LEACHATE ABATEMENT INSIDE SOLID WASTE LANDFILL

A. J. SARUBBI† and G. SÁNCHEZ SARMIENTO‡

†*Construction & Structures Department, Engng. School, Univ. Bs. As., Las Heras 2214 ,C1127AAR, Bs.As., Argentina*
‡*Physics Department, Engng. School, Universidad de Buenos Aires, Paseo Colón 850, C1063ACV, Bs. As., Argentina*
†*sar@techint.com* ‡*sanchezsarmiento@arnet.com.ar*

***Abstract*— Parameters such as chemical oxygen demand in leachate, organic biodegradable compound, specific weight, and settlements of solid waste disposed in large scale testing unit at Buenos Aires Sanitary Landfill were monitored for more than 20 years. The mathematical simulation formulae between these parameters and the solid waste age were established based on the data obtained from the testing landfill units, and justified by the data obtained at the closed landfill units. The long-term predictions for concentrations of leachate from the landfill were carried out through mathematical simulation of a set of formulae proposed. The results showed that the organic activity within the landfill was stabilized after 7 years of closing it, confirming the consolidation and biodegradable process and its rate over time. While the landfill reached this quasi-equilibrium state, the on-site treatment of leachate was achieved, with a significant reduction in costs.**

An improvement of the initial conditions in the engineering design phase was discussed, as well as, some optimization in maintenance post-closure activities. Additionally, the landfill's reintegration process and, the expansion of its capacity with minimal impact on the environment, were considered.

***Keywords*— Sanitary landfill, solid waste, biodegradation, leachate, settlement.**

I. INTRODUCTION

Sanitary landfill (SLF) is still the most common practice of municipal solid waste (MSW) disposal in Latin American countries. Basically, SLF is a large-scale bioreactor where complex and, physical, chemical and biological reactions occur. While the MSW degrades, SLF gases are generated, top surface is settled down (Ling *et al*., 1998; Liu *et al*., 2006) and organic concentrations in leachate are attenuated gradually (Bookter and Ham, 1982; Durmusoglu *et al*., 2005; Durmusoglu *et al*., 2006; Jiangying *et al*., 2004; Youcai *et al*., 2001). One of the main problems in the analysis of stabilization process is the monitoring field data. This data is critical to predict long-term conditions. Different literature was revised and, the problem was confirmed: limited monitoring period of time. In the present manuscript, field monitoring results compound a period of 21 years (7700 days), while the latest information does not collect more than 3 to 5 years of recording: Bowders *et al*. (2000), in "Settlement of Municipal Solid Waste Landfills", leachate and settlements were measured in Columbia landfill, USA for 180 days. In the same paper, cumulative settlement was registered in Lyndhurst landfill, Victoria, Australia for 700 days. Sowers (1967) studied the settlement of a building and new 10 feet fill on an old sanitary land fill of 25 feet thick for 2080 days. Machado *et al*. (2002), registered data of Bandeirantes SLF in Sao Paulo, Brazil for 2500 days. Youcai *et al.* (2001), in Shangai SLF in China measured field data for 1200 days. Kumar (2000), Coduto and Huitric (1990), and Edil *et al.* (1990) in Mission Canyon SLF, in California, USA, registered and analyzed field data for 1497 days. Edil *et al.* (1991) in Wisconsin SLF, USA, registered field data for 600 days. Sánchez-Alciturri *et al.* (1995) in Meruelo SLF in Spain, registered field data for 900 days. Merz and Stone (1962), in Spadra SLF in USA, registered field data for 500 days. Hossain (2003) in different waste landfills: Mountain View, Yolo county, Mid Penninsula, Atlantic, Richmond, Keele, and Spruce Ridge, covered a maximum period of 1350 days of field monitoring. Oweis (2006) made a theoretical study on landfill settlements due to mechanical and decompositional processes.

These waste landfills are a potential pollution source for surface and groundwater. To prevent contamination, sealing SLF surrounding strata and treating leachate are the usual practices. Leachate is formed in SLF due to the degradation of the waste together with percolation of rain water through the open discharge area or through the SLF cap (Rodriguez Iglesias *et al*., 2000). Leachate´s degradable compounds were used as a parameter to determine biodegradation effects over time (Lee *et al*., 2001).

Since all organic materials in the MSW undergo partial or total microbial decomposition (mineralization), leachate contains intermediate products together with high concentrations of toxic organics, heavy metals, and other xenobiotic materials. The exact composition is variable and site specific depending principally on the MSW´s type and age, and the operational methodology applied, that involves cover frequency and rain regime (Ehrig, 1983; Kjeldsen and Cristophersen, 2001). Proper SLF design and site management can significantly reduce the quantity and strength of leachate but will never eliminate it (Gurda and O´Hara, 1995).

The treatment of leachate is one of the most important issues in the management of a landfill. Conventionally, the leachate is pumped out from the SLF and led into the anaerobic or aerobic treatment plants. The processes for leachate treatment are always very complex

and costs are usually quite high (Sarubbi, 1997; Youcai *et al*., 2000).

The aim of this study is to characterize leachate of argentinean SLF, and the process of degradation and stabilization of SLF. As a secondary objective, provide recommendations on the treatment of leachate and the conditions of design engineering to reduce maintenance costs and integrate the SLF into the community.

II. METHODS

A. Construction of the sanitary landfill units

Sanitary landfills under study are located in the Greater Buenos Aires area, in Argentina, and, during 25 years have received over 65 million metric ton of MSW, and served as final disposal alterative of almost 10 million people. They were used as large-scale experimental in situ units because of their technical and operational standards, and, the consistent monitoring program.

The south landfill in the Buenos Aires surrounding area, Villa Dominico, has 747 hectares of which 520 hectares are of waste disposal and 227 hectares of green buffer area. This landfill started operations in October 1978 and closed in February 2004. The Villa Dominico area was selected by its geological layers so that potential out-coming leachate could be controlled through a layer of clay that varies from 1.5 to 5 m in thickness and has a permeability coefficient of 10^{-9} m/sec. The monitoring field data -used in this study- was registered from June, 1979, till January, 2004. The initial height of the first experimental module with solid waste disposal (measured at its top final cover) was 5.60 m above sea level, in 1979, and after 21 years, had a total settlement of 19% (the monitoring plate was identified as VD 1). The modules used in this study had a 20% average (AV 7 monitoring plates), and their initial conditions are showed in Table 1.

