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GAS RETENTION EFFICIENCY OF A COMPACTED SOIL LANDFILL FINAL COVER IN A SEMI-ARID CLIMATE

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Abstract

The soil final cover in municipal solid waste containment facilities plays the main role in controlling landfill gas emissions and its efficiency depends on geoenvironmental aspects (e.g. weather conditions and soil characteristics). This study aimed to evaluate the gas retention efficiency of a compacted soil final cover of a landfill located in the Brazilian semi-arid region. The researched area was a municipal solid waste landfill cell with approximately 62 million kg of disposed waste. Landfill gas emissions to the atmosphere were monitored through gas flux readings in the i) vertical gas drainage system; ii) soil-waste interface and iii) compacted soil final cover. There was no methane emission time lag and methane concentrations above 50% were observed right after landfill cell closure. However, there was a 70% reduction in methane emissions in a short-time period. The methane flux through the final cover corresponded to 9% of total methane emissions over the monitored period and it was significantly lower than the flux in the gas drainage system. Hence, the landfill final cover demonstrated an adequate gas retention efficiency.

Key words: carbon dioxide, methane, municipal solid waste, sustainable management

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1. Introduction

Landfill gas production and emission processes are affected by many factors, which could be classified into three main groups: i) local weather conditions (e.g. temperature, precipitation, pressure, etc.); ii) disposed municipal solid waste (MSW) mass condition (e.g. physical composition, temperature, pH, microbial community, gas drainage system, etc.); and iii) landfill cover layer characteristics (e.g. thickness, composing material, permeability, degree of saturation, degree of compaction, etc.) (Lee et al., 2017; Lopes et al., 2012; Sethi et al., 2013).

The Brazilian semi-arid region is characterized by irregular rains, mean annual precipitation value lower than 800 mm, dryness index up to 0.5, and drought risk higher than 60% (Sudene, 2017). These dry weather conditions might influence MSW degradation in a way that it will result in low biogas flux and low leachate production, which is a common aspect of the so-called dry tomb landfills (Fourie and Morris, 2004; Frikha et al., 2017; Lee and Jones-Lee, 2015; Sethi et al., 2013).

O'Leary and Tchobanoglous (2002) reported that landfills with insufficient moisture content were found in a "mummified" condition as shown by the minimal changes in newspaper sheets disposed years ago. Therefore, although the quantity of gas production is directly related to its stoichiometry equation, its production rate and time depend significantly on weather and landfill operational conditions.

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It is also important to note that compacted soil landfill final covers should be designed to reduce rainfall infiltrations and minimize landfill gas emissions to the atmosphere. Depending on the final cover properties and the gas drainage system efficiency, biogas flux through this layer may be higher than the one in the gas drainage system (Lee at al., 2017).

The Brazilian Standards on MSW landfills, e.g. NBR 13896 (ABNT, 1997) and NBR 15849 (ABNT, 2010), do not provide specific information on final cover such as soil type, layer thickness, and execution procedure. They only recommend the execution of a final layer able to reduce rainfall infiltration, superficial erosion, and with a water permeability value lower than the one from the natural soil of the landfill area. The Brazilian Standards also establish the need for a homogeneous natural soil deposit, which should have water permeability lower than 10^{-8} m/s and an unsaturated zone higher than 3.0 m.

Landfill projects usually neglect the biogas potential for power generation. The gas drainage systems are not designed to maximize gas generation. Their main purpose is to be in accordance with requirements for reduction in gas emissions (Fei et al., 2016). Landfill gas emission monitoring is an important aspect of MSW landfill management (Kim et al., 2010) as it allows the evaluation of the final layer efficiency and optimization of the gas drainage system, which results in environmental and technical data that can be used in methane recovery projects (Park et al., 2016). Thus, this research aims to analyze the gas retention efficiency of a compacted soil landfill final cover in the Brazilian semi-arid climate.

2. Materials and method

2.1. Experimental field

Campina Grande (7°13'50" south latitude, 35°52'52" west longitude) is a city known as one of the main industrial centers in the Brazilian northeast region and a technological hub in Latin America. The city is in a semi-arid climate and presents annual rainfall of 748 mm/year and an annual evaporation rate of 1417 mm/year (Paraiba, 2001), which results in a regional water deficit during the year. According to Köppen and Geiger (1928), the region's weather is classified as Aw (tropical with dry winter).

