Municipal Landfill Biodegradation and Settlement

By Dean K. Wall,[1] and Chris Zeiss[2]

Abstract: Landfills are frequently considered for urban development, but have limited end uses due to large differential settlements, leachate generation, and gas emissions. Current landfill design with top- and bottom-liner systems minimize entry of moisture and increase the period required for stabilization of the refuse to occur. The objective of this study is to test the ability of biological enhancement to reduce the time to reach biological stabilization of the waste to nondegradable matter, and to determine the effects of biodegradation on settlement. To accomplish this, six landfill test cells were constructed to model both settlement and decomposition over extended periods. Three cells were designed to simulate bioreactor landfills, while another three were designed to simulate secure vaults. Results demonstrate that secondary settlement is linear with the logarithm of time, and decomposition is well represented by a first-order model. Comparisons indicate that in the short term there is no significant increase in the settlement rate due to biodegradation; however, extrapolation suggests that in the long term the settlement rate will likely increase as the effects of decomposition become more significant.

INTRODUCTION

Municipal solid-waste landfills often require large tracts of land on or immediately beyond the urban growth boundary of metropolitan areas (Zeiss and Atwater 1989). This land often cannot be developed for beneficial land uses because of differential settlement, leachate generation, and landfill gas emissions. These processes continue for 20–30 years after landfill completion. As a result, while the community around the landfill experiences rapid growth because it offers inexpensive land favorably located near transportation routes, landfilled areas are left undeveloped because of the long duration of the landfill-stabilization processes.

Conventional sanitary landfills used to consist of waste compaction, regular daily cover, and access control (*Public Health* 1985). Infiltrating moisture stimulated microbial activity with waste as the substrate, while leachate was implicitly assumed to undergo natural attenuation (Robinson 1986) in soil.

In reaction to past ground-water pollution problems and to new regulations, new landfills are designed to provide top- and bottom-liner, leachate, and gas-collection systems, to minimize uncompleted landfill surface area and to maintain low-moisture conditions. Because moisture is a principal factor for biodegradation and, hence, stabilization, the stabilization period of the "dry-vault" design probably extends beyond that of a conventional sanitary landfill.

An alternate approach is to design and operate the landfill as an anaerobic biodigester. The design consists of the bottom- and top-liner systems, but may include inputs of moisture, microbes, and nutrients to stimulate biological activity. As a result, leachate and gas are produced during the period when the liner system is new and least likely to fail. By providing good conditions for enhanced biodegradation, the stabilization time of landfills may be reduced and the land more quickly returned to beneficial land use.

The goal of this research is to test the effects of enhanced biodegration on landfill settlement as a method of reducing the stabilization time. Three specific research objectives are required for the project: (1) Analyze and explain landfill settlement and biodegration mechanisms, and compare models to predict landfill stabilization; (2) develop landfill test cells to model landfill behavior and to obtain experimental data of settlement and biodegradation; and (3) test the effect of biodegradation on settlement and estimate the resulting reduction of the stabilization period. The present paper will first outline the theory of landfill settlement and biodegradation, then describe the experimental approach, and finally, analyze experimental results and provide conclusions.

THEORY OF LANDFILL SETTLEMENT AND BIODEGRADATION

Landfill Settlement

Among the practical problems of utilizing landfill sites for development, settlement may be the most significant (Sowers 1973; Morris and Woods 1990). Estimates of the total settlement

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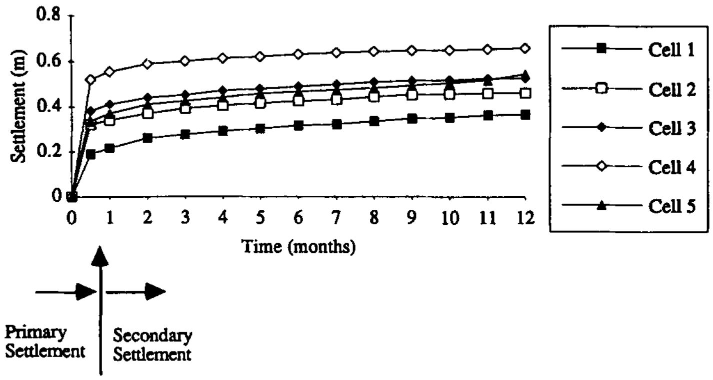

FIG. 1. Municipal Landfill Settlement over Time (Merz and Stone 1962)

of a sanitary landfill range from 25% to 50% of the landfills initial thickness (Stearns 1987). Settlement mechanisms in refuse landfills are very complex and less understood than in coarse or fine-grained soils (Edil et al. 1990). This can be attributed in part to its inhomogeneous nature, large particle sizes, compression of refuse particles, and the loss of solids due to biodegradation. Settlement occurs in essentially three distinguishable stages: (1) Initial compression; (2) primary compression; and (3) secondary compression (Morris and Woods 1990). Initial compression is rarely observed in figures illustrating landfill-settlement data. This is because the compression happens immediately when a load is applied before recording starts. However, the slower primary- and secondary-compression stages can be observed in a typical settlement versus time curve (Merz and Stone 1962) (see Fig. 1). While the influence of biodegradation on secondary compression is of interest to landfill designers and is addressed in this article, all three settlement stages are discussed, and their predictive equations are summarized here in order to compare experimental data with theory throughout landfill life.