Since 1988, the engineering design tried to improve landfill capacity and increased the MSW height of disposed material using less area of land. In the Quilmes module (identified as QL 2), an increase of the top cover height of two meters (8 m above sea level) was achieved, and its capacity was improved by 20%, and, after 20 years, the measured settlement of the top cover was 18% (average).

From July 1990 until its closure, due to the lack of land, Villa Dominico SLF increased even more the thickness of disposed MSW. A vertical expansion was designed, with higher (intensive land use) modules with 20 m of MSW thickness, creating a second level of MSW disposal over the original, with a cumulative settlement of 25% (VD 9).

Finally, Dock Sud SLF was designed with a higher level of final top cover so that more MSW could be disposed. The infrastructure (modules, embankment, cells, etc.) was located in an area with 5 to 9 m layer of clay with a 10^{-10} m/sec permeability coefficient, was started in 1991 and ended in 1992. MSW discharge operations began in March, 1992 and ended in June, 1994. After 14 years, the average settlement registered, on the top cover, was around 19% in DS 1 monitoring plates, and 18% in DS 5 site.

Table 1. Monitoring site plates and environmental conditions in Buenos Aires sanitary landfills.

Site plate N°	Initial height (m)	Monitoring period (year)	Settlement (%)	Initial OBC (% -weight)	Initial specific weight (kN/m^3)	Initial COD (mg/l)
QL 2	8	20	18	17.8	4.50	56730
AV 7	6.61	21	20	25.5	6.23	64580
VD 9	9 (1st stage) + 11 (2nd stage)	18	25	30.0	7.60	77590
DS 1	22	14	19	24.5	7.90	62000
DS 5	23	14	18	19.0	7.80	51000
VD 1	5.6	21	19	21.0	5.20	60710

B. Refuse biodegradation research

Sample preparation

Refuse samples were taken at the transfer stations in Buenos Aires city before going to the SLF, and extracted from the mass of MSW disposed in the SLF. Four different samples were collected prior to discharge, with an annual monitoring frequency for each topographic monitoring plate, following the sampling methodology of the ASTM (1992) 5231-92 norm (Standard test of the composition of unprocessed municipal solid waste). The samples were classified by their physical and chemical composition, were broken into powder by hammer, miller or grinder until the particle diameter was smaller than 0.1 mm. Then, the MSW powder from the four samples was mixed and a given weight of this mixture was sent for analysis. All the final samples of mixed powder were tripled, and the data recorded in tables and figures are the mathematical mean values.

Leachate was taken in a similar way from the collection drainage system closer to the monitoring plates located into the SLF (Fig. 1).

Analytical methods

Leachate composition was measured with the Chemical Oxygen Demand [COD: amount of an oxidant dichromate ion ($Cr_2O_7^{2-}$) that reacts with the sample under controlled conditions, being reduced to the chromic ion (Cr^{3+})] and Biochemical Oxygen Demand [BOD_5: empirical test that measures the molecular oxygen used

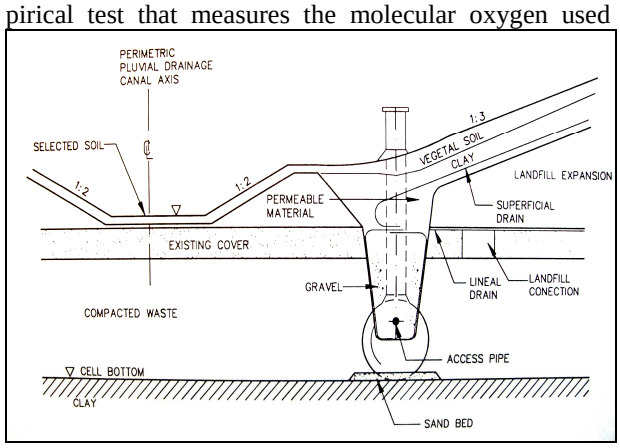

Figure 1. Leachate collection system in Argentine sanitary landfills.

during a specified incubation period (5 days) for the biochemical degradation of organic material (carbonaceous demand) and the oxygen used to oxidize inorganic material such as sulfide and ferrous iron] which were analyzed under the Standard Methods protocols (Eaton *et al*., 2005).

For Organic Biodegradable Compound (OBC) analysis, MSW sample was oxidized by potassium dichromate solution at room temperature.

MSW composition was analyzed according to the dry basis method. Dry basis refers to samples dried at 105°C for 3 hours, and the resulting weight loss is named moisture.

All the laboratory techniques followed the USEPA SW-846 (1986) norm.

Solid waste composition

The MSW deposited in the SLF under study had an average composition included in Table 2. It is worth noting that the MSW has more than 50% (wet weight) of rapid biodegradable organic matter (mainly food waste). Similar proportions are found in Latin American SLF (PAHO, 2005). This proportion of organic matter is the main aspect in terms of biodegradation and stabilization processes of the MSW and, also, in the SLF stabilization.

MSW quality changes continuously along time. The MSW placed in the 1970s is different from the MSW placed in the 1980s or in the 1990s. For example, the fraction of MSW made up of plastic material continues to increase (Ohtaki and Kiyohiko, 2000). As shown in Table 2, the increase in the plastic fraction has risen from 2% (wet weight) in 1970, 10% in 1991 and 13.8% in 2001.

In contrary, the organic degradable fraction -in terms of stabilization of SLF- has declined from 89.9% in 1970 to 71% in 2001. These values are confirmed in Latin America countries because they have similar characteristics and habits in terms of waste generation.

Table 2. Average composition of municipal solid waste in Buenos Aires sanitary landfills and Latin American countries. Source: indicated below the table.