The city population is estimated at 407,754 (IBGE, 2017). Daily MSW generation per capita is estimated at 0.64 kg, which results in about 261,000 kg/day of MSW. The landfill is located 10 km far from the urban area of Campina Grande (7°16’38" south latitude and 36º00’51" west longitude) and receives about 500,000 kg/day of MSW from Campina Grande and surrounding cities (ECOSOLO, 2016).

The studied landfill cell (cell #2) received 62,359,000 kg of MSW from December/2015 to May/2016. The cell’s dimension was 106 m x 117 m and 17 m high, and its final cover consisted of about 1.2 m of compacted soil. The gas drainage system was composed of nine vertical drains (DV-01 to DV-09) made of concrete pipes with an internal diameter of 0.3 m and an external diameter of 0.4 m.

2.2. Landfill cell monitoring plan

The monitoring plan for investigating the gas retention efficiency of the compacted soil final cover consisted of gas emission readings at the i) vertical gas drainage system; ii) soil-waste interface and iii) compacted soil final cover (Table 1).

The number of flow plate tests were calculated according to the USEPA methodology (USEPA, 2004), which recommends the use of (Eq. 3) for study areas larger than 5,000 m².

$$n = 6 + 0.15 * A^{0.5} \qquad (3)$$

where: n – number of flow plate tests; A – study area (m²).

Fig. 1 shows the landfill cell blueprint with the location of vertical gas drains (DV-01 to DV-09), gas concentration measurement devices (DMC-01 to DMC-22), and flow plate tests (EN-01 to EN-22).

Table 1. Landfill cell monitoring plan

Measurement level	***Research parameters and methods***	***Frequency***
Vertical gas drainage system (in-depth)	*Biogas qualitative outcomes:* - methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2) concentration; - via portable gas detector.	Monthly, from day 30 to day 480 after landfill cell closure.
	Biogas quantitative outcomes: - biogas outflow velocity and temperature measurement for flow calculation (Eq. 1) using a hot wire thermo anemometer: $OvbiogasSTP = 3,600*[(v*A*p*T_0)/(p_0*T)$ (1) where: $Q_{vbiogasSTP}$ – biogas volumetric flow under standard temperature and pressure (STP) (Nm³/h); v – mean biogas outflow (m/s); A – gas drain cross section (m²); p – pressure (bar); T_0 – standard temperature (273,15 K); p_0 – standard pressure (1 bar); T – temperature (K).	7 measurement campaigns were carried out from day 270 to day 570 after landfill cell closure.

Soil-waste interface (subsurface)	*Gas concentration measurement device (DMC) installation (Mariano and Jucá, 2011):* - The DMC consisted of a PVC tube and sealing accessories with 0.1m diameter and variable length, depending on the soil layer thickness. - The DMC was coupled with protection filter to avoid clogging and a valve to connect with the reading device. - The DMC was used to measure methane, carbon dioxide, and oxygen concentrations in the soil-waste interface.	Monthly, installed 365 days after landfill cell closure.
Compacted soil final cover (superficial)	*Flow plate tests:* - The gas outflow through the final cover was observed via the statical flow plate test, as described by Maciel and Jucá (2011). - The final cover biogas retention was determined using the methods described by Mariano (2008) (Eq. 2): $Retention_{gas}(\%) = 1-[(\%gas_{flowplate})/(\%gas_{DMC})]$ (2) $Retention_{gas}(\%) = 1-[C/C_C]$ where: *$Retention_{gas}$ (%)* – final cover biogas retention percentage; *% $gas_{flow\ plate}$* (C) – concentration of gas emitted into the atmosphere (obtained via flow plate test); *% gas_{DMC}* (C_C) – gas concentration at the soil-waste interface (obtained via DMC).	Carried out from day 450 to day 480 after landfill cell closure (during the drought period in the study region)
	Geotechnical characterization of final cover soil: - 31 soil samples were collected from the landfill cell following statistical criteria according to the central limit theorem (Larson and Farber, 2004).	The geotechnical characterization followed the Brazilian Standard Methods.

3. Results and discussion

3.1. Vertical gas drainage system monitoring

3.1.1. Qualitative outcomes

The monitoring results from the vertical gas drain measurements (DV-01 to DV-09) are shown in Fig. 2. The results indicate that from day 30 after landfill cell closure (monitoring day 1) the mean CH_4 concentration was more than half of the total outflow gas volume, which suggests the beginning of the methanogenic phase right after the landfill cell closure. The mean values of CH_4, CO_2, and O_2 concentrations were 57.5%, 41.2%, and 0.9%, respectively.