Initial Compression

Initial compression is settlement that occurs directly when an external load is applied to a landfill. Initial compression is generally associated with the immediate compaction of void space and particles due to a superimposed load (Tuma and Abdel-Hady 1973). This type of settlement is analogous to the elastic compression that occurs in soils and is virtually instantaneous.

Initial compression calculations have been developed for the estimation of immediate foundation settlements. These analyses are used for partially saturated fine-grained soils and all coarse-grained soils. Since refuse has a permeability in the range of clean sands and gravels (Landva and Clark 1990), and experiences an immediate settlement under load, initial compression should be accounted for. Usual methods for calculation would require the assumption or measurement of a refuse modulus of elasticity and then would solve for settlement. Since the amount of settlement was measured in this experiment, values for the modulus of elasticity can be determined using (1) (Bowles 1988)

$$E_s = \frac{\Delta q H_0}{S_i} \tag{1}$$

Primary Compression

Primary compression is compaction due to the dissipation of pore water and gas from the void spaces (Gordon et al. 1986). In a completed landfill, settlement due to primary compression will occur rather quickly, usually within the first 30 days after load application (Sowers 1973; Morris and Woods 1990; Gordon et al. 1986; Edil et al. 1990; Dodt et al. 1987). Although both processes occur simultaneously, the magnitude of primary compression is greater and masks the effects of secondary compression in this initial period. After the first 30 days, secondary compression progresses and eventually reaches the same order of magnitude as primary compression. For this reason, they are modeled separately. Terzaghi (1943) hypothesized that primary settlement in fine-grained soils was due to consolidation of the material. This refers to settlement caused by the squeezing of water from the pore spaces of a saturated material under an applied load. However, there are significant indications that mechanisms of this nature may not be responsible for primary compression in municipal solid-waste landfills. First, refuse in municipal landfills is seldom saturated as secure vault principles minimize the entry of water to the fill. Secondly, no mechanistic differences were observed in this study between landfill test cells operating at field capacity and cells operating with only inherent moisture. Thirdly, the permeability of refuse is of the same order of magnitude as sand and gravel, therefore, no pore-water pressure should develop as liquid can readily escape from the landfill mass.

The primary-compression process, as it applies to landfills, is most commonly described using the Terzaghi theory. Many researchers have utilized this approach (Sowers 1973; Landva et al. 1984; Rao et al. 1977; Gordon et al. 1986; Morris and Woods 1990; Kurzeme and Walker 1985; Moore and Pedler 1977; Oweis and Khera 1986). Although empirical in its application to landfills, the Terzaghi theory provides reasonable estimations of primary compression and typical ranges for its parameters are well established. Eq. (2) for calculating settlement due to primary compression is illustrated herein using the notation used in Holtz and Kovacs (1981)

$$S_p = H_i C_{ce} \log[(p_0 + \Delta p)/p_0] \qquad (2)$$

Secondary Compression

Secondary compression is generally due to creep of the refuse skeleton and biological decay (Sowers 1973; Gordon et al. 1986). Settlement due to secondary compression can account for a major portion of the total landfill settlement and can take place over many years (Rao 1974). Coduto and Huitric (1990) suggest that secondary compression due to creep and other compaction mechanisms can account for losses of up to 25% of the refuse thickness. Coduto and Huitric (1990) state that settlement due to biological decomposition is probably between 18% and 24% of the refuse thickness. Taylor (1942) was one of the first to identify secondary-compression effects that he termed "plastic structural resistance to compression." Barden (1965) attributed secondary-creep effects to the gradual readjustment of the soil skeleton. Barden indicated that the rate of secondary compression was strongly influenced by the viscous effects of the adsorbed double layer. The cause of secondary compression of landfills is still the subject of much controversy. Sowers (1973) attributes secondary settlement of waste to the combination of mechanical secondary compression, physicochemical action, and biochemical decay; and concludes that the secondary-compression index (C_α) is proportional to initial void ratio and favorable decomposition conditions. Sowers suggested that increased rates of degradation due to favorable biological conditions results in higher values for the secondary-compression index and therefore higher settlement rates.

