Modeling the Influence of Biodegradation on Sanitary Landfill Settlements

Sandro Lemos Machado, Miriam de Fátima Carvalho, Orencio Monje Vilar

Abstract. This paper presents a mathematical model to reproduce long term or secondary settlement of sanitary landfills. Secondary compression is assumed to be commanded by two main processes: mechanical creep compression and the biodegradation of waste. The model introduces a biodegradation parameter that relates mass loss with volumetric variations. The biodegradation of Municipal Solid Waste (MSW) organic matter was represented through gas generation, modeled as a first order decay process. The gas generation was transformed into mass loss and used to evaluate biodegradation settlements through a mass balance equation. Some qualitative approaches concerning the time origin of secondary compression processes were addressed and used in the simulations. Strategies for obtaining model parameters are also presented and the main implications of biodegradation on settlement are discussed. The results predicted by the model are compared with laboratory and sanitary landfill data and reveal high levels of agreement between measured and calculated values.
Key words: municipal solid waste, mathematical model, settlement, creep, biodegradation.

1. Introduction

Sanitary landfill is the most commonly used method of final disposition of Municipal Solid Waste (MSW) around the world. These engineering structures pose a series of formidable challenges for geotechnical engineers as they have to deal with a complex material and address problems such as slope stability, stress on foundations and settlement.

Settlement in landfills is usually described as the result of primary and secondary compression. Secondary compression is usually attributed to mechanical creep of waste components and biodegradation. If a sanitary landfill is considered a biochemical reactor, as it usually is in Sanitary Engineering, the main inputs of this giant bioreactor are waste and water and the major outputs, gas and leachate. Landfill gas generation involves the depletion of organic waste and this process implies settlements that extend over many years until complete degradation of the organic matter.

Some of the mechanisms that control settlement are analogous to the settlement of soils and can be satisfactorily modeled through the theory of Soil Mechanics. However, the additional settlement generated by mass loss in the reactor is less well studied and this is a topic of concern among researchers studying of this issue. As gas generation is by far the most predominant output from the landfill, the quantification of gas generation rates and its equivalent loss of mass offers an attractive method to use to predict settlement. In this paper, a model to represent settlement in sanitary landfill caused by biodegradation is developed and tested against field settlement data. The model is intended to improve the constitutive model of MSW developed by Machado *et al.* (2002) as it incorporates a new approach to settlement in sanitary landfills.

2. Fundamentals

2.1. MSW compression

Although geotechnical engineers are used to dealing with natural materials that follow constitutive laws which are not completely understood, when dealing with MSW they face a heterogeneous material made up of different components, each with their own peculiar behavior. MSW is also subject to chemical and biological processes that alter its composition and mechanical behavior over time. These features in particular impart many peculiarities to landfill settlement making the entire process influenced by a multitude of mechanisms.

A qualitative model to represent the compression behavior of waste was presented by Grisolia & Napoleoni (1996), which is schematically shown in Fig. 1. A general description of the compression behavior of urban waste, which matches the indications in Fig. 1, was presented by Manassero *et al.* (1996) who described the compression behavior of urban waste as composed of the following mechanisms: I) physical compression, governed by mechanical distortion, bending, crushing and reorientation of waste components; II) raveling settlements due to migration of small particles into voids among large particles; III) viscous behavior and consolidation phenomena involving both solid skeleton and single particles or components; IV) decomposition settlement due to the biodegradation of the organic components and V) collapse of components due to physico-chemical changes such as corrosion, oxidation and degradation of inorganic components.

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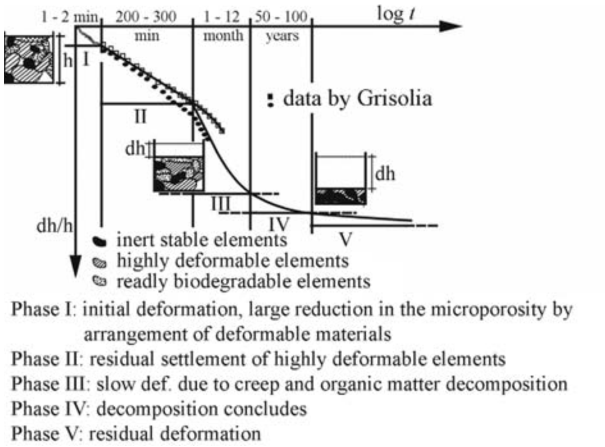

Figure 1 - Schematic view of the MSW compression process. Grisolia & Napoleoni (1996).

MSW settlement has been modeled taking into consideration that it is governed by primary and secondary compression and by using conceptual models similar to those developed for soils (Sowers, 1973; Yen & Scanlon, 1975; Edil *et al.*, 1990; Bjarngard & Edgers, 1990; Edgers *et al*., 1992; Park & Lee, 1997; Ling *et al.*, 1998 and Gabr *et al.*, 2000).

Some attempts have been made to represent biodegradation. Edgers *et al.* (1992) associate settlement to waste degradation caused by bacteria growth and Soler *et al.*(1995) relate volume decrease to the generation of methane. McDougall & Pirah (2004) have described and proposed some phase relationship for decomposable soils that may also represent the biodegradation of organic matter in a landfill. They identified a relationship between void volume changes and decomposition of solid matter that depends on a single parameter, which they call decomposition-induced void change parameter. This parameter was shown to be indicative of mechanical consequences of decomposition and its use has provided a convenient reproduction of lab data of settlement of a decomposable soil.

Marques *et al.* (2003) have developed a composite rheological model and a computer program to predict landfill settlement. The composite model considers primary and secondary mechanical compression, as well as compression from biodegradation. In this model, the secondary biological compression due to the degradation of the material is based on the solution of Park & Lee (1997), which correlates the process of material loss through biological degradation and the associated secondary settlements to the solubilization rate of the degradable matter in the solid waste.

2.2. Gas generation and MSW loss of mass

Many factors interfere in the generation of gas in a landfill. The most important of these include waste composition and the presence of readily degradable organic components, the moisture content, the age of the waste, pH and temperature. The pH and temperature are relevant to the existence and action of bacteria. For instance, the optimum pH range for most anaerobic bacteria is close to neutral (McBean *et al.*, 1995).