Fig. 2 also illustrates that the CH_4 concentrations were between 50% and 60% of the total outflow gas volume from day 30 to day 300. After that, CH_4 concentrations increased to values over 60%. Such CH_4 concentration increase occurred while the precipitation amount grew up. CH_4 concentrations decreased after the rainy season (day 450) to values between 50% and 60%. Since the methanogenic phase seems to have taken place before the monitoring campaign, it was not possible to evaluate the biogas composition corresponding to the initial waste biodegradation process.

Maciel and Jucá (2013) also observed the same issue in the Muribeca Landfill (Pernambuco State, Brazil), which was filled with about 36,659,000 kg of MSW and had an area of 5,993 m², being 9 m high. These authors reported CH_4 concentration of 50% after landfill closure, which was 10 months after the experimental cell operation had taken place. The Campina Grande Landfill cell in the current study operated for 5 months before closure.

Weather conditions in the Campina Grande's landfill area are different from Muribeca's. The former is located in a semi-arid region with cumulative rainfall value of 453.8 mm and average temperature of 30 °C during the five months of landfill cell operation. Besides that, Campina Grande Landfill cell had twice the waste capacity of Muribeca Landfill, although the organic content of the disposed MSW was similar, being 46.5% and 46% for Campina Grande and Muribeca Landfill, respectively.

Candiani (2011) analyzed the beginning of the methanogenic phase in Caieiras Landfill (São Paulo State, Brazil). The author identified a latent period of 194 days from the first day of waste disposal to methanogenic phase. After 350 days, the methanogenic phase became intense and stable with CH_4 concentrations higher than 50% of the total gas outflow. The Caieiras Landfill had a capacity of 3,786,000 kg of MSW, an area of 1,050 m², and a height of 5 m, being 4 times shorter than the Campina Grande Landfill cell. Such difference in height could have contributed to the latent period since Caieiras Landfill's waste was more exposed to external environmental conditions.

The reduced rainfall in the research area and the low water permeability of the final cover's composing soil (10^{-8} m/s) significantly reduce liquid infiltration into the cell and results in inhibition of landfill leachate production. On the other hand, the low moisture content helps the maintenance of the nutrients in the landfill cell as leaching occurs only when the waste field capacity is exceeded. Therefore, it is important to emphasize the importance of initial moisture content of the disposed waste (45% for the studied landfill cell) in the biodegradation processes.

The research area's semi-arid weather did not affect the biogas generation in a qualitative way. CH_4 concentrations were detected in the same proportion as those in the methanogenic phase in landfills from different weather conditions (Aguilar-Virgen et al., 2014; Maciel and Jucá, 2011). However, the waste's low moisture content due to drought periods might reduce biogas production.

Audibert and Fernandes (2013) stated that although literature suggests a waste moisture content of 50%-60% to maximize anaerobic processes, significant waste biodegradation was reported in Brazilian landfills with waste moisture content between 20% and 40%. The authors also highlighted the dependence between biogas production and aspects of the Brazilian weather.

3.1.2. Quantitative outcomes

Table 2 shows an overview of the biogas quantitative monitoring campaign carried out in February/2017 and June/2017 (day 270 and day 390 after landfill cell closure). The total biogas flow and CH_4 flow from the 9 vertical gas drains were 104 and 63 Nm³/h, respectively. Other 2 quantitative campaigns were performed in November/2017 and December/2017 (day 540 and day 570 after landfill cell closure), and a reduction of 70% in biogas outflow was observed in this period. Maciel and Jucá (2013) also reported a similar reduction in CH_4 flow from 97.3 Nm³/h to 29.6 Nm³/m, which is nearly 70%, that occurred 550 days after the Muribeca Landfill cell closure.