Sowers (1973) was the first to present a model for the secondary compression of refuse in sanitary landfills. The model was based on observations made at several full-scale municipal landfills. The equations presented are a modification of Buisman's theory for secondary compression of soils (Buisman 1936). The theory assumes that the secondary portion of the settlement curve is linear with respect to the logarithm of time. This behavior has been confirmed in this study and by many other researchers and field data (Landva et al. 1984; Rao et al. 1977; Gordon et al. 1986; Morris and Woods 1990; Kurzeme and Walker 1985; Moore and Pedler 1977; Oweis and Khera 1986). The notation selected for the following is as used in Holtz and Kovacs (1981)

$$S_s = H_p C_{\alpha e} \log(t/t_p) \quad \text{where} \quad C_\alpha = \Delta e/\Delta \log t; \quad C_{\alpha e} = C_\alpha/(1 + e_p) = \Delta\ \text{strain}/\Delta \log t \qquad (3, 4, 5)$$

where C_α = the slope of the void-ratio versus log-time curve; and $C_{\alpha e}$ = the slope of the strain versus log-time curve. $C_{\alpha e}$ is otherwise known as the secondary compression ratio or rate of secondary compression. Also

$$e_p = \frac{W_p}{s}\frac{\rho_s}{\rho_w} = \frac{V_v}{V_s} \qquad (6)$$

Sowers (1973) suggests that the secondary-compression index (C_α) increases linearly with the initial void ratio (e_p) and favorable decomposition conditions for municipal solid waste. The following range is provided for estimating C_α (0.03 corresponds to unfavorable conditions while 0.09 corresponds to favorable conditions):

$$C_\alpha = (0.03 \text{ to } 0.09)e_p \qquad (7)$$

Some typical values for refuse compressibility are shown in Table 1.

In attempts to provide a single equation combining the primary and secondary settlement of refuse, Edil et al. (1990) applied models previously used to describe the secondary compression

TABLE 1. Refuse Compressibility Parameters (Oweis and Khera 1986)

Reference (1)	Primary C_{ce} (2)	Secondary $C_{\alpha e}$ (3)
Rao et al. (1977)	0.16–0.235	0.012–0.046
Converse (1975)	0.25–0.3	0.07
Zoino (1974)	0.15–0.33	0.013–0.03
Sowers (1973) (for e_0 = 3)	0.1–0.41	0.02–0.07
Oweis and Khera (1986)	0.08–0.217	—
Landva et al. (1984)	0.2–0.5	0.0005–0.029

of materials. The two models that they investigated were the Gibson and Lo (1961) rheological model and the power-creep law (Edil et al. 1990). These two models were found to explain landfill settlement less accurately than the Sowers model (Wall 1992) and, hence, are not further discussed here.

Biodegradation in Landfills

To understand the contribution of decomposition to settlement three elements must be considered: (1) The amount of solid carbon that decomposes; (2) the rate at which it decomposes; and (3) how this mass loss is transformed into settlement. Refuse typically contains 40–50% cellulose, 10–15% lignin, 12% hemicellulose, and 4% protein on a dry-weight basis (Barlaz et al. 1990). Barlaz et al. also state that the cellulose-plus-hemicellulose fraction of refuse accounts for 91% of its methane potential. Cellulose concentrations of 8–30% were discovered in well-decomposed landfills by Bookter and Ham (1982). In a lysimeter study performed by Barlaz et al. (1989), mineralization of 71% of cellulose and 77% of hemicellulose was observed in 111 days. This suggests that approximately 25–40% of municipal refuse is available for biological decomposition. Obviously, if this amount of solid material was removed from a landfill, considerable settlement should occur.

Biodegradation in landfills is a four-stage process by which solid organic particles are solubilized and converted through methanogenesis to methane and carbon dioxide. It is hypothesized that this reduction in solids directly relates to an increase in the magnitude and rate of secondary settlement. Once in liquid form, the intermediate decomposition products drain out of the landfill or are converted through methanogenesis to methane and carbon dioxide. Therefore, the decomposition step that is of concern is the conversion of refuse organic solids to liquid. Detailed studies of the degradation process indicate that polymer hydrolysis is responsible for this solubilization (Barlaz et al. 1990). During the initial stages of decomposition, there is a significant amount of readily degradable soluble substrate present. Therefore, the rate of the overall process should be governed by methanogenesis. However, once the readily degradable soluble substrates are exhausted, the overall process is limited by hydrolysis. Since the most abundant carbon sources in municipal solid waste are insoluble (cellulose and hemicellulose), the majority of the decomposition process is limited by hydrolysis (Halvadakis et al. 1983). Common practice by many researchers is to assume that cellulose hydrolysis occurs by first-order kinetics (Chen 1974; McGowan et al. 1988; El-Fadel et al. 1989; Young 1989).