Temperature conditions within a landfill influence the type of bacteria that predominate and the level of gas production. After initial relatively elevated temperatures, the temperature decreases within a landfill as anaerobic conditions develop. It has been recognized that optimum temperatures for methanogenic activity within a sanitary landfill range from 30 to 40 °C, and temperatures below 15 °C inhibit this activity (McBean *et al.*, 1995). The principal constituents present in landfill gas are methane (CH_4) and carbon dioxide (CO_2), but landfill gas is commonly saturated by water vapor and presents small quantities of non-methane organic components and various other trace compounds.

There are a variety of methods and models that can be used to estimate the methane and biogas generation rate at landfills (Ehrig, 1996; USEPA, 1996; USEPA, 1998). The USEPA (1998) landfill air emissions estimation model, represented by Eq. (1), however, is generally recognized as being the most widely used approach. It is a first-order decay model, recommended by the Intergovernmental Panel on Climate Change (IPCC, 1996) for calculating methane emissions from landfills. In this equation, Q = Methane generation rate (m^3/yr), L_o = Methane generation potential (m^3/Mg of waste), R = Landfill average annual waste acceptance rate (Mg/yr), k = Methane generation rate constant (1/yr), c = Time since to landfill closure (yr) and t = time since landfill opened (yr).

$$Q = L_0 R(e^{-kc} - e^{-kt}) \tag{1}$$

The value of k is affected by a large number of factors, such as waste composition, moisture content and disposal conditions. Values of k around 0.2 yr^{-1}, which correspond to a half life of about 3 years, are associated to elevated temperatures, high moisture contents and large amounts of food waste. Values of k around 0.03 yr^{-1} are associated with dry and cold environments in developed countries. According to USEPA (1998), L_o values vary between 6.2 and 270 m^3 CH_4/Mg of waste. Developing countries often present higher L_o values, although in humid tropical regions, the large moisture content decreases the amount of available dry mass by Mg of MSW.

Besides field measurements of gas production, the parameters k and L_o can be obtained using different approaches. IPCC (1996) presents equations that use the waste degradable organic carbon fraction, DOC, in order to estimate L_o. As DOC for some fractions has average known values, waste characterization data is sometimes used to obtain L_o. A more detailed discussion on this theme can be found in Bingemer & Crutzen (1987).

3. The Proposed Model

The influence of the biodegradation processes and resulting mass loss on the field settlement is initially assessed considering the phase diagram presented in Fig. 2. In this figure, v_a, v_w, v_s are the volumes of air, water, and solids respectively, and v is the total volume. m_w, m_s, and m are the corresponding mass of these phases. The assumptions of the model by Machado *et al.* (2002) are adopted in this paper and they consider that the mechanical behavior of waste is controlled by two different effects: a) the reinforcement of MSW by the fibers (mainly composed of many types of plastics) and b) the behavior of the MSW paste, that is all the other non fibrous materials. Therefore the MSW solids are divided into two: fibers and paste solids. Eqs. (2) and (3) express these assumptions mathematically and the additional subscripts, *f* and *p*, refer to fibers and paste respectively.

$$v_{sf} + v_{sp} = v_s \tag{2}$$

$$m_{sf} + m_{sp} = m_s \tag{3}$$

Additionally, fibers are considered as having no voids, *i.e.* all the MSW voids belong to the paste. This means that solid fibers volume (v_{sf}) is similar fibers volume (v_f), ($v_{sf} = v_f$) and that:

$$v_p = v_{sp} + v_v \tag{4}$$

Figure 3 sketches the volume variation associated to the biodegradation of MSW. The resultant MSW volume variation, Δv, is computed through α factor by:

$$\Delta v = (1+\alpha)\Delta v_s \tag{5}$$

The fiber components do not supposedly lose mass over time, thus the solid volume change considered before corresponds to the paste volume variation ($\Delta v_s = \Delta v_{sp}$). The Eqs. (6) and (7) express the effect of the loss of mass on MSW void ratio and volumetric strain. In these equations, *e* refers to the MSW void ratio. In these equations, the subscript *o* refers to initial condition and the subscript *d* that the variations are due to the biodegradation process.

$$\Delta e_d = \frac{v_{vo} + \alpha \Delta v_s}{v_{so} + \Delta v_s} - \frac{v_{vo}}{v_{so}} = \frac{\alpha - e_o}{\dfrac{v_{so}}{\Delta v_s} + 1} \tag{6}$$

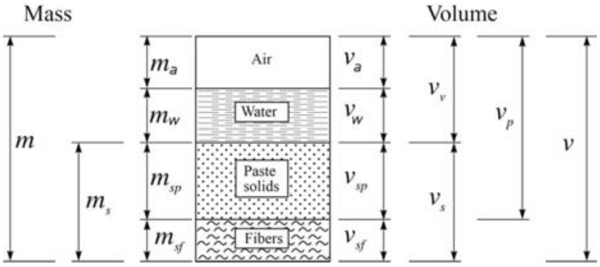

Figure 2 - MSW phase diagram.

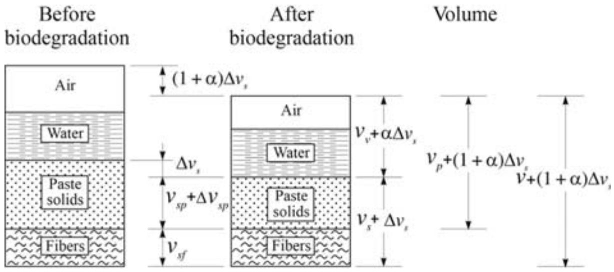

Figure 3 - Phase diagram illustrating the effect of the mass loss on the MSW volume.

$$\varepsilon_{vd} = \frac{-\Delta v}{v_o} = \frac{-\Delta v_s (1+\alpha)}{v_{so} + v_{vo}} = \frac{-\Delta v_s (1+\alpha)}{(1+e_o) v_{so}} \tag{7}$$

The α parameter, which is identical to that proposed by McDougall & Pirah (2004), expresses the fact that the additional volume variation associated with biodegradation will not produce equivalent waste compression, but rather some waste deformation that depends on the relative values of α and e_o. Furthermore, the voids generated by the decomposition process induce modifications in the waste structure which can lead to additional compression. As a first qualitative analysis it is worth commenting that if α is smaller than e_o, the MSW void ratio will increase (at least theoretically) leading to a looser waste, whereas α values larger than e_o tend to increase the waste dry density. In the particular case of α equal to e_o, biodegradation volumetric strain will arise but the relative void variations of paste and that of the waste keep the same void ratio. Finally, it should be emphasized that some tests and field results suggest that the α parameter is not a constant value, but a function of the MSW biodegradation stage and probably other variables, such as confining stress, waste composition, which will be discussed later.