Component (%wet weight)	Argentina (year)			Latin America
	1972 (1)	1991 (2)	2001 (3)	2005 (4)
Quick degradable organic components				
Food waste	63.3	51.5	33.4	46.4
Paper & cardboard	20.3	17,0	24.1	18.7
Greentrash	0.0	3.0	5.0	0.8
Subtotal 1	83.5	71.5	62.5	65.9
Slow degradable organic components				
Textile	3.0	2.7	2.5	3.6
Rubber	0.5	0.1	0.4	0.06
Leather	1.0	1.0	0.4	0.06
Wood	1.9	1.8	1.3	0.3
Diapers	-	-	4.1	0.8
Subtotal 2	6.4	5.6	8.6	4.8
Subtotal 1 + 2	*89.9*	*77.1*	*71.0*	*70.7*
Non biodegradable components				
Plastic	2.0	10.0	13.8	9.1
Metal	3.3	2.9	2.5	2.6
Glass	4.8	7.0	5.2	5.4
Inert material (ash, sand, dust)	-	2.0	1.7	10.7
Hazard and pathogenic waste	-	-	1.7	0.8
Miscelaneous smaler than 12,7mm	-	1.0	4.2	0.7
Subtotal 3	10.1	22.9	29.0	29.3
TOTAL	100.0	100.0	100.0	100.0
Average moisture content	55-60	53.1	54.7	56.7

References: (1) Levy and Alegre (1972); (2) Sarubbi *et al*. (1991); (3) Pescuma *et al*. (2001); (4) PAHO (2005).

Leachate characterization in Argentine landfills

Several leachate investigations were held from 1980 up to 2002 as part of an environmental monitoring program and the vertical expansion project (Sarubbi *et al*., 1994), to characterize leachate as a function of its age (Theisen *et al*, 1996). The results were summarized in Table 3 and compared to international literature in Fig. 2.

Leachate is a complex and highly variable mixture of soluble organic, inorganic, bacteriological constituents and suspended solids in an aqueous medium. The leachate BOD_5 concentrations decreased with time and had a large variation among the different cells and modules. In those where MSW had been emplaced for longer periods, not only the BOD_5, COD, and total organic carbon (TOC) contents on the leachate were lower, but also the ratio of BOD_5:COD and COD:TOC tended to decrease. Nitrogen is hard to reduce and maintains a consistent concentration for a long time. In Fig. 2 the abatement of González Catán and Villa Dominico argentinean SLF´s leachate is shown, and the COD exponential trend was proposed based on the field data sampled for 20 years.

C. Mathematical formulae on composition of leachate and solid waste over time

Organic Biodegradable Compound

MSW undergoes aerobic biodegradation almost immediately after it is generated, that is in the garbage bin. Once in the SLF, after its disposal, the aerobic process continues because of the presence of trapped oxygen (air in a porous media). Then, MSW goes through a

Table 3. Leachate monitoring campaigns in Buenos Aires´ sanitary landfills.

COD Monitoring Campaign (year)	Elapsed time (years)										
	0.5	1	2	3	5	7.5	10	12.5	15	17.5	20
1989	50400	36730		32910	24870	10700	6430				
1994	51000	45300	29850		32300		7450	2450			
1994	62000	38720	31260	40230		19560		4350			
1995	85450	29590	33440	45710	10440		5820		3060		
1996			34560	23780	19850	12320	7370		2180		
1997	76540	47980		34780			5270	3180		710	
1998			40190	19640	15648	10042	6350		2510		
1998	42400		27890		16000			3380	1390	980	90
1999		45190			15660	14425			1930	760	540
2000			28640	27200		5532		3483	3073	860	320
2001	45630	46680		14600		9890	3200			1320	837
2002	72320			25870	8200	5400	4400	3420	2340	1100	450
Average COD	60718	41456	32261	29413	17871	10984	5786	3377	2355	955	447

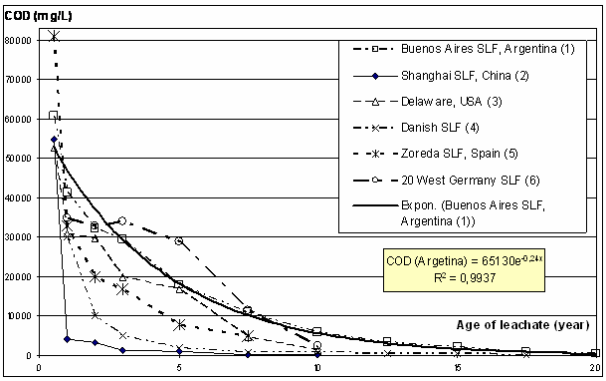

Figure 2. Leachate´s COD concentration results measured in the Argentine sanitary landfills (reference 1: Sarubbi, 1997, and Sarubbi *et al*, 1994) and comparison with international literature (2: Youcai *et al*, 2000; 3: Watson, 1989; 4: Kjeldsen and Christophersen, 2001; 5: Rodríguez Iglesias *et al* , 2000; 6: Ehrig, 1983).

facultative degradation stage (up to 2 years), and finally, the ambient for MSW organic phase degradation becomes strictly anaerobic and continues for a long time (more than 10 years).

The organic biodegradable compound (OBC_t) of the MSW at a time *t*, can be defined with an exponential function of waste age, and the refuse biodegradation in SLF conform to the following first-order kinetic Eq. 1:

$$OBC_t = OBC_0 . \left\{ e^{-10.K_h.RBC_0.t} \right\}, \qquad (1)$$

where, OBC_0: starting MSW organic biodegradable compound of the MSW, determined by the quality study of urban garbage, and based on the evolution related to population habits and differential collection systems (expressed as mass percentage), at the initial stage, that is after the disposal at the SLF; RBC_o: starting coefficient of rapid biodegradable composition, that depends on MSW porous structure, environmental conditioning factors and, MSW moisture (Sarubbi *et al*., 1991) at its initial stage, immediately after its disposal. It comes from Table 2. K_h: coefficient that considers the hydrolysis rate of degradation (Table 4 shows a research related to hydrolysis degradation rates), and *t*: elapsed time from the moment MSW is disposed of at the SLF (measured in years); the sub-index *t:* stands for the stage in time after its disposal at the SLF.

The evolution of the average OBC sampling results is compared in Fig. 3 with the proposed model (Eq. 1).