Relationship of Settlement and Biodegradation

Farquhar and Rovers (1973) suggests a decomposition rate constant for organic material in landfills of 0.365 yr^{-1}. Recently, Suflita et al. (1992) recorded cellulose biotransformations of 0.055–0.087 yr^{-1} in the New York Fresh Kills landfill. This is quite different from the assumption made in predicting settlement, where the mass of solids is assumed to be constant for the duration of the settlement process. Since biodegradation occurs mainly during the secondary compression stage, it is suggested by several researchers that it increases the rate of secondary compression (Sowers 1973; Leckie and Pacey 1979; Kurzeme and Walker 1985; Oweis and Khera 1976; Yen and Scanlon 1975; Charles and Burland 1982). Thus, if the biological processes are enhanced, the time required for stabilization will be reduced. Leckie and Pacey (1979) confirmed these findings when they investigated the effects of leachate recycle on a refuse test cell. In their analysis of landfill–settlement-rate data, Yen and Scanlon (1975) found that settlement rates were higher in landfills where conditions were favorable to decomposition than in landfills where conditions were unfavorable. However, consolidation tests done by Landva et al. (1984) show no significant difference between secondary-compression rates in older (i.e., 10–20 years and older) and more recent (still operating) fills. Also, in tests performed by Rao et al. (1977) it was found that the effects of biological decomposition did not significantly influence the rate of secondary compression. Chen (1974) developed a numerical settlement model that incorporated a first-order expression to account for biodegradation. He found the model to be insensitive to changes in the degradation rate constant between 0.012 and 0.788 yr^{-1}. The upper value is quite high and is very close to 0.693 yr^{-1}, which Hoeks (1983) associated with the rapid decomposition of food waste.

METHODOLOGY

The method used in this study consisted of preliminary data analysis, experimental design, and analysis of results. Preliminary work included researching existing techniques for describing landfill settlement and biodegradation and applying them to available data in order to more rigorously test the relationship between biological decomposition and settlement. The experimental program consisted of characterizing the refuse stream, designing and operating six landfill test cells for an extended period. The cells were uniquely designed to monitor both compression and decomposition. Analysis of the results included testing the fit of various settlement models and calculating the settlement associated with various mechanisms.

Three landfill test cells were designed to simulate a dry-vault landfill, while the other three were operated as bioreactor landfill cells. Dry-vault cells were operated in a fashion to inhibit biodegradation, while bioreactor cells were operated to encourage biodegradation. By controlling the cells in this fashion, the contribution of biological enhancement to settlement was isolated. This allowed existing settlement models to be tested with data from the actively decomposing and biologically inactive cells.

Test cells were filled in November 1991 with shredded municipal solid waste from the city of Edmonton's Strathcona transfer station. At the time of filling, two random samples were obtained to characterize the refuse. This included composition, particle size, moisture content, and volatile solids content. Waste composition for both samples consisted of on average 42% paper, 21% organics, 8.5% plastic, 3% metals, 4% textiles, and 17% fines. Using the Rosin-Rammler method (Hasselriis 1984), the characteristic particle size was 3.5 cm for samples No. 1 and 4.9 cm for sample No. 2, and slopes were 1.30 and 0.65, respectively. Refuse moisture content was 53.6% (dry weight) and volatile solids content was 68.6% of dry refuse.

Test cells were designed to perform as both lysimeters and consolidometers. This required accounting for both geotechnical- and environmental-design considerations, which frequently resulted in trade-offs having to be made between the two. A maximum cell height of 1.7 m and diameter of 0.57 m were selected due to handling and storage limitations. Decomposition monitoring required that cells be completely sealed with appropriate valves for gas and leachate handling. For settlement modeling, a dead load of approximately 200 kg was applied to each cell, which corresponded to an average overburden pressure of roughly 10 kN/m^2. This is essentially equivalent to having an additional 2–3 m layer of refuse overlying the cell. Windows were installed along the entire height of each cell to allow for visual observations of refuse to be made throughout the settlement and decomposition process. A diagram of a typical test cell can be seen in Fig. 2.

The test cell diameter of 0.57 m required the reduction of particle size of the refuse. Sowers (1973) suggests that field-scale-test cells using unprocessed refuse should have a diameter of 1–2 m. By reducing the refuse particle size to a characteristic size below 20% of the test cell diameter, smaller test cells can be used. This does, however, create concern regarding whether or not shredded waste may exhibit increased biodegradation due to the larger surface area and moisture access available for bioactivity. The shape of curves and the parameter values for settlement and degradation in the test cells will be compared with reported data from actual comparable landfills.