Equations (6) and (7) can be rewritten, including the values of ρ_s and ρ_{sp} to calculate v_{so} and Δv_s if the initial MSW dry mass and the amount of loss of mass are known. This gives rise to the following equations:

$$\Delta e_d = \frac{(e_o - \alpha)}{\dfrac{m_{so}\rho_{sp}}{-\rho_{so}\int_o^t \dfrac{\partial m_s}{\partial t}\, dt} - 1} \tag{8}$$

and

$$\Delta \varepsilon_{vd} = \frac{-\rho_{so}\int_o^t \dfrac{\partial m_s}{\partial t}\, dt\,(1+\alpha)}{(1+e_o) m_{so}\rho_{sp}} \tag{9}$$

Equation (10) puts Eq. (9) in an incremental way.

$$d\varepsilon_{vd} = -\left(\frac{\rho_{so}}{\rho_{sp}}\right)\left(\frac{1}{1+e_o}\right)(1+\alpha)\frac{\partial m_s}{\partial t}\frac{1}{m_{so}}dt \quad (10)$$

In Eqs. (8) to (10), ρ_s and ρ_{sp} are the specific densities of MSW solids and of paste particles respectively. ε_v refers to the MSW volumetric strain. The specific density of biodegradable paste solids was introduced to consider that the material to be decomposed differs in density from the inert material.

In many instances, the creep compression of MSW has been successfully modeled by the Gibson & Lo (1961) proposition. It is a simple model, requiring the use of only one variable. In this case, the MSW creep compression is:

$$d\varepsilon_{vc} = \frac{c_\alpha dt}{(1+e_o)\ln(10)t} \quad (11)$$

In this equation, C_α = MSW secondary compression index and $d\varepsilon_{vc}$ = volumetric strain increment expected as a function of the MSW creep compression. As secondary compression is being considered as composed of mechanical creep compression and of biodegradation compression, it is now possible to calculate the increment in the MSW volumetric strain:

$$d\varepsilon_v = d\varepsilon_{vd} + d\varepsilon_{vc} = \left[\frac{c_\alpha}{(1+e_o)\ln(10)t} - \left(\frac{\rho_{so}}{\rho_{sp}}\right)\cdot \left(\frac{1}{1+e_o}\right)(1+\alpha)\frac{\partial m_s}{\partial t}\frac{1}{m_{so}}\right]dt \quad (12)$$

The main hypothesis of this proposition rests on the fact that the MSW loss of mass can be calculated from gas generation data. This is made with the use of Eq. (13), where C_m is the organic matter methane yield, considering a complete methane conversion (m^3 CH_4/dry-Mg). The value of Q may be calculated using Eq. (1) if the first order decay method is used to predict the gas generation process.

$$-\frac{\partial m_s}{\partial t} = \frac{Q}{C_m} \quad (13)$$

The use of Eqs. (1) and (13) conducts to Eqs. (14) and (15). Equation (14) is more appropriate for a global analysis, considering the landfill as a whole whereas Eq. (15) is more suited for numerical integration purposes.

$$-\frac{\partial m_s}{\partial t}\frac{1}{m_{so}} = \frac{L_o(1+w)(e^{-kc} - e^{-kt})}{C_m(t-c)} \quad (14)$$

$$-\frac{\partial m_s}{\partial t}\frac{1}{m_{so}} = \frac{L_o k(1+w)e^{-kt}}{C_m} \quad (15)$$

This way, Eqs. (12) and (15) (or Eq. (14)) encompass the complete formulation of the proposed approach in order to calculate MSW long term volumetric strains. It depends on the C_α and α parameters, together with the parameters related to gas generation which are L_o, k.

The coefficients of secondary compression, C_α and α, can be obtained from consolidation tests if enough time is allowed for mechanical secondary compression and mass loss to take place, or from back analysis of data from landfills. It is important to note that the time origin for creep compression and biodegradation may differ. It is usually assumed that creep compression starts immediately after waste landfilling and the start time can be roughly estimated from laboratory tests, analyzing the shape of the long term compression curves. The beginning of the biodegradation process is a much more complicated subject and is very difficult to estimate from laboratory tests as it is difficult to reproduce real field conditions. In places where favorable degrading conditions are present, biodegradation processes start very early. In this case, it is thought that the use of a common time origin for both processes, creep and biodegradation, is acceptable for practical purposes. In the absence of favorable conditions, there is a time delay in the biodegradation process that should be taken into account in the use of Eq. (12).

The parameters L_o and k can be obtained from the literature for certain conditions of waste composition, landfill operation and climate. L_o can also be obtained from laboratory tests designed to measure gas generation, such as BMP (Biochemical Methane Potential) tests. If BMP tests are performed using landfill samples of different ages, the k parameter can be derived. The other information needed includes the physical indexes of the waste, namely the initial void ratio and specific densities of paste, fibrous material and the MSW as a whole.

C_m values vary according to the waste component considered, but C_m values between 400 and 500 m^3 CH_4/dry-Mg are frequently found in published papers. According to Barlaz *et al.* (1990), values of C_m of 414.8 m^3 CH_4/dry-Mg and 424.2 m^3 CH_4/dry-Mg can be considered for cellulose and hemicellulose, respectively. Tchobanoglous *et al.* (1993) present biogas yields from 750 to 900 m^3/dry-Mg. As the biogas methane fraction usually varies from 0.5 to 0.6, similar values of C_m are predicted by the authors. If the waste composition is known, Eq. (16) (Tchobanoglous *et al.*, 1993) may be used to compute C_m values for different waste components and for the MSW as a whole. In Eq. (16), the indexes a, b, c and d are used to represent the empirical mole composition of the organic material. Table 1 shows waste components compositions (dry weight) suggested by Tchobanoglous *et al.* (1993) and Table 2 presents the values of C_m and water consumption predicted for each waste component.

$$\mathrm{C}_a\mathrm{H}_b\mathrm{O}_c\mathrm{N}_d + \frac{[4a-b-2c-3d]\mathrm{H_2O}}{4} \rightarrow \frac{[4a+b-2c-3d]\mathrm{CH_4}}{8} + \frac{[4a-b+2c+3d]\mathrm{CO_2}}{8} + d\,\mathrm{NH_3} \quad (16)$$

Perhaps the most difficult task is separating the contributions of parameters C_α and α, since this would require laboratory tests that extend over long time periods, and the α value is probably not a constant value throughout the decomposition process. Some possible ways to obtain these parameters are outlined below.

