

## Predicting Bioreactor Landfill Air Space by Estimating Geotechnical Properties of Waste

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### Abstract

Intensive research has focused on the settlement of the typical Municipal Solid Waste (MSW) in bioreactor landfills, but relatively little attention has been given to the settlement of individual refuse components. The objective of this paper is to estimate and compare the compressibility parameters of different waste fractions, such as: textile, paper, and mixed waste through measuring the change in the physical properties, and settlement characteristics of waste in six lab-scale bioreactor landfills operated under anaerobic conditions. Primary compression index ( $C_c$ ), and coefficient of volume compressibility ( $m_v$ ) were estimated for all three waste materials using time-settlement data. The primary compression index ( $C_c$ ) increased from 0.31 for textile waste to 0.45 for paper waste, and 0.63 for mixed waste. It can be noted that  $C_c$  increased with increasing the waste organic content. The value of the coefficient of volume compression ( $m_v$ ) suggests that the biodegradation increased the values of  $m_v$  of all types of waste samples. Textile waste incorporated the lowest value of  $m_v$  compared to all other solid waste fractions. This may be attributed to the fact that the textile is slowly biodegradable compared to paper and food wastes as stated earlier. Textile waste cells had the least value for all compressibility parameters. Proper estimation of the waste compressibility parameters would allow engineers and landfill designers formulate mathematical models to better estimate available air space saving and expected time-dependent deformation patterns at field scale bioreactor landfill cells, which subsequently increases life time of bioreactor landfills.

**Keywords:** *Compressibility of Solid Waste, Bioreactor Landfills, Compression Index, Coefficient of Consolidation, Waste Settlement*

### 1. Introduction

Open dumping is the common method of municipal solid waste (MSW) disposal in developing countries. Disposal of municipal refuse by open dumping has adverse environmental effects on soils, plants, groundwater, aquatic organisms and humans. An urgent necessity to evolve innovative and efficient methods of MSW management in developing countries has been stressed by Visvanathan et al. [1]. Efficient use of landfill air space becomes more significant in the context of urban regions of developing countries where scarcity of land space continues to limit the possibility of any new development [2].

Current landfill disposal techniques consider landfill site as an environmentally unfriendly passive storage system. The biodegradation of organic compounds is restricted for low moisture in landfill, which cannot provide microorganism with feasible conditions [3]. The dumped refuse will biodegrade slowly, which lengthens the process of landfill stabilization and

settlement and result in a significant negative impact on the environment.

An increased demand in land, regulatory restrictions, environmental pollution and an escalating amount of public opposition have all created reasons to avoid using landfilling techniques or improve the current landfilling techniques that are being used [4]. Bioreactor landfill design is based on the acceleration of in-situ biodegradation by reaching optimal water content for biodegradation, which lies high above the moisture content at waste placement [5].

Among other environmental benefits, bioreactor landfill achieves faster stabilization times and herewith efficiently reduces the pollution potential of the landfill [6] while contributing to better biogas recovery. The proper operation of landfills, and especially bioreactor landfills, requires their extensive monitoring.

The monitoring of settlements is crucial to calculate the final mass of waste that might be disposed of in the landfill, to determine when the final cover should be placed, and to avoid

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damage to biogas recovery and leachate recirculation systems [7]. It is also essential to ensure a safe long-term mechanical behavior of the landfill, as settlements are a significant problem of the post-closure period [8, 9] and may hinder potential recreational or commercial land use of landfills [10]. A large number of processes are involved in the settlement mechanisms, with two major drivers which are mechanical and biochemical processes.

It is commonly accepted that the secondary settlement of MSW occurs through mechanical and biological processes [7, 11]. Thus, mechanisms of secondary waste settlement can be divided into two categories, mechanical settlement, and biodegradation-induced settlements. Mechanical settlement is caused by physical distortion, bending, crushing and reorientation of particles due to the applied load and creep [12]. Biologically-induced settlements are a consequence of anaerobic biodegradation of organic matter, which induces a loss of solid mass mainly converted into biogas and proportionally far less into dissolved and suspended solids in the leachate.