Bioreactor test cells (1–3) were operated under enhanced biological conditions. Temperature was maintained at 25°C, refuse was initially saturated with distilled water, and leachate recycle was performed in conjunction with buffer and sewage sludge addition. Fifty liters of water were required to bring the enhanced cells to field capacity; after which, leachate was recycled on a weekly basis. A constant volume of 4 L a week was maintained by discarding volumes in excess of 4 L and adding distilled water if there was less than 4 L. For the first half of the study Na_2CO_3 was used as a buffer. In the latter half, K_2CO_3 to avoid potentially toxic cation concentrations. A total of 195 g of Na_2CO_3 and 40 g of K_2CO_3 were added. Two-hundred milliliters of

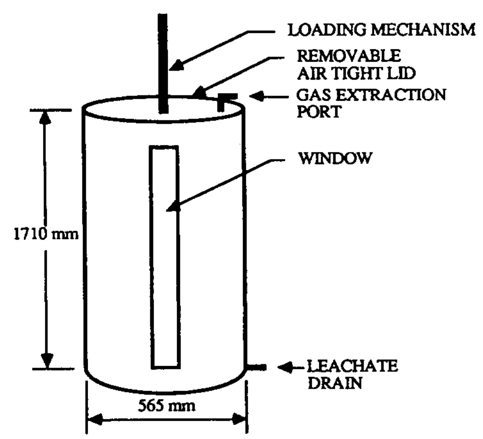

FIG. 2. Landfill Test-Cell Design

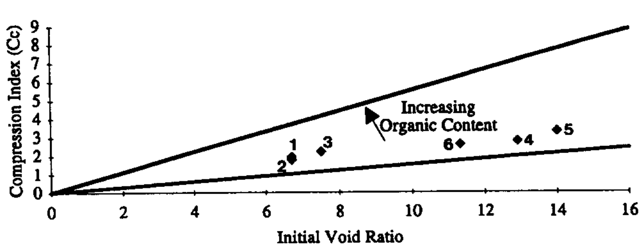

FIG. 3. Primary Compression Index Range (Sowers 1973)

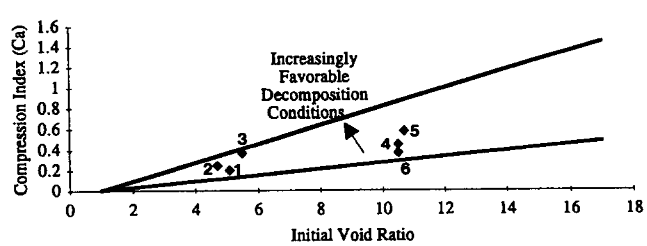

FIG. 4. Secondary Compression Index Range (Sowers 1973)

anaerobically digested sewage sludge were added to the enhanced cells during leachate recirculation. In contrast, the dry vault cells (4–6) were operated under biologically inhibiting conditions. Temperature was maintained at 4°C, and no additional moisture or microbial seed was added. All cells were monitored for gas composition (CO_2 and CH_4) and volume, leachate pH and total organic carbon, and refuse settlement. In order to calculate rate constants, first-order kinetics were used on carbon mass-balance data:

$$M_C(t) = M_C(0)\cdot e^{-kt} \tag{8}$$

Much of the total volatile solids in municipal waste is not organic nor easily degradable. The fraction of organic carbon is suggested to be 56% of the refuse (Golueke 1972). In order to obtain a more accurate estimate of degradable initial substrate mass C_0, the moisture content was determined and subtracted; thereafter the total volatile solids were determined. The initial carbon content was determined by dividing the total volatile solids by 1.8, corresponding to Golueke's (1992) estimate of 56%. The results are tested by t-tests of the differences of means between wet bioactive cells and dry vault cells, which are assumed to be normally distributed.

ANALYSIS

Initial Compression

Biological enhancement involved the addition of large volumes of water and leachate to the test cells. Refuse in enhanced cells 1–3 was brought to practical field capacity by adding water in increments of 5 L until gravity drainage occurred. The moisture addition of a total of 50 L ensured initial moisture supply and resulted in changes in the settlement process. Application of water to the refuse resulted in a settlement of approximately 30% under no additionally applied load. The addition of water was also observed to significantly affect the initial and primary settlement processes.

The parameters required for prediction of initial settlement were calculated (Table 2) and applied to (1). The lower experimental values in this study were expected due to the low initial densities achieved in the test cells. It was found that the addition of water significantly increased the amount of initial compression in the wetted cells above that in the dry cells ($t_{\text{calculated}}$ = 2.601, significant at 95% confidence interval). This is likely caused by the increase in effective stress and by the change in elasticity module due to the addition of water. Water addition was estimated to increase effective stress by 2–6 kPa, which is significant compared to the dry overburden pressure of 10 kPa. Calculated values for the modulus of elasticity are quite low when compared to values obtained from actual landfills by Moore and Pedler (1977). Their values ranged from 50 to 700 kPa depending on the refuse density.