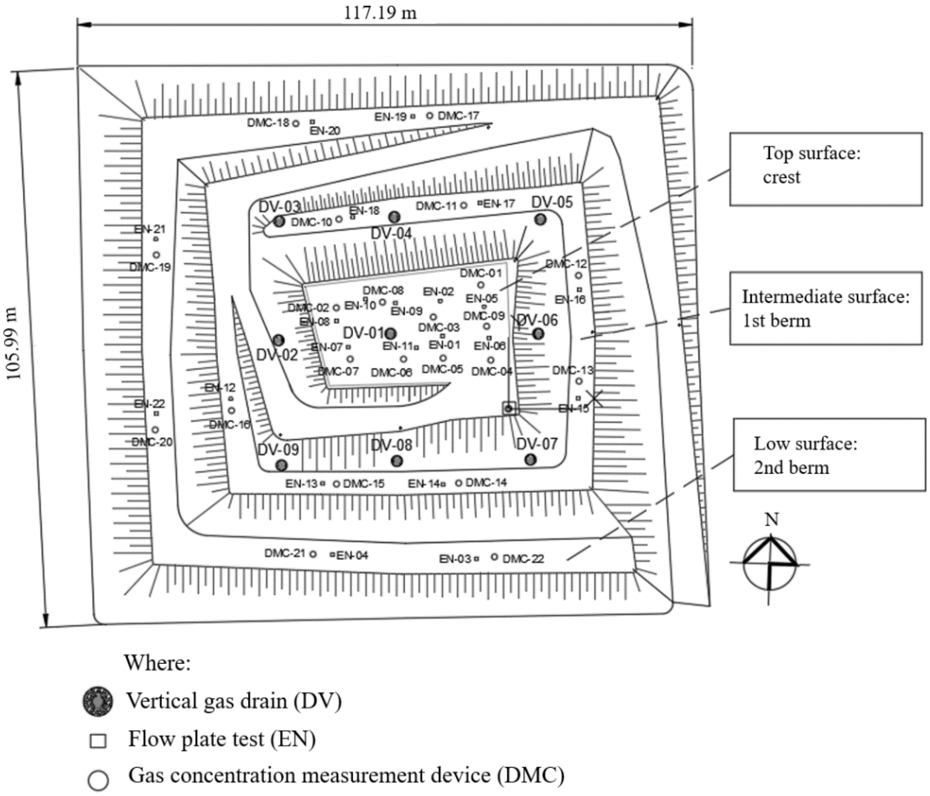

Fig. 1. Landfill cell blueprint

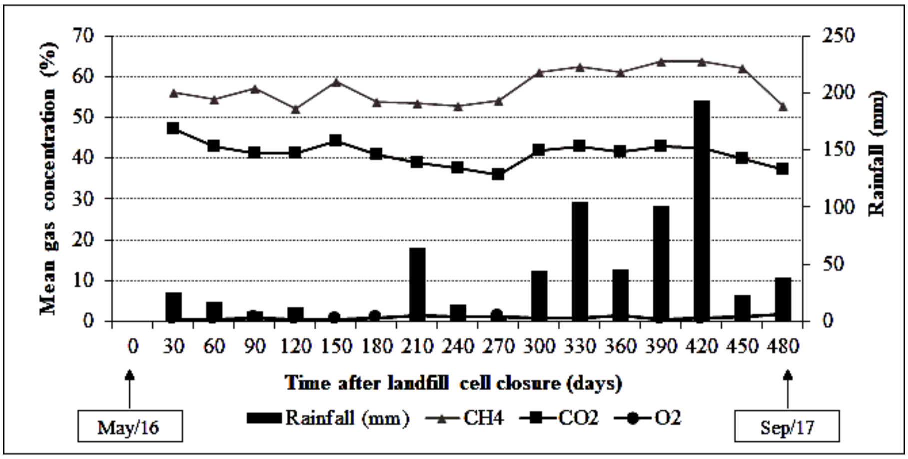

Fig. 2. Mean concentrations of methane (CH_4), carbon dioxide (CO2), and oxygen (O_2) from the vertical gas drainage system and oxygen (O_2) from the vertical gas drainage system

Table 2. Overview of the biogas quantitative monitoring campaign

Parameters	***Detected value***
Biogas mean outflow velocity (m/s)	3.0
Biogas mean temperature (ºC)	35.0
Biogas total flow (Nm³/h)	104.0
CH_4 average concentration (%)	60.5
CH_4 total flow (Nm³/h)	63.0
CH_4 average flow throughout gas vertical drains (Nm³/h)	7.0
Biogas daily outflow volume (Nm³)	2,495.4
CH_4 daily outflow volume (Nm³)	1,511.4

Considering a disposed MSW mass of 62,359,000.44 kg, the rate of biogas capture per ton of MSW varied from 15.20 Nm³/t.year (day 270) to 4.11 Nm³/t.year (day 570) on a humid basis. Since the quantitative monitoring campaign started on day 270, it is important to emphasize that this rate could be higher than 15.20 Nm³/t year on day 0. These rate values are within the range mentioned by Willumsen and Bach (1991) when referring to data collected in 86 landfills from different countries. These authors observed that the rate values were time-dependent and most of them ranged from 0.8 to 10 Nm³/t year, although some of them reached 20 Nm³/t year.