The compressibility of landfills can be measured by a specific number of parameters. These parameters, once obtained from lab work, can also be used to create mathematical models which can later predict future settlement of landfills. Parameters necessary for settlement analysis include the compression index ( $C_c$ ) to estimate primary settlement, with the secondary compression index ( $C_{\alpha}$ ) used to estimate the settlement that occurs while the waste is subjected to a constant load. Other parameters also used are the coefficient of compressibility ( $a_v$ ), and the coefficient of volume compression ( $m_v$ )

Intensive research has focused on the settlement of the typical MSW in bioreactor landfills [6, 7, 8], but relatively little attention has been given to the settlement of individual refuse components. Proposing a single compressibility parameter for landfill settlement calculations may lead to inaccurate predictions. The objective of this paper is to estimate and compare the compressibility parameters of different waste fractions; textile, paper, and mixed waste through measuring the change in the physical properties, and settlement characteristics of waste in six lab-scale bioreactor landfills operated under anaerobic conditions. Additionally, the impact caused by waste overburden load and waste density increase in the form of subsequent waste layers on the same bioreactors is examined.

## 2. Experimental Procedure

### 2.1. Materials and methods

Three groups of laboratory scale anaerobic bioreactor landfills were operated for 110 days to evaluate the compression characteristics of different solid waste samples. Each group consisted of two bioreactor cells. Figure 1 provides the configuration of the complete bench-scale bioreactor used in this experiment. Each cell has a diameter of 0.55 m, height of 0.92 m, and total capacity of 220 L. A detailed description of the bioreactor cells configuration is given in Elagroudy et al. [13]. To avoid leachate ponding over the applied load, cylindrical loads were used for cell loading. The curve surface of the cylinder will ensure the passage of all re-circulated leachate. To ensure equal load distribution and uniform density

for loaded cells, two circular plastic meshes were put underneath the cylindrical load.

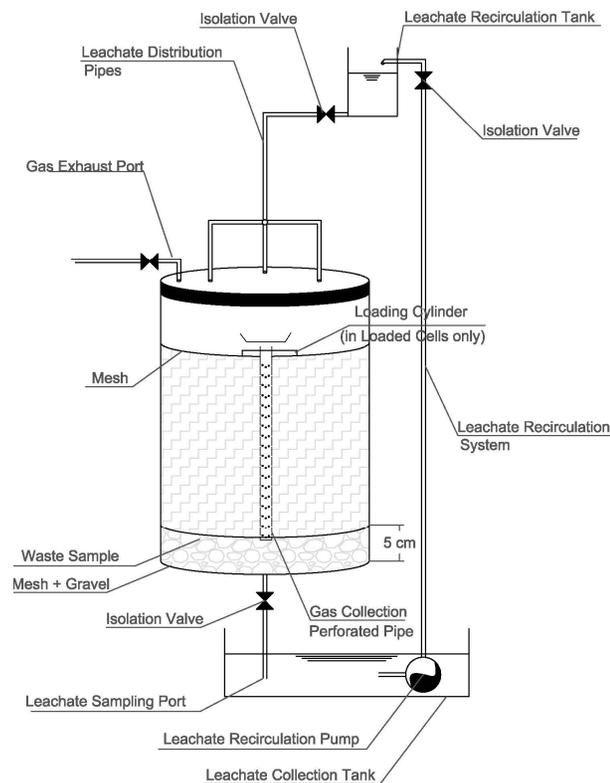


Fig. 1. Schematic diagram of bench-scale bioreactor cell

All cells were operated with leachate recirculation and pH control at a neutral level through the addition of the basic buffer (NaOH) to the recirculated leachate. They were all placed in  $23 \pm 2^\circ\text{C}$  room temperature. The SW fraction used in the two cells of the first group is paper, while textile and mixed waste were used in the cells of the second and third group, respectively. The three unloaded cells act as control cells corresponding to each of the three loaded ones.

Based on their loading condition and matrix components, the six bioreactors were named as UP, LP, UT, LT, UM, and LM (U: Unloaded; L: Loaded; P: Paper; T: Textile; M: Mixed waste). The detailed information, together with the solid waste composition for the six cells is summarized in Table 1. The bioreactor cells (UP), (UT), and (UM) functioned as control cells for (LP), (LT), and (LM), respectively.