Table 4. Hydrolysis degradation rate research. Unit: day^{-1}.

Source of research	Hydrolysis degradation rate
El-Fadel et al. (1996a & 1996b)	
Quick	0.006-0.000002
Medium	0.001-0.0000003
Slow	0.0002-0.0000006
Lee et al. (2001)	0.00375-0.002
Lee et al. (1993)	0.0008
Manna et al. (1999)	
Quick	0.00063-0.00189
Slow	0.00008-0.00016
Young (1995)	
Quick	0.00274
Medium	0.000548
Slow	0.00000113
Zacharof & Butler (2001)	0.0027-0.0055

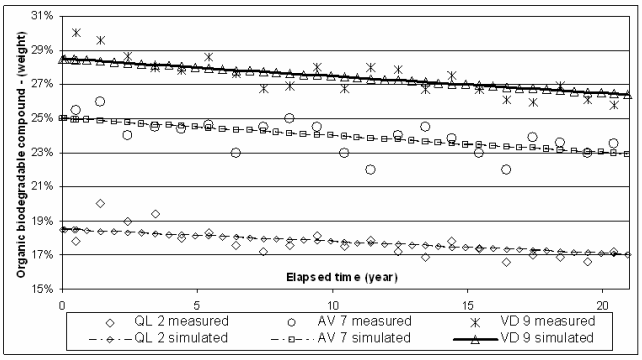

Figure 3. Measured and simulated OBC of waste disposed in the Villa Dominico sanitary landfill.

Solid waste specific weight

The degree of compaction is directly related to different SLF factors and MSW characteristics. Different factors should be assessed on a case-by-case basis. The age and degree of biodegradable process, management of biogas (quality, generation rate, and extraction techniques), as well as leachate management (quality, generation quantity and extraction techniques), temperature and hydraulic characteristics of MSW [hydraulic conductivity determined from pumping test is about 10^{-5} m/sec. (Oweis and Ellwood, 1990)], heavy equipment used for MSW compaction, soil cover frequency of the open operative discharge area, climatic conditions, among other variables, influence the compression index and finally, its specific weight (Chia-Nan *et al*., 2006).

The specific weight of MSW disposed, SW_t can be defined by the following expression:

$$SW_t = SW_{t-1}.(1 + \frac{OBC_t}{OBC_0})^{t/100}, \qquad (2)$$

where, OBC_t: organic biodegradable compound of MSW under study (expressed in % weight) at time *t*; OBC_0: initial organic biodegradable compound of MSW (expressed in % weight); SW_{t-1}: specific weight of the MSW in its previous stage (previous time period) in kN/m^3; SW_0: initial specific weight of MSW when SLF was covered and disposal operation finished (also in kN/m^3).

Figure 4 shows SW variation with time taking into account field data of argentinean SLF and simulated results.

Leachate

Generally, BOD_5 and COD leachate concentration values are high during the first five years, but they rapidly decrease to relative low values (Kjeldsen and Christophersen, 2001), and this characteristic was related to the degree of decomposition of the MSW´s organic compound. Therefore, MSW´s organic compound decreases in terms of BOD_5 or COD, and helps to assess OBC evolution. The variation of leachate´s composition is achieved by the following formula:

$$COD_t = COD_{t-1} . \left\{ e^{-\beta . t} \right\} \qquad (3)$$

$$\Phi COD_t = 1 - \frac{COD_t}{COD_0} \qquad (4)$$

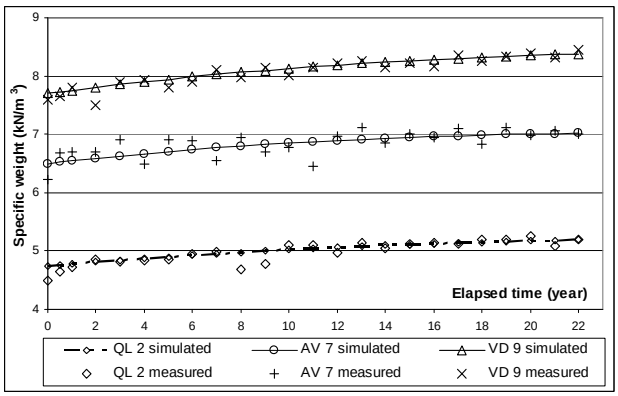

Figure 4. Specific weight of municipal solid waste disposed at Villa Dominico sanitary landfill.

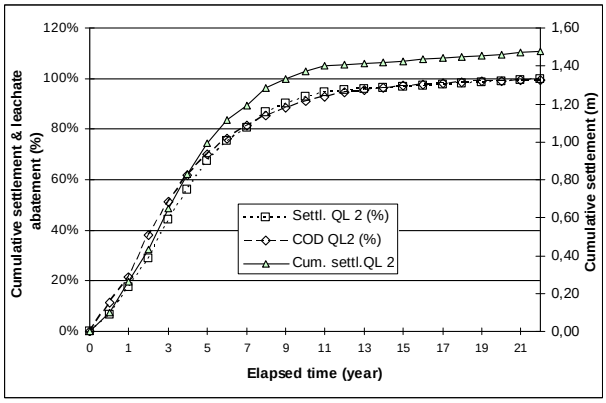

Figure 5. Cumulative settlements and leachate COD concentrations in Quilmes sanitary landfill.

where: COD_t: is the variation in the composition of MSW leachate COD concentration with time t, and, COD_0: is the initial determined concentration of COD of MSW leachate (t=0); FCOD_t: Proportional leachate abatement relation that will be used to understand the biodegradable process at the elapsed time t; b: COD biodegradability coefficient of leachate composition, that was determined to be 0.24 from the field data; t: elapsed time since the moment of leachate´s generation measured in year.

D. Results

The process of biodegradation of organic components of MSW is complex and difficult to model. However, the changes in certain representative parameters of the SLF, can be investigated through the temporal relationship between reduction in the OBC of MSW, the increase of their specific weight, the increasing settlements of its top cover, and the abatement of the leachate through its variable COD.