The rate of biogas capture per meter of drainage is shown in Table 3. This rate was determined by considering biogas outflow values and the depth of each vertical gas drain. The results varied from 0.66 to 1.23 Nm³/h.m (day 270) and from 0.18 to 0.33 Nm³/h.m (day 570). A relationship between rate of biogas capture and depth of vertical gas drains could be perceived by observing the values of 1.23 Nm³/h.m for DV-05 and 0.66 Nm³/h.m for DV-01, even though DV-01 was deeper than DV-05 (Table 3).

3.2. Soil-waste interface monitoring (subsurface)

The subsurface investigation was done by installing gas concentration measurement devices (DMC) and monitoring the concentrations of CH_4, CO_2, and O_2 in order to verify points of greater biogas generation in the landfill cell. The results obtained are shown in Fig. 3, which is arranged according to the location of the DMCs (crest, 1st, and 2nd berm).

For each installed device, the average concentrations of CH_4, CO_2, and O_2 are presented, as well as the thickness of the covering layer at each point. As seen in Fig. 3, CH_4, CO_2 and O_2 concentrations ranged from 0.4 to 64.3%, 6.1 to 45.0%, and 0.6 to 14.4%, respectively, which indicates a great data dispersion. These results suggest that percolation of methane over the landfill surface is highly variable (Mariano and Jucá, 2011; Börjesson et al., 1998). Also, CH_4 concentrations higher than 50% were associated to measurement points deeper than 0.9 m. The CO_2 concentrations ranged from 20 to 45% except for DMC-08, DMC-18, and DMC-19, which presented CO_2 concentrations lower than 20%. Regarding O_2, concentrations higher than 5% were detected at points with the lowest CH_4 concentrations (DMC-08, 18, and 19).

Even though the MSW portion closer to the soil-waste interface was more likely to be influenced by environmental conditions, there was a reduced concentration of O_2 in this area (except for DMC-08). Such fact could have enhanced anaerobiosis and generated CH_4 concentrations greater than 40% in 9 out of the 22 monitored points (Fig. 3). DMCs were installed 365 days after the landfill cell closure (except DMC-01, 02 and 03), and that explains the low concentrations of O_2 and the efficiency of the final layer of MSW.

Mariano and Jucá (2011) found O_2 concentrations ranging from 7 to 15% in 7 out of 19 measurement points at the soil-waste interface in Muribeca Landfill cell. According to these authors, the detection of O_2 concentrations in the interface indicates the presence of cracks in the soil cover layer which might create preferential gas flow pathways. In the Controlled Landfill of Londrina (Paraná State, Brazil), Audibert and Fernandes (2013) evaluated the concentrations of CH_4, CO_2, and O_2 at the soil-waste interface.

They installed 10 inspection tubes, like the ones used in this study. The concentration of CH_4 varied between 2.1% and 42% (average of 16.3%), CO_2 between 0.8% and 50% (average of 17.1%) and O_2 between 0.6% and 19.7% (average of 12.9%). They also found out that 7 out of the 10 tubes had O_2 concentrations above 11.5%.

Table 3. Rate of biogas capture per meter of drainage

Vertical gas drain	***Depth (m)***	***Rate of biogas capture per meter of drainage (Nm³/h.m)***			
		Biogas		***CH_4***	
		t = day 270 (Feb/17)	***t = day 570 (Dec/17)***	***t = day 270 (Feb/17)***	***t = day 570 (Dec/17)***
DV-01	18.3	0.66	0.18	0.34	0.10
DV-02	16.6	0.66	0.19	0.38	0.12
DV-03	12.1	0.84	0.22	0.42	0.12
DV-04	11.7	0.92	0.23	0.49	0.15
DV-05	11.3	1.23	0.32	0.71	0.18
DV-06	12.9	0.99	0.33	0.56	0.21
DV-07	13.5	0.72	0.23	0.38	0.14
DV-08	12.7	1.01	0.30	0.52	0.19
DV-09	13.0	1.16	0.21	0.62	0.13