Table 1. Bioreactor cell configuration

Cell ID	Matrix	Waste Composition		
		Paper (%)	Textile (%)	Mixed (%)
UP	Unloaded Paper	100	-	-
LP	Loaded Paper	-	-	-
UT	Unloaded Textile	-	100	-
LT	Loaded Textile	-	-	-
UM	Unloaded Mixed	40	40	20
LM	Loaded Mixed	-	-	-

The textile waste comprised of different types of textile; cotton, wool, silk, nylon, and polyester. Paper waste consisted of newspaper, school and office paper, all forms of packaging paper, computer and printing paper, magazines, and cardboards. Food Waste was a mixture of vegetables, rice, chicken bones and macaroni. Paper and textile wastes were shredded to a size of 100-150 mm.

**2.2. Cell Loading**

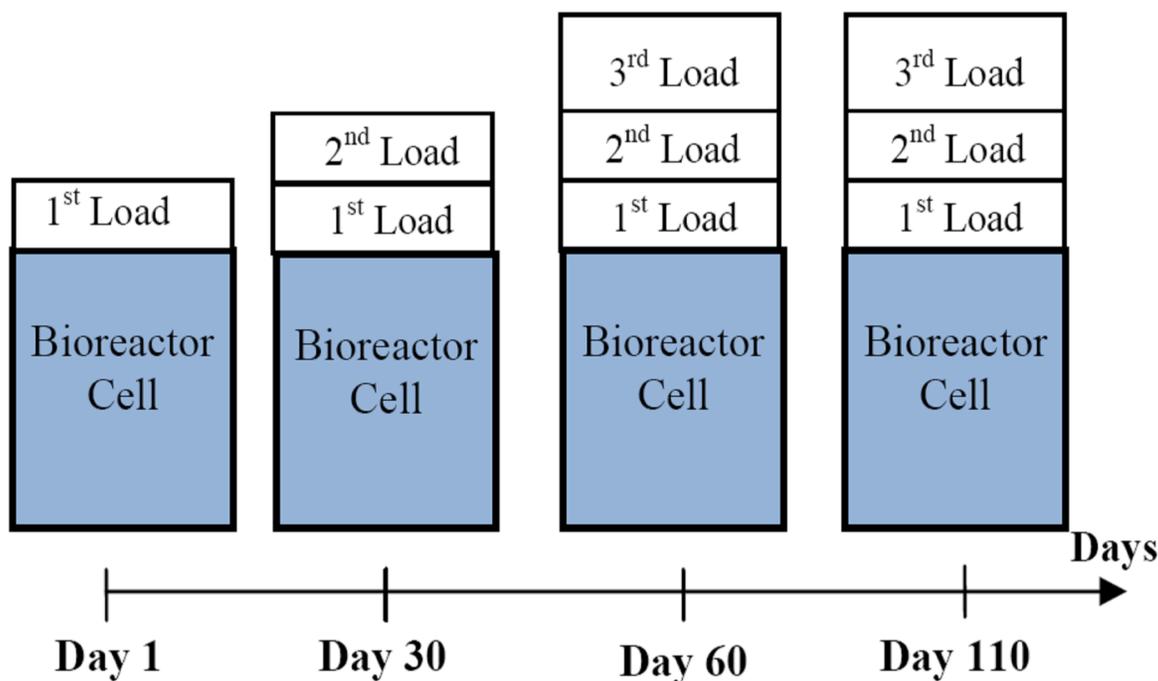
At day 1 of the experiment, the three loaded cells (LP), (LT) and (LM) were loaded with an equal load (1<sup>st</sup> Load) of 10Kg. At day 30, an additional load (2<sup>nd</sup> Load) of 10Kg/cell was applied to the three loaded cells thus the total load on each cell reached 20Kg. After another 30 days (Day 60), an additional load (3<sup>rd</sup> Load) of 20Kg/cell was added summing up the total load to 40Kg/cell. The load of 40 kg/cell was left till the end of the experiment (Day 110). Figure 2 and Table 2 present the timeline for adding the load to the bioreactor cells. The loads added represent the above layers of solid waste in the landfill. All loads were made of steel coated cylindrical loads. The curve surface of the steel cylinder will ensure the passage of all re-circulated leachate. The value and duration of the loads applied are shown in Table 2 and Figure 1. Time settlement data gathered from each load increment were employed to plot strain versus log-time graphs. The data acquired from the compression tests were used to back calculate primary and secondary compression indices.