Primary Compression

The parameters required for application of (2) were calculated from test-cell data (see Table 2). Values obtained for the modified compression index (C_{ce}) are well within the range of values obtained by other researchers. Also, calculated values for the compression index (C_c) fall within the range suggested by Sowers (1973) (see Fig. 3). This plot suggests that the landfill test cells are equivalent to an actual landfill that has a low organic content. It was found that the addition of water significantly increased the amount of primary compression that occurred ($t_{\text{calculated}}$ = 3.116, significant at 95% confidence interval).

TABLE 2. Settlement Test Results

Landfill cells (1)	Bulk density ρ_B (kg/m³) (2)	H_0 (m) (3)	Δq (kN/m²) (4)	S_{actual} (m) (5)	E_s (kN/m²) (6)	Hi (m) (7)	P_0 (kN/m²) (8)	C_{ce} (kN/m²) (9)	H_p (m) (10)	$C_{\alpha e}$ (best fit) (11)	R^2 (model) (12)
(*a*) Initial settlement [see (1)]											
Bioactive n = 3	268.1	1.01	10	0.23	43.57	—	—	—	—	—	—
Inert n = 3	225.2	1.44	10	0.28	52.23	—	—	—	—	—	—
(*b*) Primary Settlement [see (2)]											
Bioactive n = 3	—	—	8.2	0.14	—	0.78	1.8	0.25	—	—	—
Inert n = 3	—	—	8.2	0.14	—	1.17	1.8	0.21	—	—	—
(*c*) Secondary Settlement [see (3)]											
Bioactive n = 3	—	—	—	0.09[a]	—	—	—	—	0.64	0.033–0.056	0.988–0.991
Inert n = 3	—	—	—	0.04[a]	—	—	—	—	0.98	0.037–0.049	0.996

[a]Measured between t_p = 30 days and t = 219 days into test.

Secondary Compression

The secondary compression parameters for (3) were calculated with the experimental data (see Table 2). Values calculated in this study for the secondary compression ratio ($C_{\alpha e}$) are within literature ranges but are indicative of relatively high settlement rates. The linear logarithm time model used by Sowers seems to provide a remarkably good fit to the secondary settlement data collected in this experiment based on the obtained nonlinear regression coefficients (R^2) of 0.991–0.988 [see Table 2(*c*)]. Calculated values of the secondary compression index (C_{α}) are compared to values obtained by Sowers (1973) in Fig. 4. Comparisons show that the test cells in this study are equivalent to landfills with varying degrees of decomposition conditions. This appears to be indicative of actual conditions in the test cells. Enhanced reactors are generally higher in the favorable range, while inhibited cells are generally in the lower range. Reactor No. 3, the most biologically active test cell, is near the upper limit for favorable decomposition conditions. It was found that neither the addition of water or biological enhancement had a significant effect on the amount or rate of secondary compression ($t_{\text{calculated}}$ = 0.332, nonsignificant at 95% confidence interval) (see Table 3).

Decomposition Results

Leachate total organic carbon (TOC) concentrations decreased from initial values of 19,000–25,000 mg/L to 18,000–20,000 mg/L after 225 days. Initially, pH was between 4.0 and 4.7; the values rose to between 5.8 and 6.6 with the addition of buffer. After buffer addition was discontinued, pH settled at a constant range of 5.6–5.9. Simultaneously, cumulative gas volumes increased to over 800 L/cell, whereby over 25% was methane in the most active cell. The production rate at the end of the period for the most active cell was 130-L gas per month. Two cells, however, were still in the anaerobic nonmethanogenic phase and, hence, showed slightly slower decomposition.

Effect of Biological Enhancement

In the first period of secondary settlement, the slow process of solubilization through biodegradation appears to have little effect on secondary settlement rates. As previously discussed, biodegradation results in a net loss of solid organic matter. Once solubilized and removed from the system, settlement of corresponding magnitude theoretically should occur. To determine whether an effect of solids removal on settlement is probable, the percentage of carbon decomposed to date and estimated five-year predictions were compared to present and future secondary

TABLE 3. Compression due to Settlement Mechanisms (Expressed as Percentage of Each Respective Initial Height at Beginning of Settlement Stage)

Parameter (1)	Cell 1 (2)	Cell 2 (3)	Cell 3 (4)
Initial waste mass (kg)	103.3	105.2	95.5
Refuse solids (kg)	67.3	68.6	62.2
Total volatile solids (kg)	46.2	47.1	42.7
Initial organic carbon mass C_0 (kg)	25.7[a]	26.2[a]	23.7[a]
Carbon mass lost (kg)	0.600	0.504	0.68
Time *t* (days)	222	225	229
First-order rate constant·*k* (yr^{-1})	0.0383	0.0312	0.0478

[a]Calculated by dividing total volatile solids by 1.8 (Golueke 1972).