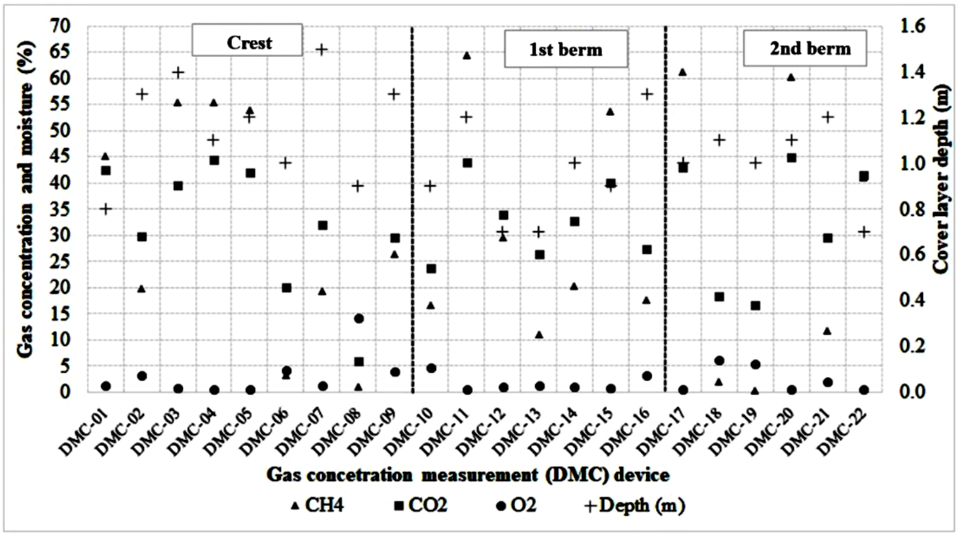

Fig. 3. Landfill gas concentration at soil-waste interface and landfill final cover thickness

Regarding the differential pressure in the DMC, no pressure gradients were detected in any of the 22 monitored points in this study. On the other hand, Audibert and Fernandes (2013) reported a mean biogas pressure gradient of 1,225 Pa bellow the compacted soil layer. These authors reported that such value is probably associated with a large volume of liquid under the soil cover layer that was applying pressure on the waste.

In this current study, during 570 days after the cell closure, no cracks with the presence of leachate were identified in the final cover layer. In addition, during the gas flow measurement, no liquid levels were observed inside the 9 gas drains.

3.3. Compacted soil final cover monitoring (superficial)

Flow plate tests were performed from day 450 to day 480 after landfill cell closure. This period was also the driest one during the monitoring time (precipitation indexes were less than 5 mm in this period).

3.3.1. CH_4 iso-flux map

Fig. 4 shows the CH_4 iso-flux map that was interpolated by using SURFER®14 software. This analysis was performed just for methane as its emission has major impacts on the operation of landfills (Huber-Humer et al., 2011; Solomon et al., 2007). The mapping process was important for extrapolating the 22 plate flow tests results, which leaded to a better understanding of the fugitive methane emissions throughout the landfill cell final layer. Fig. 4 shows that CH_4 flow in the central area of the landfill cell was not detected. This is probably justified by the proximity between this area and the vertical drains, which capture the gas more efficiently. Mariano and Jucá (2011) reported in their study that areas with higher CH_4 flow through the cover layer are located at the cell's borders and that CH_4 flow tends to reduce towards the center of the landfill. The authors also detected lower CH_4 emissions in the center of their studied landfill cell.

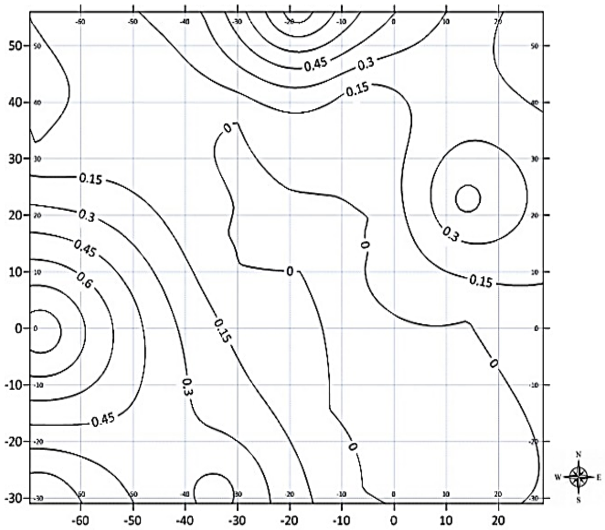

Fig. 4. Volumetric outflow of CH_4 from the landfill cell ($NL/m^2.h$)

The total CH_4 emissions were obtained by quantifying the areas with the same gas outflow values. This resulted in a total gas flow of 1.66 Nm^3/h for the studied period. The average CH_4 outflow values from the vertical gas drains were 58.6 Nm^3/h (day 270) and 17.4 Nm^3/h (day 570). Thus, given that time variability of biogas fugitive emissions was not taken into consideration, the CH_4 outflow through the landfill cover layer corresponded to about 2.8% (day 270) and 8.7% (day 570) of the total emissions. These results did not account for CH_4 oxidation.