3.1. The nature and magnitude of the α parameter

Understanding the nature of the α parameter is a key task in accessing the influence of mass loss on MSW volumetric strains. The analysis of coupled laboratory or field data, where settlements and gas yields have been measured simultaneously can be used to determine α.

Mehta *et al.* (2002) describe a field experiment that was performed to evaluate the effects of leachate recirculation on waste decomposition and field settlement. The experiment comprised one control cell without any kind of treatment, and an enhanced cell that underwent leachate recirculation. Figure 4 presents data from Mehta *et al.* (2002), with respect to settlement and gas production in the control and enhanced cells analyzed.

Both cells initially had about 930 m^2 of surface area and were 12 m thick. Cells were filled from April through October 1995 and the final cover was put in place in November 1995. Settlement measurements and gas collection were initiated on 12 June 1996. After 1,231 days, cumulative methane production reached 63.1 and 27.9 m^3 CH_4/Mg of wet waste in enhanced and control cells, respectively. The corresponding average settlements were about 14.2% of the waste thickness in the enhanced cell and 2.74% in the control cell.

From the data presented by Mehta *et al.* (2002), the MSW initial densities were calculated and reached about 0.710 Mg/m^3 and 0.696 Mg/m^3 for the control and the enhanced cells respectively. The initial water content in both cells was assumed to be about 17.6% (average value, dry basis, obtained considering control cell samples).

In order to study the nature and magnitude of the α parameter gas generation data must be converted in loss of mass through C_m. Equation (17) was used to convert gas production in mass loss during a given time interval. In the absence of waste composition data a value of C_m = 450 m^3 CH_4/dry-Mg was employed.

$$-\frac{\Delta m_{s\,t_i}^{\;t_{i+1}}}{m_{so}} = \frac{\dfrac{\int_{t_i}^{t_{i+1}} Q\,dt}{m_o}(1+w)}{C_m} \tag{17}$$

Figure 5(a) presents the cumulated loss of mass calculated using Eq. (17) and data shown in Fig. 4(b). As it can be seen, enhanced cell presented a mass loss of about 17% while the loss of mass in the control cell was of about 7.4%. Data presented in Figs. 5(a) and 4(c) were used to study the influence of the loss of mass in the observed settlements along the decomposition process. Mass loss intervals

Table 1 - Waste components composition (% dry weight). Tchobanoglous *et al.* (1993).

Waste organic component	C	H	O	N	S	Ash
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	5.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Textiles	55.0	6.6	31.2	4.6	0.2	2.5
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5

Table 2 - Organic matter methane yield (C_m) and water consumption according to Eq. (16).

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

($-\Delta m_{s\,t_i}^{\;t_{i+1}} / m_{so}$) of about 5% were chosen and the induced settlement increments ($\Delta\varepsilon_v$) were computed to each cell. Figure 5(b) presents the obtained results in terms of the ratio $\Delta\varepsilon_v / [-\Delta m_{s\,t_i}^{\;t_{i+1}} / m_{so}]$. The results were plotted considering the average cumulated loss of mass of each interval.

According to data presented in Fig. 5(b), as the decomposition process goes on, the loss of mass becomes more effective in producing new settlements. This is particularly true if it is considered that the influence of the creep process tends to decrease along time. The behavior illustrated in Fig. 5 evidences that the α parameter is not constant along time, but tends to increase with the amount of organic matter already decomposed. Equation (18) was then used to calculate values of α to the same mass loss intervals employed in Fig. 5(b) and a linear relationship was adopted to fit the experimental results (Eq. (19)).

$$\alpha = \left[\Delta\varepsilon_v (1+e_o) - c_\alpha \log\left(\frac{t_{1+i}}{t_i}\right)\right] \cdot \left(\frac{\rho_{sp}}{\rho_{so}}\right) \frac{m_{so}}{-\Delta m_{s\,t_i}^{\;t_{i+1}}} - 1 \tag{18}$$

$$\alpha = \alpha_o + \alpha^* \frac{-\Delta m_s}{m_{so}} \tag{19}$$

where α_o refers to the initial value of α before any loss of mass, α^* refers to the rate of increase in the α values as the degradation process progresses and $-\Delta m_s/m_{so}$ corresponds to the cumulative loss of mass. According to McDougall & Pirah (2004), α must be equal or larger -1, as more negative values imply waste expansion as a consequence of mass loss, which seems not feasible physically. Values of α from -1 to 0 imply some degree of arching within the fill, in the sense that only a portion of the voids generated by the loss of mass will be compressed.