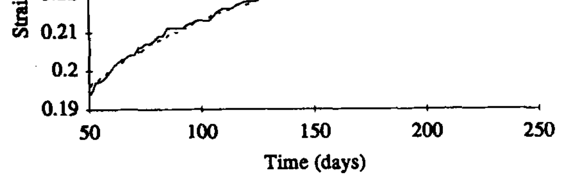

FIG. 5. Comparison of Measured and Predicted Landfill Strain versus Time (Continuously Collected Data) (—— = Actual; - - - = Predicted)

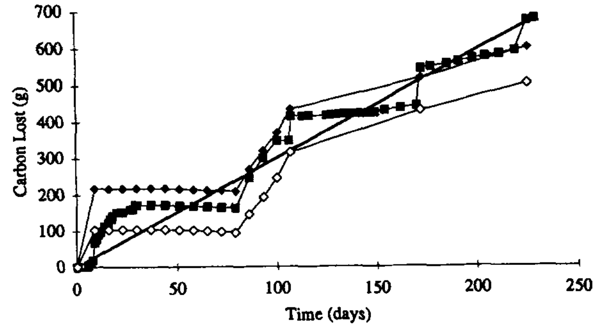

FIG. 6. Comparison of Measured and Predicted Carbon Loss (—■— = Cell 3 Data; —— = First-Order Model; —♦— = Cell 1 Data; —◇— Cell 2 Data)

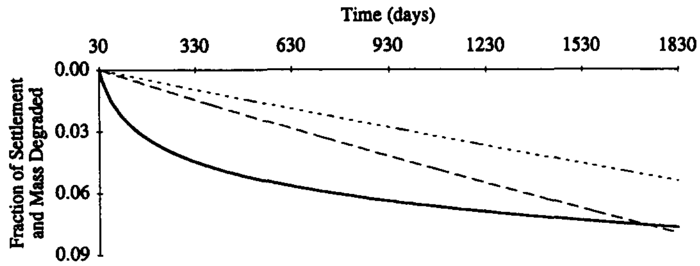

FIG. 7. Comparison of First-Order Decomposition and Secondary Settlement (—— = Secondary Settlement; – – – = First-Order Decomposition—Minimum; — — = First-Order Decomposition—Maximum)

settlements and rates. First-order decomposition rate constants based on the initial carbon mass ranged from 0.0312 to 0.0478 yr^{-1} (equivalent to half-lives of 15–22 years) (see Table 3).

The total mass of solids decomposed to date accounts for a small fraction of the total solids (approximately 1%). Secondary settlement for this period accounts for a deformation of approximately 4%. Although these numbers are of the same order of magnitude, a comparison between inhibited and enhanced reactors revealed that decomposition does not have a significant effect on the rate of secondary settlement. At this time, the contribution of decomposition to settlement may be masked by either bridging between refuse particles or the creation of a skeleton of large objects or both.

Decomposition and settlement data obtained from the test cells were compared to available models. Decomposition was found to be adequately represented by a first-order kinetic model. Secondary settlement, as previously discussed, was found to be linear with the logarithm of time and could be represented well by (3). Comparisons of settlement and decomposition data to their respective models can be seen in Figs. 5 and 6. Carbon loss in the reactors was found to be primarily associated with the reduction in organic concentration in the leachate. Therefore, in the short term, test cell operation influenced the shape of the carbon-loss curve. However over longer periods, these effects becomes less pronounced and the actual degradation kinetics are observed.

Five-year future predictions can be derived from settlement and biodegradation models. By using the first-order model and the measured rate constants (Table 3) between 0.0312/yr and 0.0478/yr, the organic carbon mass lost in five years amounts to

$$C_0 - C_t = C_0 - C_0 \cdot e^{-k \cdot t} = 25 \text{ kg } (1 - e^{k \cdot 5\text{yr}}) \tag{9}$$

which indicates that 5.5–8.0% of the total refuse solids mass (of roughly 66 kgs) will decompose (see Fig. 7). From Fig. 7, it can be seen that settlement occurs initially at a faster rate than decomposition but then slows considerably. This predicts that decomposition will become increasingly significant over time. Predicted secondary settlement, using measured C_{ae} values and (3), amounts to 8% of height after the first 225 days. Extrapolating this compression data over a 25-year design life predicts that a secondary settlement of 5–11 cm would occur in the test cells.