The total CH_4 flow at the final cover layer detected in this study (0.15 $NL/m^2.h$) was almost 25 times lower than the maximum value recommended by the Australian standard Carbon Farming Initiative, which is 3.78 $NL/m^2.h$ (CFI, 2013). This suggests the efficiency of the final cover layer of landfill cell and the gas drainage system. The cover layer efficiency is an important parameter when implementing projects on biogas energy recovery systems.

Audibert and Fernandes (2012) reported an average CH_4 flow value of 1,764 Nm³/h in the final cover layer of the Controlled Landfill of Londrina, which corresponded to 88.8% of total gas emissions. The CH_4 flow in the vertical gas drains was reported to be 222 Nm³/h (11.2% of total gas emissions). Thus, they concluded that the studied gas drainage system was inefficient.

Silva et al. (2013) studied fugitive emissions in 2 landfills in São Paulo city, Brazil. At the Bandeirantes Landfill, CH_4 flow of 0.00126 Nm^3/m^2.h (1.26 NL/m^2.h) was obtained from a total of 504 Nm³/h through the entire layer area. The total flow in the vertical drainage system was 2,610.60 Nm³/h, which represents a leakage percentage of 16%. At the Caieiras landfill, the CH_4 flow of 0.01222 Nm^3/m^2.h (12.22 NL/m^2.h), with a total fugitive emission of 3,840.6 Nm^3/h and total flow through the drains of 7,250.0 Nm^3/h, so about 35% of the landfill emissions came from the cover layer.

3.3.2. CH_4 retention efficiency of the compacted soil final cover

The landfill gas retention percentage in the cover layer (Fig. 5) was determined through the CH_4 and CO_2 concentrations from the flow plate tests (surface) and the concentration values from the measurement devices (DMC, subsurface). The final cover retention efficiency was high and ranged from 93.7 to 100% for CH_4 and 89.9 to 99.3% for CO_2 (Fig. 5). Several factors contributed to such efficiency:

- Landfill gas pressure at the soil-waste interface: no gas pressure gradients were detected at any of the 22 monitored points under the cover layer. The following 2 facts might indicate the lack of liquid pocket formation in the landfill: i) the leachate production stopped on day 390 after landfill cell closure and ii) the low soil moisture at the soil-waste interface (less than 10%);
- CH_4 concentration at the soil-waste interface: the increase in CH_4 concentration at the interface did not imply a reduction of gas retention by the final cover layer. A reduction in gas retention efficiency at the soil-waste interface points resulting in CH_4 concentrations lower than 20% was observed. The concentrations at the soil-waste interface could only indicate a higher or lower amount of gas emission to the atmosphere in case there was no final cover;
- Layer thickness: it ranged from 0.7 to 1.5 m. Similar CH_4 retention efficiency values were found at points with varying layer thickness. With this, it is possible to infer that the absence of gas pressure gradient under the cover layer minimized the importance of layer thickness;
- Soil permeability by water and air: laboratory water permeability tests for the soil from the cover layer resulted in permeability values of about 10^{-8} m/s, which is suitable for landfill cover layers (ABNT, 1997). In situ infiltration tests indicated even lower permeability values, in the order of 10^{-9} m/s. The air permeability test, on the other hand, resulted in values of 10^{-7} m/s. Both values for water and air permeability are suitable for promoting reduction of biogas emissions through the cover layer (ABNT, 1997; Lopes et al., 2012; Mariano, 2008; USEPA, 2004);
- Soil Saturation (S): the biogas outflow was low despite of the fact that the soil cover layer was unsaturated (average S=40.2%). This suggests that this parameter was not a decisive factor in the efficiency of gas retention by the cover layer. The absence of gas pressure under the cover layer, the low water and air permeability of the soil, the degree of compaction of the cover layer and the efficiency of the gas drainage system minimized the potential influence of the cover layer's degree of saturation on fugitive emissions;