In disagreement with some recent research linking the process of biodegradation and stabilization of the SLF, to the generation of biogas (Chia-Nan *et al.*, 2006; Oweis, 2006), this study proposes a linkage with the process of abatement of the leachate. The main objection is that the rate of biogas generation depends on a number of parameters such as the type of collection and extraction system, the extraction flow, the extent of the MSW mass gathering into the SLF, atmospheric conditions, and besides, it is recognized that even an efficient system can not collect more than 60% of the total potential biogas generated (Brown and Caldwell, 1994).

In Fig. 5 the abatement of leachate COD concentration, is compared with cumulative settlement of the plate named QL 2 in absolute and relative values.

The similarity in the curves of both stabilization processes was notorious. On the one hand, the process of mechanical-physical stabilization through the settlements of the MSW height, and secondly, the process of lowering the organic load of leachate expressed through its COD. This similarity led to the confirmation of the relation between the organic degradability of MSW disposed in the SLF, through its settlements or through the leachate´s organic concentration (in terms of COD) and vice versa. This relation was confirmed in several sites, such as, AV 7 monitoring plate at Avellaneda SLF. The link between physical reactions (settlements) and chemical and biodegradable reactions (leachate abatement) is showed in Fig. 6.

Although specific studies should be performed case by case, the field measurements showed that after 7 years, approximately 80% of the main MSW´s organic reactions have almost ceased, and therefore, other activities (like construction of another MSW lift, or expansion or rehabilitation of the SLF) could be set up on the sanitary landfill final cover (Fig. 7 represents the data of the VD 9 monitoring plate at the Villa Dominico SLF in Buenos Aires, Argentina).

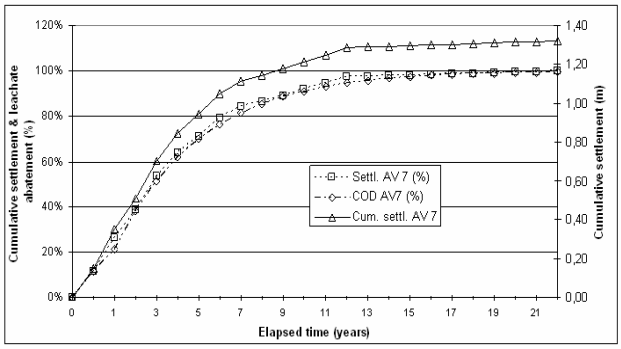

Figure 6. Cumulative settlements and leachate abatement comparison in Avellaneda sanitary landfill.

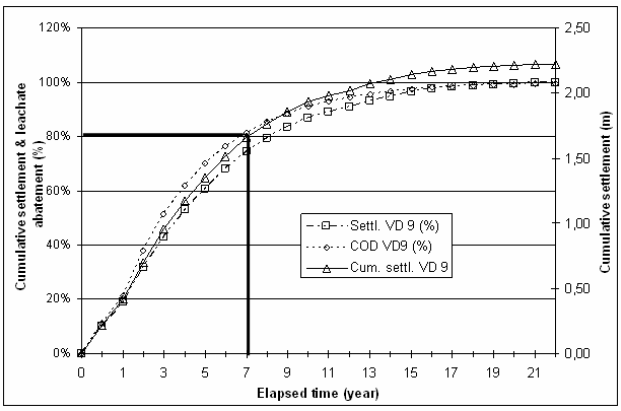

Figure 7. Cumulative settlements and leachate abatement in Villa Dominico - Buenos Aires sanitary landfills.

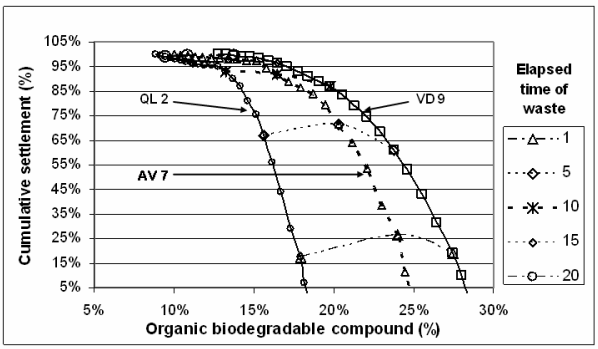

Figure 8. Cumulative settlements and OBC of municipal solid waste disposed in Buenos Aires sanitary landfills.

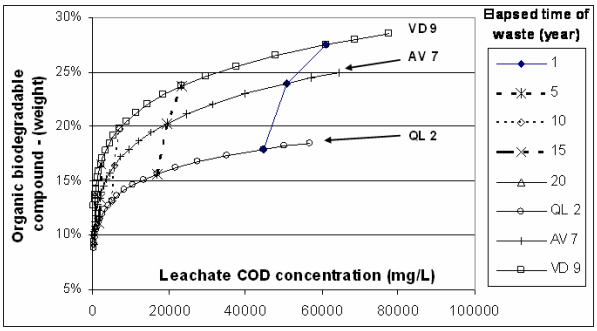

Figure 9. Organic biodegradable compound and leachate COD referred to waste age, in Argentine sanitary landfills.

If MSW is saturated of leachate, the analysis requires the solution of coupled stress-diffusion equations. The coupling is approximated by the effective stress principle, which treats the saturated waste as a continuum, assuming that the total stress at each point is the sum of an effective stress carried by the MSW skeleton and a pore pressure in the fluid permeating the MSW. This fluid pore pressure can change with time (if external conditions change, such as the addition of a load to the MSW). The gradient of the pressure through the waste, which is not balanced by the weight of fluid between the points under discussion, will cause the fluid to flow. Flow velocity is proportional to the pressure gradient in the fluid according to Darcy's Law. The discrete process of the semi-infinite, totally loaded stripes of cover soil and waste have been studied with satisfactory results (Sarubbi *et al*, 2001; Sarubbi and Sánchez Sarmiento, 2002).

In terms of OBC, it can be defined a relation between cumulative settlement and the age of the MSW since its disposal. In Fig. 8 for 20-25% of OBC, in the first year, it is estimated to reach the 25% of total cumulative settlement. With 20% of OBC, in the first 5 years from the disposal date, the MSW will achieve a 70% of the total potential cumulative settlement. This result is important because allows to determine, in advance, the potential cumulative settlement of a SLF based on the organic characteristics of the MSW disposed of.