Although secondary and primary compressions occur simultaneously, the magnitude of primary compression is greater and masks the effects of secondary compression in the initial period. After the first 30 days of loading, secondary compression progresses and eventually reaches the same order of magnitude as primary compression [8, 14]. This explains why the load added to the cells was increased after 30 days.

**Table 2. Applied loads on the cells**

Load	Property	LP, LT, LM
1 <sup>st</sup>	Weight (Kg)	10
	Stress (N/m <sup>2</sup> )	405
	Duration (d)	0-30
2 <sup>nd</sup>	Weight (Kg)	10
	Additional Stress (N/m <sup>2</sup> )	405
	Duration (d)	31-60
3 <sup>rd</sup>	Weight (Kg)	20
	Additional Stress (N/m <sup>2</sup> )	810
	Duration (d)	61-110

The disadvantage of the load surcharge system in this study is that the applied stress is not high. However, since the unit weight of the waste is less than that of soil and also the height of waste cell is usually not more than 3 meters, the overburden pressure is not high. Hence, it was considered suitable for this study.



**Fig. 2. Loading sequence of cells LP, LT and LM**

3. Results and Discussion

3.1. Settlement

Table 3 shows the percentage of settlement that took place in the bioreactors with respect to initial height. Figure 3 illustrates the change in settlement with time for each group of cells. The total percentage in the loaded cells of all three groups was higher than in unloaded cells, which reveals the effect of added load that represents the subsequent layers of waste on settlement. The mixed waste cells encountered the highest settlement. UM and LM experienced the highest total settlement in all groups due to the presence of organic waste.

Table 3. Average settlement that occurred in bioreactors

Group	Cell ID	Final Settlement (%)	Mean percentage settlement reduction (%)
1	UP	4.4	11.5
	LP	18.5	
2	UT	7.4	7.9
	LT	8.3	
3	UM	11.5	16.2
	LM	20.9	

3.2. Primary Compression Index (Cc)

The settlement data acquired from the lab-scale bioreactors were used to back calculate primary compression index. The primary compression index ( $C_c$ ) is used to estimate the primary settlement of MSW resulting from an increase in vertical stress using the following Equation.

$$\Delta H_{primary} = \frac{C_c}{1 + e_0} H_0 \log \frac{\sigma_0 + \Delta \sigma}{\sigma_0} \quad (1)$$

Where  $\Delta H_{primary}$  is the primary waste settlement,  $\Delta \sigma$ , the change in vertical effective stress,  $e_0$ , the initial void ratio, and,  $C_c$ , the primary compression index is defined by Holtz and Kovacs [15] and is written as:

$$C_c = \frac{-\Delta e}{\Delta \log \sigma} \quad (2)$$

Where  $\Delta e$ , is the change in void ratio,  $\Delta \varepsilon$ , the change in linear strain defined as a change in height ( $\Delta H$ ) divided by the original height ( $H_0$ ). The linear strain is related to void ratio by equation 3:

$$\varepsilon = \frac{\Delta H}{H_0} = \frac{\Delta e}{1 + e_0} \quad (3)$$

The following expression is used to calculate the void ratio (e):

$$e = \frac{HG_s \gamma_w A}{W_s} - 1 \quad (4)$$

Where  $G_s$  is the specific gravity,  $A$ , the surface area of the bioreactor cell,  $\gamma_w$ , the unit weight of water, and,  $W_s$ , the mass of solid waste obtained by drying the sample and calculating the moisture content. The results are presented in Table 4. Table 5 provides other published waste compressibility values, for comparison to those calculated in this study. It can be observed from Table 5 that the values of compression parameters vary largely. This wide range is due to the large variation of wastes involved, the various ages of the landfills, and the forces to which various layers have been subjected. Our results are comparable with other published values.