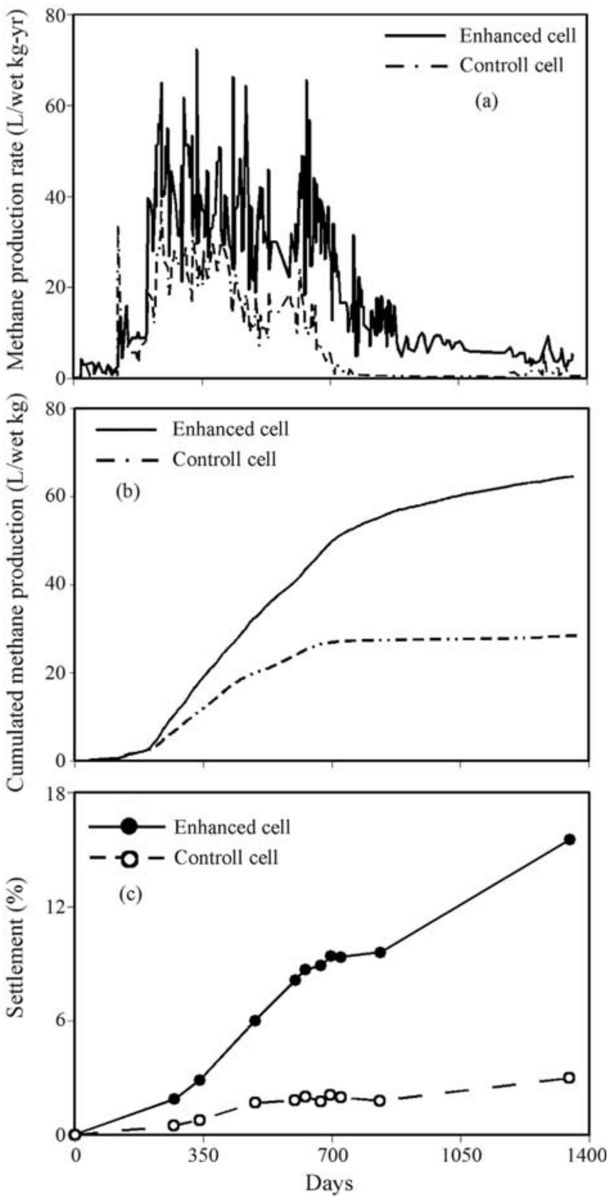

Figure 4 - (a) Methane production rate in enhanced and control cells, (b) cumulative methane production and (c) observed settlements. Metha *et al.* (2002).

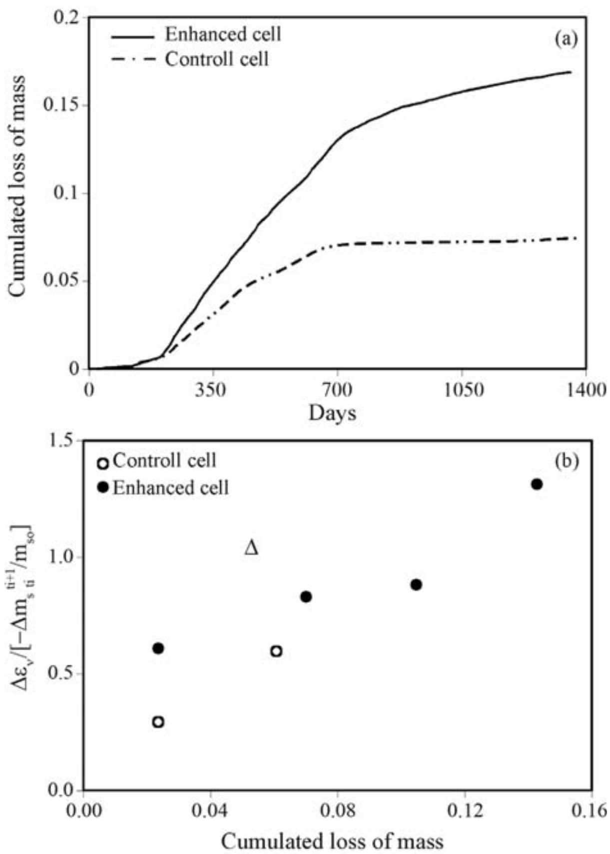

Figure 5 - (a) Cumulated loss of mass and (b) Influence of the loss of mass in the observed settlements.

The MSW particles specific density was assumed to be ρ_s = 1.75 Mg/m^3 and the paste specific density, ρ_{sp} = 1.8 Mg/m^3. These values were obtained from fresh waste from Salvador-Brazil (Machado & Carvalho, 2006). Initial void ratios of e_o = 1.90 and e_o = 1.96 were calculated for the control and enhanced cells, respectively. As the calculated values of α are C_α dependent, the value of C_α was chosen to produce α_o = -1 and then α_o = 0, when fitting Eq. (19) to experimental values. Values of C_α = 0.01, corresponding to α_o = 0 and α^* = 18.1 and C_α = 0.079, corresponding to α_o = -1 and α^* = 24.2 were found. Figure 6 shows the obtained results. As can be observed, the control cell presented smaller α values. The adjusted curves have the following coefficients of determination: r^2 = 0.87 for α_o = 0 and r^2 = 0.83 for α_o = -1.

The values showed above were used to calculate experimental settlements. Equation (20) was used for this purpose and Fig. 7 shows the obtained results. A value of $t_{o(creep)}$ = 255 days was adopted, corresponding to the period between the end of the filling process and the first settlement reading. The loss of mass that took place from the beginning of landfill to the first elevation measurement was ignored (this means that the time origin adopted for the mass loss process coincides with the beginning of the measurements: t_o = 0). This was considered a reasonable approach as the values of methane yields are quite small (Figs. 4a and 4b) at the beginning of the measurement process. As can be seen, the use of α_o = 0 yields calculated values that better fit the experimental data of both cells. It is believed that part of the observed scattering could be attributed to the fact that some variables such as the gas and settlement started to be measured just 8 and 17 months after the end of the filling process, respectively.

$$\varepsilon_v = \frac{(1+\alpha_o)\left[\dfrac{\int_{t_o}^{t} Q\,dt}{m_o}\right](1+w)\rho_{so}}{(1+e_o)\rho_{sp}C_m} + \frac{\alpha^*\left[\dfrac{\int_{t_o}^{t} Q\,dt}{m_o}\right]^2(1+w)\rho_{so}}{2(1+e_o)\rho_{sp}C_m^2} + \frac{C_\alpha \log\left(\dfrac{t}{t_{o\,(\text{creep})}}\right)}{(1+e_o)} \qquad (20)$$

Considering the results presented in Figs. 6 and 7 and the discussion presented before, it seems reasonable, for the sake of simplicity, to consider α_o = 0. It is believed that an eventual weakness of the model that could arise when assuming α_o = 0 can be counterbalanced by benefits of the use of only one variable, α^*. Assuming α_o = 0 implies that at the beginning of the biodegradation process, the mass loss increases the MSW void ratio. The resulting compression is equivalent to the voids left by the decomposed organic matter. The mass loss will increase the MSW void ratio until the value of $\Delta m_s/m_{so} = e_o/\alpha^*$ (at this moment, $\alpha = e_o$). From this moment on, additional mass loss will make the waste denser. The maximum value of α is limited by the maxi-