Analyzing the OBC, the leachate´s COD concentration with MSW´s age, it can be stated that for higher concentrations of COD there should be higher levels of OBC and that, both processes achieve lower levels as time goes by (see different curves with 1, 5, 10, 15 and 20 elapsed years from disposal date, in Fig. 9).

Studying the evolution of specific weight with leachate´s COD concentration, in Fig. 10, it can be seen that higher levels of COD relate to lower specific weight of MSW disposed. In terms of operative methodology, it means that at an initial state, the quality of leachate can determine the SW and the rate of descend through the elapsed time. The biodegradation process can be used to design structural stages with time, and inferred the settlement caused by the SW variation.

The representative parameters previously described can be summarized in Fig. 11. For different concentrations of leachate´s COD, it can be expected certain levels of OBC, and at the same time, certain related cumulative settlements. The SLF design should incorporate these potential scenarios where settlements can be considered from the beginning of the operative stage, discharging more MSW to achieve higher height and there fore, optimizing the capacity of the SLF (and saving money in terms of infrastructure and disposal volume).

For leachate management, its quality determines the timing for its treatment. It is recommended to maintain the leachate in the SLF until the first 5 years. After that, it can be sent out of the SLF for treatment in adequate facilities. Also, it is advisable to mix different leachates according to their ages, for achieving an uniform quality (equalization). In this way, the treatment process is optimized in terms of time-efficiency and costs. Also, maintenance works after the SLF closure, can be minimized using the concepts of settlements and stabilization process described.

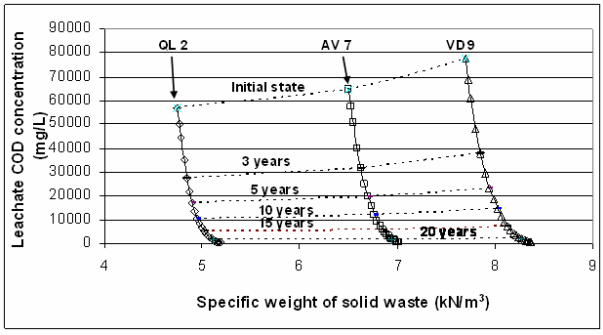

Figure 10. Leachate COD related to specific weight of municipal solid waste in Buenos Aires sanitary landfills.

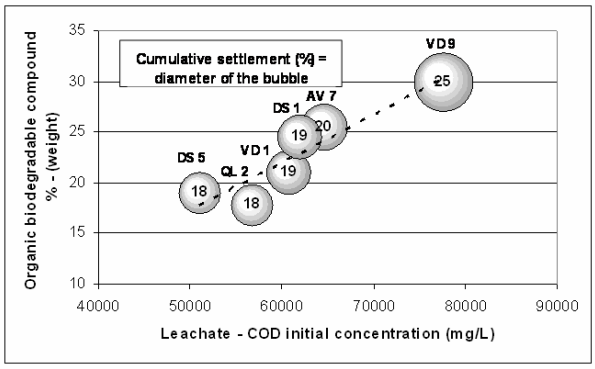

Figure 11. Representative parameters of municipal solid waste disposed in Buenos Aires sanitary landfills.

Limitations of this investigation

The magnitude of the representative parameters proposed in this study (leachate COD concentration, cumulative settlement, specific weight and OBC) can be influenced by MSW properties, the SLF operational methodology and climatic site conditions.

The MSW properties vary considerably from locations, countries, regions, depending on human habits. MSW with its moisture, addition of nutrients to enhance degradation, can influence the biodegradation rate.

The operational methodology depends of heavy equipment used, incoming tonnage, distribution and compaction efficiency of the MSW disposed, leachate and biogas management, external loads applied over the SLF, characteristics of the covers (soil/synthetic materials), its frequency (daily, temporary or final) of SLF operation, among others.

External conditions also affect the stabilization process: ambient temperature, pressure, humidity and general climatic conditions (rain, snow, etc.).

These parameters are all interdependent variables. For instance, if leachate or biogas systems are installed, they create a favorable environment for decomposition and accelerate settlements and the stabilization process, including the abatement of leachate´s organic load.

In view of these concerns, the use of the formulas and results presented in this investigation should be tempered with judgment and technical criteria.

In a general action plan to use the information presented in this manuscript, the quality of MSW should be investigated as a first step. From there, the leachate characteristics and OBC should define trends of behavior in terms of potential stabilization process. If any additional feature -such as SW, MSW´s height, cover frequency- is obtained, the process and its results will be defined more precisely.

Discussion

In Latin American countries, most solid waste is currently disposed of in open pits, un-controlled landfills and sanitary landfills. At the same time, lack of land for new facilities, saturation of the existing ones, and stricter legal regulations, oblige to maximize the actual capacity of the existing landfills and design more efficiently the new ones. On the other hand, understanding the waste stabilization process inside the landfill can prevent possible pollution arising from biological action. The applicability of the results of this study should conform to each site depending on the parameters modeled: characteristics of solid waste (OBC, SW, hydrolysis), characteristics of the leachate (leachate composition in terms of COD, BOD), and settlements of SLF.

Overall, the characteristics of solid waste (Table 2), leachate´s properties (Fig. 2) and sanitary landfills in Latin America are similar. Therefore, the findings and inferences from this study can be applied fairly well with certain limitations (explained before).

Design engineering should consider the stabilization and abatement results for a better leachate treatment, as well as, settlements should be analyzed for an optimization of the volume (capacity) of the landfill and the potential re-uses of its final top cover. Also, the geotechnical stability of additional lifts should be designed in a more safety way.