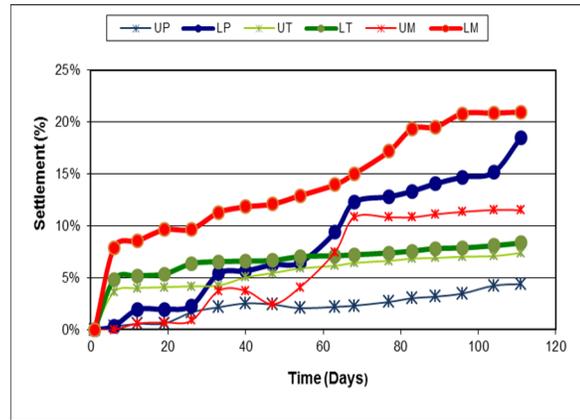


Fig. 3. Settlement variation in the bioreactors of each group

Table 4. Compression parameters determined from lab-scale bioreactor readings

Group	$m_v$ ( $m^2/N$ )		$C_c$
	First Approach	Second Approach	
1	$1.56 \times 10^{-5}$	$5.75 \times 10^{-5}$	0.451
2	$4.96 \times 10^{-6}$	$1.6 \times 10^{-5}$	0.309
3	$2.32 \times 10^{-5}$	$7.73 \times 10^{-5}$	0.625

The coefficient of primary compression ( $C_c$ ) for waste samples showed an increasing trend from 0.309 for textile waste to 0.451 for paper waste, and 0.625 for mixed waste. It can be noted that  $C_c$  increased with increasing the organic content which matches the settlement results presented in Table 2. Moreover, the range of ( $C_c$ ) values fall within the values obtained by Durmusoglu [16] that ranged from 0.259 to 0.990.

Table 5. Published compressibility parameter for MSW samples

Source	$m_v$ ( $m^2/N$ )
[17]	$5 \times 10^{-7} - 2 \times 10^{-6}$
[18]	$2.9 \times 10^{-7} - 5 \times 10^{-6}$
[19]	$4 \times 10^{-7} - 1.25 \times 10^{-6}$
[20]	$6.7 \times 10^{-7} - 5 \times 10^{-6}$
[21]	$5 \times 10^{-7} - 5 \times 10^{-6}$
[16]	$4.48 \times 10^{-7} - 2.5 \times 10^{-7}$

### 3.3. Coefficient of Volume Compression ( $m_v$ )

The coefficient of volume compression is the slope of the strain-vs.-pressure curve. This value gives a measure of the change in volume per unit of effective stress as expressed in Equation 5. When graphed, the slope of the resulting curve gives the value of the desired coefficient as shown in Figure 4.

$$m_v = \frac{\Delta H / H}{\Delta \sigma} = \frac{\text{Strain}}{\text{Stress}} \quad (5)$$

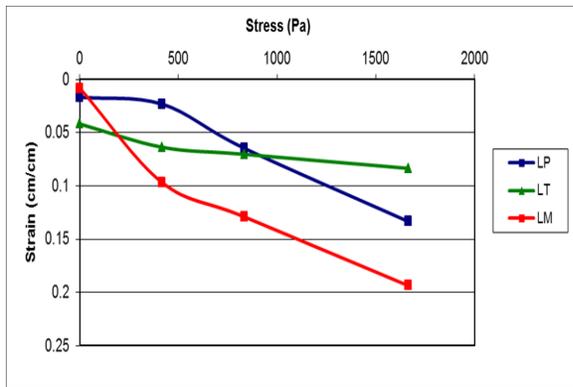


Fig. 4. Stress vs. strain for loaded bioreactor cells

To determine the effect of biodegradation of each of the three waste components (Textile, Paper, Mixed waste) on the value of  $m_v$ , the value of  $m_v$  was calculated using two approaches; First considered only the effect of load, second incorporated the effect of both load and waste biodegradation. To eliminate the effect of waste biodegradation on the coefficient of volume compression and include only the effect of load, as in the first approach, the values of the strain used were determined by subtracting the settlement values obtained from the control cell of each group of cells from those obtained from the loaded cell of the same group. While in the second approach, the settlement values obtained from the three loaded cells were directly used thus the effect of biodegradation is included.

