmospheric air of the bio-digestors was replaced by N2. This avoided the presence of CO_2 and O_2 in the air prior to the beginning of the gas generation process. The gas composition was obtained using GEM™2000 gas analyzer (CH_4, CO_2, O_2). Gas production was obtained by monitoring the gas pressure inside the bio-digestors during the tests. The biodigestors were installed in a chamber with controlled temperature (38 - 40 ºC). Fig. 8 shows the materials used in the BMP tests.

Figure 8: Materials used in the BMP tests. a) shredded waste; b) bio-digestors; c) bioreactors in the chamber and d) biogas composition determination

Field measurements of methane recovery rates and estimation of fugitive emissions

Recovery rates of biogas and methane were measured in the control center of the gas collection system at the MCL. Values of specific methane generation rate (L $CH_4/m^2 \cdot h$) were obtained dividing the superficial drains production by the area covered by the drains. These values were used to estimate fugitive emissions in the exposed areas of MCL (areas where temporary covers are used and those without any cover installed such as at the disposal front). Fig. 9 shows the evolution of the covered/uncovered areas in recent years. Figure 10 shows the estimated fugitive emissions in MCL calculated as described above. For areas with the final cover installed the fugitive emissions were estimated to be 5% of the value estimated using the superficial drains.

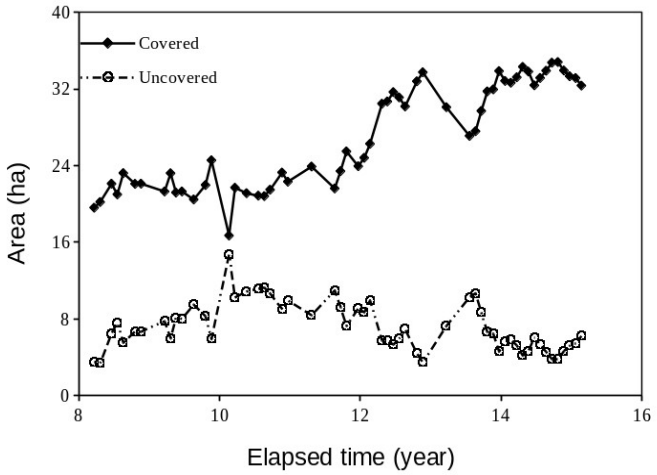

Figure 9: Evolution of the covered/uncovered areas in recent years

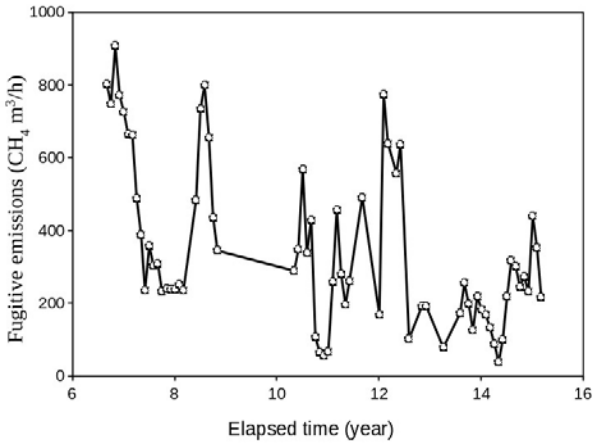

Figure 10: Estimated fugitive emissions

The monthly individual measurements of gas production in each active drain (either deep or superficial) were used to obtain the amount each cell produces in the methane recovery rate of MCL as a whole. Table 3 shows the actual number of active drains in each cell of MCL.

Table 3: Number of vertical drains in MCL cells

Cell Number	Number of drains
Cell 1 to 4	39
Cell 5	26
Cell 6	110

RESULTS AND DISCUSSIONS

Methane production potential

Fig. 11a presents L_0 values for samples of different ages calculated based on waste composition (Machado *et al*., 2009). Fig 11b shows the obtained values from BMP tests. Also presented in both figures is the fitting of Eq. 6 to experimental results and the upper and lower limits for a 70% confidence interval. Table 4 summarizes the obtained fitting results. Values of L_0 = 62.7 m^3 and 83.8 CH_4 / Mg-MSW were obtained based on the waste composition and BMP tests, respectively. Higher values of L_0 had already been expected for BMP tests compared to values estimated from the waste composition because BMP tests are performed under optimal conditions increasing the values of the biodegradability of the MSW components.