III. CONCLUSIONS

The SLF stabilization process can be represented by the following parameters: cumulative settlements, leachate´s COD concentration, specific weight and organic biodegradable compound. Their relationships quantify the biodegradability of the refuse inside the SLF. The principal results of this investigation can be summarized as follows:

1. Although specific studies should be performed case by case, the field measurements showed that after 7 years, approximately 80% of the main MSW´s organic reactions have almost ceased, and therefore, other activities (like construction of another MSW lift, or expansion or rehabilitation) could be set up on the sanitary landfill final cover.
2. The organic biodegradable compound of solid waste is an exponential function of waste age, and the refuse biodegradation in landfill conforms to the first-order kinetics pattern (Eq. 1), depending on waste composition, environmental conditioning factors and degradation hydrolysis rate.
3. Leachate from the SLF under study was characterized by a high strength of BOD_5, COD and nitrogen. Whilst COD and BOD_5 leachate concentrations sharply decrease in the first few years after closure of the SLF, nitrogen maintains a consistent concentration for a long time.
4. Leachate´s COD abatement is also an exponential function of waste age and follows the first-order kinetics pattern (Eq. 3 and 4).
5. Leachate and organic biodegradable compound of disposed solid waste can be used for defining the abatement curve of the cumulative settlements of sanitary landfill top cover.
6. The sanitary landfill-time curve of stabilization process can be well described by the leachate abatement process even if specific investigations should be performed for different types of solid waste and landfill conditions.
7. Leachate treatment should consider its natural attenuation process inside the sanitary landfill, or re-injecting techniques, before sending it to specific treatment facilities.
8. Proper landfill design and site management can significantly reduce the quantity and strength of leachate but will never eliminate it.
9. Further monitoring of long-term sanitary landfill parameters is still required to quantify the expected rate of waste decomposition, leachate abatement and settlement for different quality conditions of waste and landfills.
10. The development of techniques to quantify them is an important start in understanding the different stages of waste-landfills and the potential re-use of the site and the long-term maintenance works.

11. The design of future landfills has to create as much recreational space as practicable, consistent with providing maximum capacity for waste disposal. In order to achieve this latter objective, maximum slopes of 1:3 or 1:4 are often norm, and for steep slopes a herringbone network of "U" channels on the slopes has to be installed to reduce the scouring effect of surface runoff and infiltration.

REFERENCES

ASTM, *Standard test of the composition of unprocessed municipal solid waste*, ASTM 5231-92 (1992).

Bookter, T.J. and R.K. Ham, "Stabilization of solid waste in landfills," ASCE, *J. Env. Eng.*, **108**, 1089 (1982).

Bowders, J., M. Bouazza, E. Loehr and M. Russell, "Settelement of Municipal Solid Waste Landfills", *4th Kansai Int´l Geotechnical Forum*, Kyoto, Japan (2000).

Brown and Caldwell, Consultants, *Villa Dominico Vertical Expansion Project for Saneamiento y Urbanización S.A.* Ca. USA (1994).

CEAMSE, "Estudio de Composición de los residuos sólidos urbanos de la ciudad Buenos Aires", Instituto Ingeniería Sanitaria, Universidad de Buenos Aires, GCBA (2006)

Chia-Nan, L., C. Rong-Her and C. Kuo-Sheng, "Unsaturated consolidation theory for the prediction of long-term municipal solid waste landfill settlement", *J. Waste Manage. Res.*, **24**, 80-91 (2006).

Coduto, D.P. and R. Huitric, *Monitoring landfill movements using precise instruments*, Geotechnics of Waste Fills – Theory and Practice, ASTM STP 1070, 358-370 (1990).

Durmusoglu, E.M., M. Yavuz Corapcioglu and K. Tuncay, "Landfill Settlement with Decomposition and Gas Generation," *J. Env. Engrg.*, **131**, 1311-1321 (2005).

Durmusoglu, E.M., M. Yavuz Corapcioglu and K. Tuncay, "Modeling of Settlement in Saturated and Unsaturated Municipal Landfills," *J. Geomech.*, **6**, 269-278 (2006).

Eaton, A.D., L.S. Clesceri, E.W. Rice and A.E. Greenberg, *Standard Methods*, AWWA, WEF & APHA. 21st Edition (2005).

Edil, T.B., V. J. Ranguette and W.W. Wuellner, *Settlement of municipal refuse. Geotechnics of Waste Fills-Theory and Practice*, ASTM STP 1070, Landva and Knowles, eds., West Conshohocken, Pa., 225-239 (1990).

Edil, T.B., P.J. Fox and L.T. Lan. Observational procedure for settlement of peat. *Proc. Geo-Coast* 91 Conf., Port and Harbor Res. Inst., Japan, 165-170. (1991).

Ehrig, H.J., "Quality and quantity of sanitary landfill leachate," *J. Waste Manage. Res.*, **1**, 53-68 (1983).

El-Fadel, M., A.N. Findikakis and J.O. Leckie, "Numerical modelling of generation and transport of gas and heat in sanitary landfills: I. Model Formulation," *J. Waste Manage. Res.*, **14**, 483-504 (1996a).

El-Fadel, M., A.N. Findikakis, and J.O. Leckie, "Numerical modelling of generation and transport of gas and heat in sanitary landfills: Formulation, II. Model Application," *J. Waste Manage. Res.*, **14**, 537-551 (1996b).

Gurda, J. and M. O´Hara, "Leachate Management", Waste Tech´95: Landfill Technology, Technical Proceedings; National Solid Waste Management Association, New Orleans, LA, USA, 176-210 (1995).

Hossain, M.S., M.A. Gabr and M.A. Barlaz, "Relationship of Compressibility Parameters to Municipal Solid Waste Decomposition," *J. Geotech. and Geoenvir. Engrg.*, **129**, 1151-1158 (2003).

Jiangying, L., X. Dimin, Z. Youcai, C. Shaowei, L. Guojian and Z. Qi, "Long-term monitoring and prediction for settlement and composition of refuse in Shanghai Laogang Municipal Landfill," *J. Env. Manage.*, **34**, 441-448 (2004).

Kjeldsen P. and M. Christophersen, "Composition of leachate from old landfills in Denmark", *J. Waste Manage. Res.*, **19,** 249-256 (2001)

Kumar, S. "Settlement prediction for municipal solid waste landfills using power creep law," *J. Soil and Sediment Contamination*, **9**, 579-592 (2000)

Lee, J.J., I.H. Jung, W.B. Lee and J.O. Kim, "Computer and experimental simulations of the production methane gas from municipal solid waste," *J. Water Science and Tech.*, **27,** 225-234 (1993).