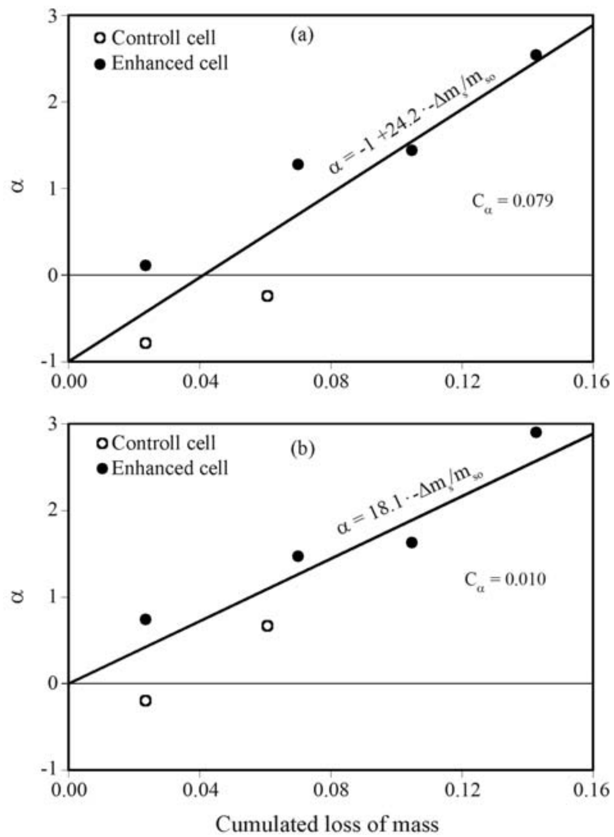

Figure 6 - Calculated values of α during the decomposition process. (a) C_α = 0.079 and α_o = -1 and (b) C_α = 0.01 and α_o = 0.

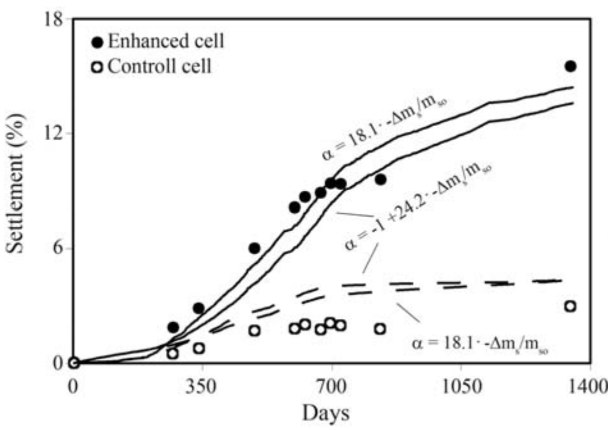

Figure 7 - Comparisons between measured and calculated values of settlements using the values of α_o and α* showed in the Fig. 6.

mum amount of organic matter available for decomposition, as expressed in Eq. (21).

$$\alpha_{\max} = \alpha^* \frac{-\Delta m_{s(\max)}}{m_{so}} = \frac{\alpha^* L_o (1+w)}{C_m} \tag{21}$$

If the enhanced cell is analyzed separately, a value of C_α = 0.041 is needed to produce α_o = 0 and a value of α^* = 17.8 is obtained from best fitting. These parameters yield the calculated results shown in Fig. 8 that nicely match the experimental results. For numerical purposes, the incremental form of the equations to calculate long term variations in the MSW void ratio and volumetric strains are presented in Eqs. (22) and (23).

$$d\varepsilon_v = \left[\frac{c_\alpha}{(1+e_o)\ln(10)\,t} - \left(\frac{\rho_{so}}{\rho_{sp}}\right)\left(\frac{1}{1+e_o}\right) \times \left(1-\alpha^* \frac{\Delta m_s}{m_{so}}\right) \frac{\partial m_s}{\partial t} \frac{1}{m_{so}} \right] dt \tag{22}$$

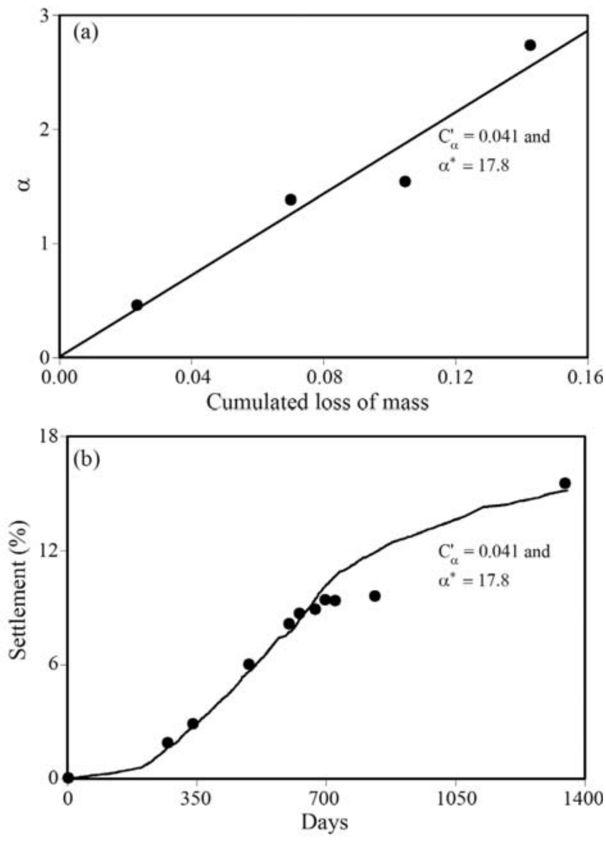

Figure 8 - (a) Calculated values of α during the decomposition process, adopting C_α = 0.041 and α_o = 0 in the enhanced cell. (b) Comparisons between measured and calculated values of settlements if only the enhanced cell is considered.

$$de = \left[\left(\frac{\rho_s}{\rho_{sp}}\right)\left(-\alpha^* \frac{\Delta m_s}{m_{so}} - e\right) \frac{\partial m_s}{\partial t} \frac{1}{m_{so}\left(1+\frac{\Delta m_s}{m_{so}}\right)} - \frac{c_\alpha}{\ln(10)\,t} \right] dt \tag{23}$$

3.2. Validation of the proposed model

Olivier & Gourc (2007) and Olivier *et al.* (2005) have presented other sets of data that allow to calculate the α parameter. The results refer to tests performed on a rigid cubic cell of about 1 m^3, in which MSW samples were tested under a vertical stress of 130 kPa. The enhanced tests, performed using leachate recirculation, presented coefficients of secondary compression, normalized through ($1+e_0$), C^*_α, of about 0.32 during intense leachate recirculation and an average value of C^*_α = 0.072. The standard or control test, without leachate recirculation, presented an average value of C^*_α = 0.035, which is close to the C^*_α obtained in the enhanced test before the leachate recirculation phase, indicating the similar composition and behavior of the waste. The control test was performed during a period of 8.5 months whereas the enhanced test was performed during a period of about 22 months.