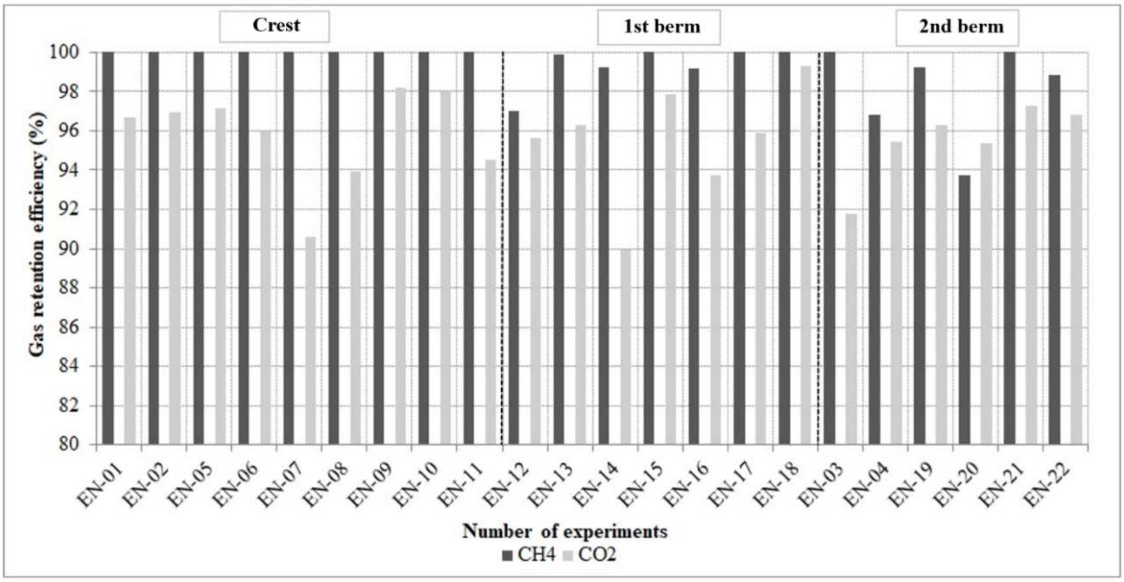

Fig. 5. Gas retention efficiency of the compacted soil landfill final cover

• Degree of compaction (DC): the average degree of compaction of the soil at the monitored points was 91.84% and this parameter played a fundamental role in the gas retention. Although DC values between 80 and 85% were obtained in almost 15% of the experiments, the CH_4 retention efficiency of the final cover still had values higher than 93% in all monitored points. The low degree of saturation and the absence of gas pressure gradients under the cover layer also contributed to such average degree of compaction value. Although DC values ranging between 80 and 85% were detected, it did not result in a loss of gas retention efficiency of the cover layer as CH_4 retention was higher than 93% in all 22 measured points;

• Vertical gas drainage system: it significantly influenced the reduction of biogas flow in the landfill cell mainly due to all the drains which were satisfactorily functioning without any evidence of pipe obstruction and to the absence of gas pressure gradients at the soil-waste interface.

4. Conclusions

The high CH_4 concentration values were compatible to the methanogenic phase of biodegradation and were observed right after the landfill cell closure. The quick reduction in biogas flow (for 570 days) indicates the importance of disposed MSW volume in landfill cells. Thus, a high amount of waste volume is needed to maintain CH_4 outflow at a favorable level to enable the energy recovery for a longer period.

There is no relationship between the depth of vertical gas drains and the rate of gas capture per meter of drainage in the landfill cell.

The CH_4 emissions throughout the final cover layer of compacted soil were relatively small, even though the measurement was done in the dry season. The low fugitive emissions of biogas into the atmosphere were due to the lack of gas pressure gradient under the cover layer, the efficiency of the gas drainage system, the high degree of compaction of the soil layer and low permeability of soil by water and air. It would be possible to reduce the thickness of the final cover layer without losing the efficiency of gas retention, but the average degree of compaction needs to be equal or greater than the one obtained in this studied landfill cell (91.8%).

No leachate was detected in the soil-waste interface. The leachate production stopped on day 390 and the soil portion close to the interface had low moisture content, which suggested a low moisture content for the disposed MSW mass as well.

The low oxygen concentrations in the soil-waste interface indicated a low influence of external conditions on the upper waste layers, which might be due to the efficiency of the soil final cover layer.

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