CONCLUSION

By comparing three bioactive with three inert cells, settlement of refuse under an applied load was observed. Prior to load application, the addition of water to refuse field capacity resulted in an average immediate settlement of 30%. The moisture addition caused changes in the refuse, which significantly increased the magnitudes of initial and primary settlement that subsequently occurred. Initial compression was observed to take place immediately upon load application and accounted for a 26% and 17% decrease in the initial refuse height for enhanced and inhibited test cells, respectively. Primary compression occurred within the first 30 days and resulted in a further refuse compression of 15% in enhanced cells and 12% in inhibited cells. Experimentally determined values for the primary-compression index were within expected ranges for full-scale landfills. Contrary to initial and primary settlement, secondary compression was not significantly increased by the addition of water. In the first stage (225 days) of this study, secondary settlement accounted for an additional compression of 4% in the biologically enhanced test cells and 2% in the inhibited cells. Settlement during this time period was observed to be linear with respect to the logarithm of time and exhibited typical landfill values for the secondary-compression index. Judging from the similarities in shape between full-scale landfill settlement curves and curves for the test cells, the same mechanisms are likely responsible for settlement. This is also demonstrated by the fact that calculated settlement parameters from the test cells resemble values observed in actual landfills. The close resemblance of experimental behavior to full-scale observations suggests that test cells can effectively model actual landfill behavior.

The effects of biodegradation were not observed to significantly influence the magnitude or rate of secondary settlement in 225 days. First-order rate constants derived from the mass of carbon decomposed during this time period ranged from 0.0312 to 0.0478 yr^{-1}, corresponding to refuse half-lives of 15–22 years. When compared to literature values, these ranges are typical for moderately degradable materials under actual landfill conditions but seem low for enhanced bioreactors. Predicted decomposition and settlement rates indicate decreases in total refuse solids and height in the order of 5–10% over five years. This suggests that the contribution of decomposition to settlement will become significant in time (see Fig. 7). Since the carbon mass loss is relatively low, a skeleton may have evolved so that settlement continues as though carbon loss were not occurring. However, over time, crucial areas of the skeleton components are predicted to suffer decay to the point where further, accelerated settlement may occur. Thus, ensuing settlement patterns are expected to show increases as skeleton elements give way.

Further research is presently being conducted to verify if decomposition and settlement will continue to proceed as extrapolated results indicate. These sustained studies over extended periods will be capable of evaluating, in the long term, the link between secondary compression and refuse decomposition.

While in the short term, biodegradation does not influence secondary settlement, the increase in degradation rates in the longer term has important ramifications. Enhancing initial settlement with the addition of water can significantly increase the capacity of the landfill and improve the use of scarce landfill volume. In a rural setting, the application of the biodigester concept with addition of moisture and recirculation of leachate can lead to a design that is suitable for use in small rural landfills, where the cost for a full sophisticated design might be prohibitive. While the leachate collection and liner systems are still required, special treatment plants for the leachate before discharge or hauling to sewage treatment plants may be avoided if the leachate can be recirculated and treated in the landfill. The landfill is simply operated as an anaerobic digester that treats leachate and degrades the solid waste while conserving the liquid mass.

The more fundamental applications of the biodigester concept would be to diminish the overall environmental risks and impacts of landfills by actively stabilizing the easily and moderately degradable fractions of the waste stream while liner and leachate collection systems are in their best (newest) conditions during the first five–ten years of a new landfill's life. Thereafter, when the risk of liner failures may increase, smaller fractions of degradable materials remain. In contrast, a dry vault landfill will keep the waste intact. When leakage occurs the virtually full amount of degradable waste is susceptible to degradation and leachate and gas generation. In order to minimize the net risks, the biodigester design may be more suitable, particularly in areas where moderate to heavy precipitation is common and, hence, liner failures result in leachate generation. Further research and evaluation of the key issues are necessary and are progressing.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_α = secondary compression index;
$C_{\alpha e}$ = rate of secondary compression = $C_\alpha/(1 + e_p)$;
C_c = primary compression index;
C_{ce} = modified primary compression index = $C_c/(1 + e_0)$;
E_s = modulus of elasticity (kN/m^2);
e_0 = void ratio after initial compression;
e_p = void ratio after primary compression;
H_i = height of refuse after initial compression;
H_0 = initial height of refuse (m);
H_p = height of refuse after primary compression (m);
k = first-order rate constant;
M_c = carbon mass in waste;
p_0 = existing overburden pressure at midlevel of layer;
S_i = settlement due to initial compression (m);
S_p = settlement due to primary compression;
S_s = settlement due to secondary compression (m);
s = degree of saturation;
t = time (days);

t_p = time for primary compression to occur (usually 30 days);
V_s = volume of solids;
V_v = volume of voids;
W_p = refuse waster content after primary compression;
Δp = increment of overburden pressure at midlevel of layer;
Δq = stress increase in stratum (kN/m^2);
ρ_s = density of refuse solids; and
ρ_w = density of water.