According to the framework presented in this paper, the differences observed in C^*_α values can be explained by the fact that in both cases this parameter embraces MSW mechanical creep and the secondary compression due to the mass loss. As the mass loss was more intensive in the enhanced tests, there was an increase in C^*_α values. The C^*_α values obtained by Olivier & Gourc (2007) can be related to the C_α and α^* values presented in this paper through Eq. (24).

$$c^*_\alpha = \frac{c_\alpha}{(1+e_o)} - \frac{\rho_{so}}{(1+e_o)\rho_{sp}\log\left(\frac{t}{t_o}\right)}\left(\frac{\Delta m_s}{m_{so}}\right) - \frac{\alpha^*\rho_{so}}{2(1+e_o)\rho_{sp}\log\left(\frac{t}{t_o}\right)}\left(\frac{\Delta m_s}{m_{so}}\right)^2 \tag{24}$$

The value of α^* can be obtained considering the difference between the measured C^*_α (see Eq. (25)) values in the control and enhanced tests. To apply Eq. (24) to both conditions, it was assumed that the decomposition process started just after two months from test beginning, in both cases. At this time, noticeable changes were observed in the CO_2 and CH_4 concentrations, indicating the beginning of anaerobic biodegradation. Considering the time period from this point up to the enhanced test final, an average value of C^*_α = 0.136 is obtained. The values obtained for log (t/t_o) were 1.05 and 0.63 considering the enhanced and control tests respectively. The MSW mass loss was about 17.9% in the enhanced tests and about 5.7% in the control. At the beginning of the secondary compression process, average MSW dry unit weight was about $\rho_d = 0.62$ Mg/m^3. Assuming $\rho_s = 1.75$ Mg/m^3 and $\rho_{sp} = 1.8$ Mg/m^3, it is possible to obtain $e_o = 1.82$. Using these values in Eq. (25), yields $\alpha^* = 16.7$.

$$c^*_{\alpha\,(\mathrm{enh})} - c^*_{\alpha\,(\mathrm{cont})} = \frac{\gamma_{so}}{(1+e_o)\gamma_{sp}}\left[-\left(\frac{\dfrac{\Delta m_s}{m_{so}}\left\{1-\dfrac{\alpha^*}{2}\dfrac{\Delta m_s}{m_{so}}\right\}}{\log\left(\dfrac{t}{t_0}\right)}\right)_{\mathrm{enh}} + \left(\frac{\dfrac{\Delta m_s}{m_{so}}\left\{1-\dfrac{\alpha^*}{2}\dfrac{\Delta m_s}{m_{so}}\right\}}{\log\left(\dfrac{t}{t_0}\right)}\right)_{\mathrm{std}}\right] \quad (25)$$

According to Olivier *et al.* (2005) an average L_o reduction of about 40.9% in the BMP tests performed before and after the enhanced test was observed. Considering a period of 20 months of effective waste degradation and applying the first order decay method (Eq. (26)), a value of $k = 0.32$ yr^{-1} is obtained. As the intensity of the leachate recirculation varied during the test, the value of k obtained should be regarded as an average value. The relatively elevated value of k may be justified by the optimum controlled conditions of the test, which was performed with temperature control (≈ 35 °C) and leachate recirculation.

$$k = \frac{\ln\left(\dfrac{L_o(t)}{L_o(0)}\right)}{t} \quad (26)$$

The mass loss in the enhanced test can be calculated with the aid of Eq. (27). As before, t_o corresponds to the initial time assumed for the decomposition process (2 months) and t_f corresponds to the test duration (22 months). Eqs. (22) and (27) can now be used to predict the long term settlement obtained by Olivier & Gourc (2007). According to the authors, the secondary compression may be assumed as starting about 8 hrs after the test beginning. This was the initial time adopted for creep compression. The value of C_α was adopted as $C_\alpha = 0.035(1 + e_o)$, as the loss of mass was ignored at the test beginning (see Eq. (24)). Figure 9 presents the fit between the results calculated by the model and the experimental results obtained by Olivier & Gourc (2007).

$$\frac{\Delta m_s(t)}{m_{so}} = \frac{\dfrac{\Delta m_s(t_f)}{m_{so}}(1-e^{-k(t-t_o)})}{(1-e^{-k(t_f-t_o)})} \quad (27)$$

The framework developed here was also checked against field data from the Bandeirantes Landfill (Carvalho, 1999), located in the city of São Paulo, Brazil. Some data obtained from settlement plates installed there in conjunction with laboratory data (Vilar & Carvalho, 2004) using waste from the same landfill were used to test the ability of the model to reproduce field behavior.

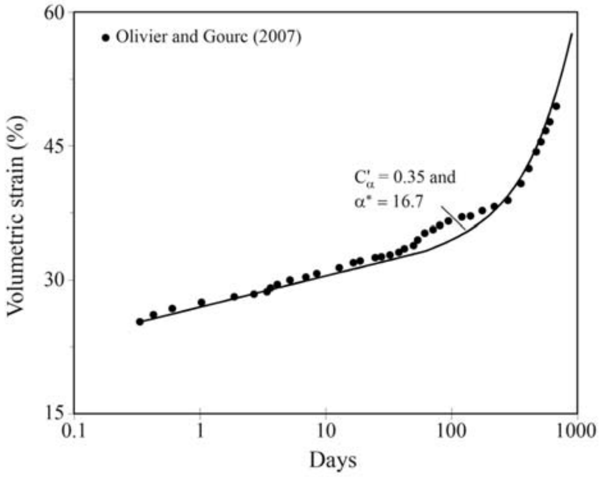

Figure 9 - Comparison between measured and calculated values of settlements. Experimental data obtained by Olivier & Gourc (2007).

Figure 10 presents data obtained from settlement markers SM 11, SM 12, SM1 3 and SM 21, located in the area AS2 of the Bandeirantes landfill. These markers correspond, respectively, to the following initial height of waste: 28 m; 37 m; 26 m and 58 m. The settlement data are supposed to represent only secondary compression, as the settlement markers were installed some months after the final cover. Although some differences can arise during filling at each location, just one simulation was carried out considering all measurement points, since the laboratory results were assumed to represent the average behavior of waste from all these places.