Lee, K., H. Suk, S. Choi, C.H. Lee and S. Chung, "Numerical evaluation of landfill stabilization by leachate circulation," *J. Env. Engr.*, **127**, 555-563 (2001).

Levy, N. and M. Alegre, "Estudio de Calidad de Residuos Sólidos de Ciudad Buenos Aires," Instituto Ingeniería Sanitaria, Universidad de Buenos Aires, Secretaría de Servicios Públicos de la Municipalidad de Bs. As. (1972)

Ling, H. I., D. Leshchinsky, Y. Mohri and T. Kawabata, "Estimation of municipal solid waste landfill settlement," *J. Geotech. and Geoenvir. Engr.*, ASCE, **124**, 21-28 (1998).

Liu, C-N, R-H. Chen and K-S. Chen, "Unsaturated consolidation theory for the prediction of long-term municipal solid waste landfill settlement," *J. Waste Manage. Res.*, **24**, 80-91 (2006).

Machado, S.L., M.F. Carvalho and O.M. Vilar, "Constitutive Model for Municipal Solid Waste," *J. Geotech. and Geoenv. Engrg*, **128**, 940-951 (2002).

Manna, L., M.C. Zannetti and G. Genon, "Modeling biogas production at landfill site," *J. Resources, conservation and recycling*, **26**, 1-14 (1999).

Merz, R.C. and R. Stone. "Landfill settlement rates," *Public Works*, **93**, 103-106; 210-212 (1962)

Ohtaki, A. and N. Kiyohiko, "Report: Ultimate degradability of various kinds of biodegradable plastics under controlled composting conditions," *J. Waste Manage. Res.*, **18**, 184-189 (2000).

Oweis, I.S. "Estimate of Landfill Settlements due to Mechanical and Decompositional Processes," Technical Note, ASCE, *J. Geotech. and Geoenv. Eng.*, **132**, 644-650 (2006).

Oweis, I.S., R. Ellwood and D. Greene, "Hydraulic characteristicsof municipal refuse," *J. Geotech. Eng.*, **116,** 539-553 (1990)

PAHO, Pan American Health Organization, *Regional Report on the Evaluation of Municipal Solid Waste Management Services for Latin America and the Caribbean*; Regional Office of World Health Organization, Spanish version, 53-59 (2005).

Pescuma, A., M.E. Guaresti and M. De Luca, *Estudio Cualicuantitativo de los Residuos Sólidos Urbanos de la ciudad Buenos Aires*, Instituto Ingeniería Sanitaria, Universidad de Buenos Aires, Buenos Aires Government (2001)

Rodríguez Iglesias, J., L. Castrillón Peláez, E. Marañón Maison and H. Sastre Andrés, "A comparative study of the leachates produced by anaerobic digestion in a pilot plant and at a sanitary landfill in Asturias, Spain," *J. Waste Manage. Res.*, **18**, 86-93 (2000).

Sánchez-Alciturri, J. M., J. Palma, C. Sagaseta and J. Canizal *Three years of deformation monitoring at Meruelo landfill. Waste disposal by landfill – GREEN 3*, Sarsby ed., A. A. Balkema, Rotterdam, The Netherlands, 365-371 (1995)

Sarubbi, A.J. *Leachate Treatment Plant, González Catán Landfill, Argentina*, CEAMSE-SYUSA, Unique Work registered N° 983227, National Direction of Patents of Argentine Republic (1997).

Sarubbi, A.J. and G. Sánchez Sarmiento, "Consolidation of sanitary landfills," XXVIII Sanitary and Environmental Interamerican Engineering Congress (AIDIS), Cancún, México (2002).

Sarubbi, A.J., M.E. Ronnow, and M.S. De Luca, *Estudio de la Calidad de los Residuos Sólidos de la Ciudad de Buenos Aires*, Instituto de Ingeniería Sanitaria, Facultad de Ingeniería de la Universidad de Buenos Aires (1991).

Sarubbi, A.J., H. Theisen and J. Nissen, *Villa Dominico Landfill Vertical Expansion Project*, SYUSA-Brown and Caldwell Consultants (1994).

Sarubbi, A.J., G. Sánchez Sarmiento and C. Jouglard, "Consolidation of Sanitary Landfills," ABAQUS Users' Conference, Maastricht, The Netherlands (2001).

Sowers, G.F., "Foundation problems in sanitary landfills," *ASCE Environmental Engineering Conference*, Dallas, USA (1967).

Theisen, H., J. Nissen, A.J. Sarubbi and C. García Márquez, "Villa Dominico Landfill Vertical Expansion Project. Leachate Treatment System Design," *Water Environment Federation WEFTEC´96* - 69th Annual Conference Exposition, Dallas, Texas, USA (1996).

USEPA SW-846, *Test Method for evaluating solid waste physical/chemical methods*, Chapter nine (1986)

Watson, R., A *case study of Leachate generation & recycling at two sanitary landfills. Disposal of Solid Waste*, Mc Graw-Hill (1989).

Youcai, Z., C. Zhugen, S. Qingwen and H. Renhua, "Monitoring and long-term prediction of refuse compositions and settlement in large-scale landfill," *J. Waste Manage. Res.*, **19**, 160-168 (2001).

Youcai, Z, L. Jiangying, H. Renhua and G. Guowei, "Long-term monitoring and prediction for leachate concentrations in Shanghai refuse landfill," *J. Water, Air, and Soil Pollution*, **122**, 281–297 (2000).

Young, A. *Mathematical model of the methanogenic ecosystem. In: Microbiology of Landfill Sites.* Eric Senior, Lewis Publishers, Second Edition, USA (1995).

Zacharof, A.I. and A.P. Butler, "Application of a stochastic leachate and biogas model to the Broghorough test cell experiment data incorporating data uncertainty," *Proc. Eight Int´l Waste Management & Landfill Symposium*, Sirdinia, Cagliari, Italy, 119-128 (2001).

Received: December 29, 2007
Accepted: August 15, 2008
Recommended by Subject Editor: José Pinto