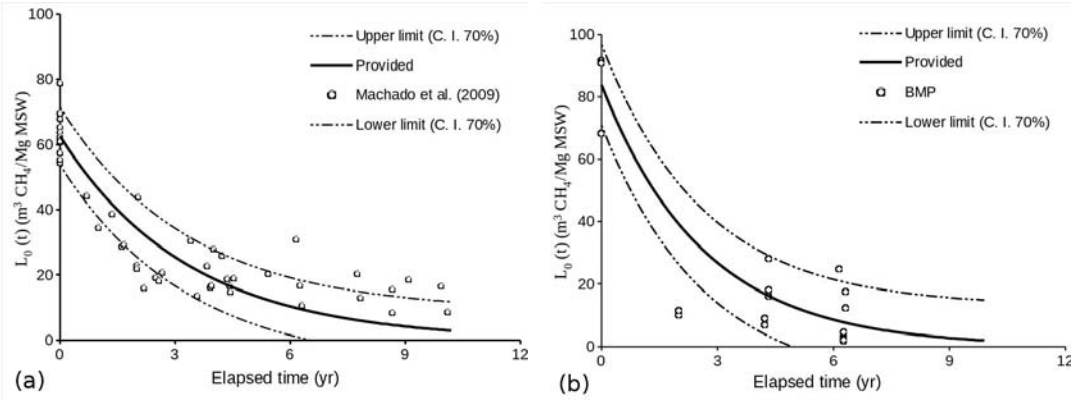

Figure 11: Estimated values of L_0(t) and their adjusted trends based on **a)** Machado *et al*. (2009) and **b)** BMP

Table 4: Values of L_0 and k with their statistical measurements

Method	L_0 (m^3 CH_4/Mg MSW)	k	σ_v	R^2
Machado *et al*. (2009)	62,66	0,30	8,84	0,89
BMP test	83,83	0,38	12,91	0,93

The correspondent values of k were 0.30 and 0.38 $year^{-1}$ reflecting the high rate of mass loss inside the waste fill. These values are higher than those presented previously by Machado *et al*. (2009) and suggested by IPCC (2006) for humid tropical regions (0.15 to 0.20 yr^{-1}) and are coherent with results presented more recently by Faour *et al*. (2007). The differences between the k values obtained in both procedures may be linked to the differences in the number of experimental results and to the higher L_0 values in the case of the BMP tests.

It is worth noting that in both graphs there is a sharp decrease in the remaining methane production potential L_0 (t) during the first three years after landfilling in such a way that the first order decay model is not able to reproduce faithfully the experimental data in this case. This sharp decrease in the gas generation rate has been reported by other authors such as El-Fadel *et al*. (2012).

The need to adopt a higher order model for gas emission estimation has been pointed out by some authors such as Amini *et al*. (2012), but this will certainly have an impact on the simplicity of the model. After 4 years the L_0 values almost stabilize at around 20 m^3 CH_4 / Mg-MSW. This means that a reasonable fraction of the methane potential remains unexplored in the field.

Field measurements of methane recovery rates and estimation of methane production

Fig. 12 compares the predicted and obtained results using Eq. 7 for Methane production rates (average values for each month) in different MCL cells. The results presented in Fig. 12 embrace the field methane recovery rates and the fugitives emissions presented in Fig. 10. MSW decomposition parameters obtained considering waste composition were used due to the larger data set. In each figure, an upper and lower limit for predictions with a confidence interval of 70% can also be observed. The time indicated in the graphs refers to the beginning of the landfill operation.

In spite of the fact that methane generation rate is dependent on the landfill operational conditions such as the presence of daily cover, number of active drains, amount of covered/uncovered area, good agreement between the predicted and measured values up to 11.5 years (2009 January) can be observed (see Figure 12a, considering the landfill as a whole). After this period, recovery rates are always below the lower limit of predictions, except in the period of August to October 2009. Although not shown in this paper, if the values of L_0 and k obtained from BMP results are used Eq. 7 results are shifted up and the differences between experimental and predicted results are higher. After 13.5 years (2011 January) the recovery rates are improved but the experimental values are still below the lower limit of predicted results.

The differences between experimental and predicted results affect cell 6 more significantly. This was already expected as changes in the operational practices in the field occurred during the period of operation of this cell. In the case of the cells 1 to 4, the experimental and predicted recovery rates are similar.

Concerning the landfill practices some points may have contributed to the discrepancies observed between the predicted and experimental results of methane recovery rates. 11.5 years after the beginning of the landfill operation, there was a need to dispose fresh waste on top of two year old material. As illustrated above, the remaining L_0 values of the MSW samples decreased very fast in this period indicating a very active decomposition process in the field. Furthermore, according to São Mateus *et al*. (2012) waste compression can release large amounts of free water to the waste mass. This water will migrate downward reaching the older layers of waste, possibly changing the equilibrium conditions for optimal anaerobic methanogenic decomposition processes to occur.