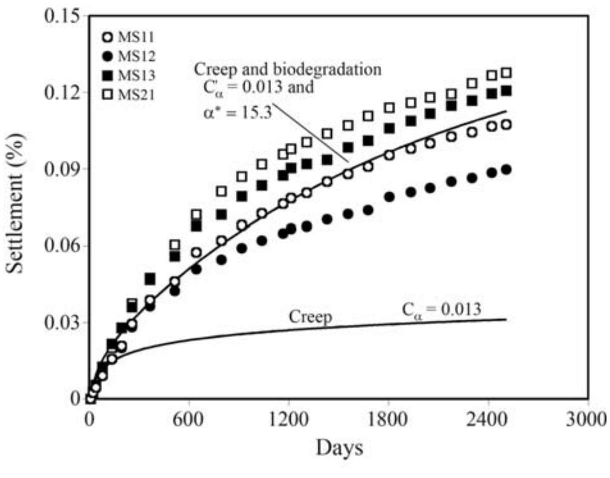

Figure 10 - Comparison between measured and calculated values of settlements from Bandeirantes landfill.

The landfilling of AS2 area started in January, 1981 and finished in October, 1991. Although the landfill procedures were not the same for all the locations in that area, these starting and closure dates were assumed to be the same for all the settlement plates. The first attempt to calculate field settlement data used Eq. (13), considering only mechanical creep compression, which was assumed as starting in October, 1991.

The comparison between calculated and field results is presented in Fig. 10. As can be seen, there is a good fit with the field results for the early stages of settlement. However, the model tends to underestimate the long term values, as one would expect. The tests carried out by Vilar & Carvalho (2004) lasted about 40 days and used 15 year old MSW. Therefore it is supposed that the effect of biodegradation is not incorporated in the obtained C_α and that this fact causes the model to underestimate the experimental field values.

A better adjustment is obtained when both mechanical and biodegradation creep is considered. These processes are embodied in Eq. (22). The following parameters were assumed considering the data presented by Britto (2006) when testing MSW from Salvador, Brazil: $k = 0.21$ year^{-1} and $L_o = 75$ m^3 CH_4/Mg of waste. An average α^* value of 15.3 was adopted, together with the values of ρ_s, ρ_{sp}, and C_m used in the previous simulation. The initial void ratio was estimated at 2.5 and this value is associated with an average water content of 50% and MSW initial density of $\rho = 0.75$ Mg/m^3. Equation (28) was used to compute the loss of mass from the beginning of the operation of the area AS2. In this equation, t_{op} refers to the operational time of the area before closure. The biodegradation process was taken as initiating just after waste filling as the long period of operation of area AS2 makes the influence of a time-lag in the calculated results negligible.

Figure 10 also includes the calculated values considering mechanical creep and biodegradation effects through Eq. (22). As can be seen, there is good agreement between field data and predicted values obtained for the settlement marker MS 11. The calculated values deviate slightly for the other points of measurement and the differences shown are believed to be due to the differences in landfilling procedures and on the assumption of parameters that rely on average values. It is believed that parameters resulting from tests specially designed to yield customized parameters or from back analysis of existing landfills, together with more precise construction data, such as times of beginning and closure of landfill, could improve model prediction as the general pattern of settlement curves are correctly duplicated by the model results.

$$\frac{\Delta m_s}{m_{so}} = \frac{L_o(1+w)\{(e^{k\,t_{op}}-1)(e^{-k\,t_{op}}-e^{-k\,t})+(k\,t_{op}-1+e^{-k\,t_{op}})\}}{t_{op}\,C_m\,k} \tag{28}$$

4. Conclusion

A comprehensive model to simulate secondary settlement of Municipal Solid Waste (MSW) has been developed and tested against real data from laboratory tests and landfills. Mechanical creep compression as well as biodegradation of waste were considered the main sources of secondary compression. Creep compression was modeled in a manner similar to that used for soils that exhibit creep considering that the process depends on a single parameter, the coefficient of secondary compression.

Phase relationships for degradable material are proposed and biodegradation volumetric variations are assessed through a single biodegradation parameter. The nature and magnitude of this parameter was analyzed considering some laboratory and field data available. It was shown that this parameter does not remain constant throughout the degradation process, but rather depends on certain variables. In the proposed model, it was assumed that the biodegradation parameter is dependent on the amount of organic matter already decomposed.

The depletion of organic matter in MSW was represented through gas generation, modeled as a first order decay process. The gas generated was transformed into mass loss and used to evaluate biodegradation settlement through a mass balance equation.

It was demonstrated that model parameters can be obtained from laboratory tests and from field data and certain strategies to relate biodegradation parameters to gas generation and the coupling of mass balance equation and settlement are presented. The model predictions provided data that compared favorably with laboratory and field data regarding settlement and thus imparted credibility to the model for predicting long term landfill settlements.

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List of Symbols

c: time since to landfill closure
C'_α: MSW secondary compression coefficient
C^*_α: MSW secondary compression index, involving creep and mass loss
C_m: methane specific yield
C_α: MSW secondary compression index
DOC: Degradable Organic Carbon fraction
dx: infinitesimal variation of x
dx_c: infinitesimal variation of x due creep process.
dx_d: infinitesimal variation of x due decomposition process.
e: MSW void ratio
k: methane generation rate constant
L_o: methane generation potential
m_{sf}, m_{sp}, m_w, m_s, and m: masses of fibers and paste solids, water, solids and total
MSW: municipal solid waste

Q: methane generation rate
R: landfill average annual waste acceptance rate
t: time since landfill opened, time elapsed
t_{op}: landfill operation time ($t_{op} = t - c$)
v_a, v_w, v_s, v_v, v_p and v: MSW volumes of air, water, solids, voids, paste and total
v_{sf} and v_{sp}: volumes of fibers and paste solids, respectively
w: MSW water content (dry basis)
x_o: initial value of variable x
α: parcel of MSW coupled long term compression generated by waste mass loss process.
A^*: rate of increment of the MSW coupled time differed compression
ρ_s: unit weight of the MSW components
ρ_{sf}: unit weight of the fiber components
ρ_{sp}: unit weight of the paste components
Δx: finite variation of the generic variable "x"
Δx_c: finite difference in variable x due creep process.
Δx_d: finite difference in variable x due decomposition process.
ε_v: MSW volumetric strain