Equation 5 yielded values of  $m_v$  that fall within the range of  $4.9 \times 10^{-6}$  to  $2.32 \times 10^{-5} \text{ m}^2/\text{N}$  without taking the effect of biodegradation and in the relatively narrow range of  $3.6 \times 10^{-5}$  –  $7.7 \times 10^{-5} \text{ m}^2/\text{N}$  while taking the effect of biodegradation as presented in Figure 5. This observation suggests that the biodegradation increased the values of  $m_v$  of all types of waste samples. In both approaches, textile waste incorporated the lowest value of  $m_v$  compared to all other solid waste fractions. This may be attributed to the fact that the textile is slowly biodegradable compared to paper and food wastes as stated earlier.

Table 5 shows the range of the values of  $m_v$  reported by other researchers [16-20]. It can be noted that our range is slightly lower than what is found in the literature. The variation between results from this study and those reported in the literature may be attributed to difference in waste composition and apparatus scale. In addition, the effect of waste biodegradation on coefficient of volume compression was not taken into consideration by previous researchers.

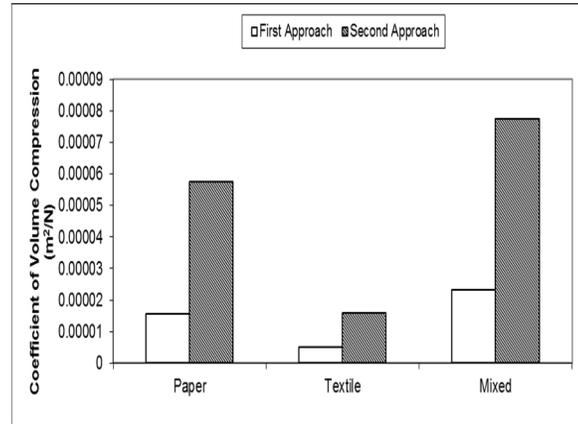


Fig. 5. Coefficient of volume compression ( $m_v$ ) using the two approaches

### 4. Conclusion

Six lab-scale bioreactors with three waste compositions (textile waste, paper waste, and a mixture of textile, paper and food waste) were employed to determine the compression characteristics of solid waste samples. The variation between compressibility values resulting from this study and those reported in the literature is attributed to difference in waste composition and apparatus scale. Mixed waste experienced the highest settlement (20.9%) compared to the paper and textile waste that exhibited a maximum settlement of about (9.0%). Significant difference in the waste settlement was noted in the presence and absence of load. The primary compression index ( $C_c$ ) increased from 0.31 for textile waste to 0.45 for paper waste, and 0.63 for mixed waste. It can be noted that  $C_c$  increased with increasing the waste organic content. The value of the coefficient of volume compression ( $m_v$ ) suggests that the biodegradation increased the values of  $m_v$  of all types of waste samples. Textile waste incorporated the lowest value of  $m_v$  compared to all other solid waste fractions. This is attributed to the fact that the textile is slowly biodegradable compared to paper and food wastes as stated earlier.

The factors obtained from this study can be used to predict the recovery of the bioreactor landfills air space, which could reach from 20 to 25% of the original landfill air space, in other words, increase the life time and the accommodated capacity of the landfill by 25%. This fact can directly affect the financial aspects of operating bioreactor landfills and indirectly contribute to reducing the negative impacts of landfill on the environment.

### Nomenclature

$A$	surface area of the bioreactor cell, $\text{m}^2$
$C_c$	Primary compression index
$C_\alpha$	Secondary compression index
$D$	Diameter of the jet, m
$G_s$	specific gravity
$H_0$	Original height, m
$T$	Temperature of the jet, K
LM	Loaded mixed cell
LP	Loaded paper cell
LT	Loaded textile cell
$m_v$	coefficient of volume compression, $\text{m}^2/\text{N}$

UM	Unloaded mixed cell
UP	Unloaded paper cell
UT	Unloaded textile cell
$W_s$	Dry mass of solid waste, Kg

*Greek Symbols*

$\gamma_w$	unit weight of water, Kg/m <sup>3</sup>
$\Delta e$	Change in void ratio
$\Delta \varepsilon$	Change in linear strain
$\Delta H_{primary}$	Primary waste settlement, m
$\Delta \sigma$	Change in vertical effective stress, N/m <sup>2</sup>
$\varepsilon$	Linear strain
$e_0$	Initial void ratio

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