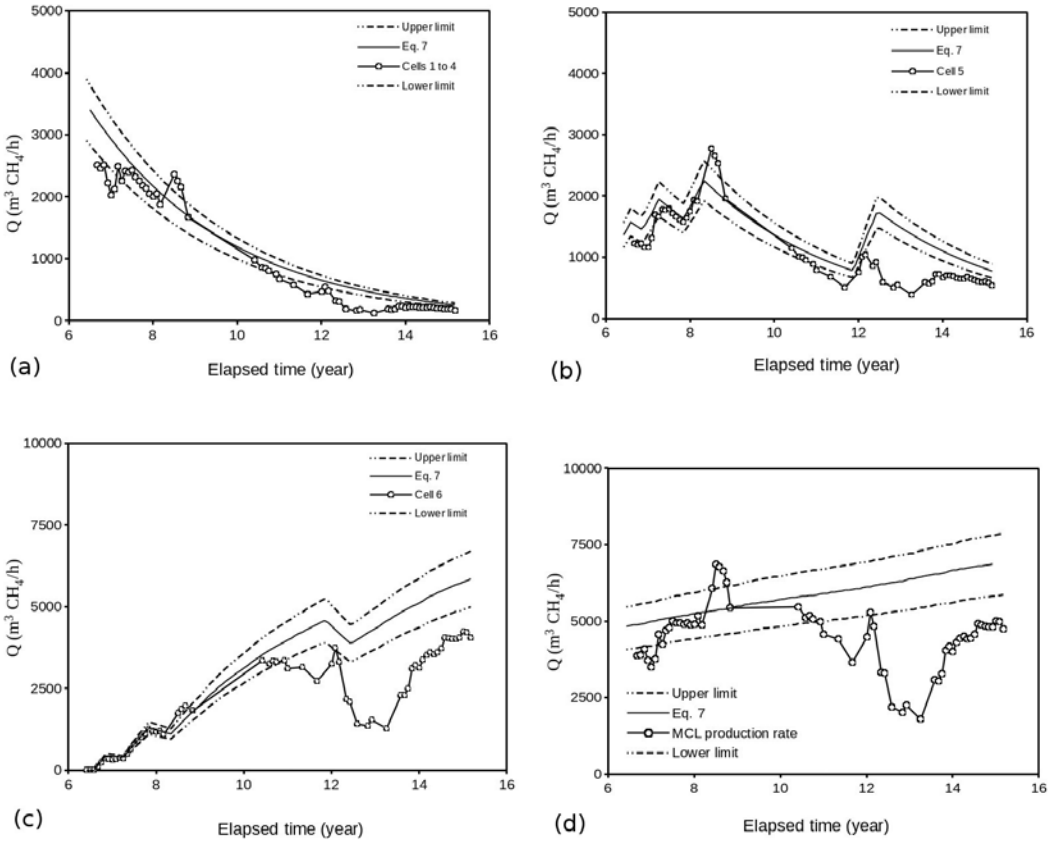

Figure 12: Predicted and experimental field methane recovery rates **a)** MCL as a whole; **b)** cells 1 to 4; **c)** cell 5 and **d)** cell 6

Another point that must be highlighted are the excavation activities that took place in the field in order to improve the drainage and biogas recovery systems. During these operations the final cover of part of the landfill was removed increasing the fugitive emissions and changing the anaerobic environment to aerobic, at least for shallow depths of waste.

CONCLUSIONS

This paper presents results of MSW characterization tests performed over time in the Metropolitan Center Landfill, Salvador-BA. Besides for waste characterization, the obtained results were used to estimate the methane production potential, L_0, in samples of different ages. BMP tests were also performed with this purpose.

The studied MSW presented high values of moisture and organic content which in a tropical climate conditions leads to a favorable environment for the rapid decomposition of the MSW organic content. The average MSW water content and the paste TVS decreased from 100% and 60% to stabilized values of 60% and 20% in four years of decomposition, respectively. Furthermore, there was a reduction in the size of the MSW constituents and the MSW grain size curves for aged samples are located to the left of the fresh ones.

The parameters of the first order decay equation (L_0 and k), estimated using waste composition (Machado *et al*., 2009) and obtained from BMP tests (BMP), presented compatible results. Values of L_0 = 62.7 m^3 and 83.8 CH_4 / Mg-MSW were obtained based on waste composition and BMP tests, respectively. Higher values of L_0 had already been expected for BMP tests since BMP tests are performed under optimal conditions compared to field conditions.

The corresponding values of k were 0.30 and 0.38 $year^{-1}$, respectively, reflecting the high rate of mass loss inside the waste fill. These values are higher than those presented previously by Machado *et al*. (2009) and suggested by IPCC (2006) for humid tropical regions (0.15 to 0.20 /yr) and are coherent with results presented more recently by Faour *et al*. (2007).

It is shown that although there is a good adherence between experimental and predicted results at the beginning of the operation of the gas extraction system. After 2009 January (11.5 years after the start of the landfill operation), the methane recovery rate in the field decreased below the lower limit of the predicted values. These fluctuations in the methane recovery rate seem to be linked with the management practices adopted in the field. After 13.5 years (2011 January) there is recuperation in the recovery rates but the experimental values are still below the lower limit of the predicted results.

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