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Modified Model for Municipal Solid Waste in Simulated Controlled Sanitary and Bioreactor Landfills

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Abstract: The degradation of Municipal Solid Waste (MSW) over time and associated settlement is of special importance when estimating additional space, designing temporary and final closure covers of landfills as well as planning vertical expansion of existing facilities. Most settlement models applied to solid waste were developed for inorganic soils or peat. Furthermore, these models were not developed considering all the factors effect on settlement, furthermore they applied to simulate the conventional landfills only. In case of bioreactor landfills, waste settlement will include creep as well as biological components due to the accelerated degradability of waste particles as leachate is recycled. The objective of this study is to present a settlement prediction model which accounts for changes in material characteristics as a function of the waste degradation rate. As biodegradation takes place, the organic solid mass is redused and the void ratio increases with a subsequent increase in waste settlement. In general, published settlement models do not capture these phenomena. The model developed herein is based on the results of an experimental result. Settlement components including primary, creep and biodegradation effects are identified as a function of the state of decomposition. One-dimensional oedometer tests (50 mm cell) was performed on shredded refuse in pilot-scale reactors for measurement of compression indices representing primary (C_c^*), creep (C_α) and biological (C_β) on samples ranging from fresh to well-decomposed refuse. The time factors, t_1, t_2 and t_3 for the compressibility were determined from the long term settlement curve and utilized for model development. The proposed model was verified using the settlement model parameters obtained from laboratory test and comparing predicted settlement with observed field settlement from sanitary and bioreactor simulators landfills.

Key words: MSW, vertical, inorganicsoils, biological, biodegradation, bioreactor and fills

INTRODUCTION

Landfilling is one of the most a common , economic and feasible means of disposing Municipal Solid Waste (MSW), ranging in it is occupation from several to hundreds of acres (Ling *et al*., 1998). Efficient use of landfill space becomes more significant in the context of urban regions of developing countries where a lack of land space limits the possibility of any new development (Grisolia, 1996). Even though the closed landfill is considered a viable site of land utilization, the performance of any structure built on a landfill will depend to a great extent on the ability to predict the anticipated settlement. Moreover, prediction of settlement contributes to the determination of the useful lifespan of the landfill and assists in the design of its components such as cover and liner systems (El-Fadel and Khoury, 2000).

Traditional soil mechanic models: MSW settles under its own weight and external loads are placed on the landfill. External loads include daily soil cover, additional waste layers, final cover and facilities such as buildings and roads such settlement lasts very long period of time (Zhang and Wang, 2008; Babu *et al*., 2009).

Settlement of MSW is known to be a function of many factors such as the material, density achieved after compaction of the landfill, the thickness of the cover, MSW composition like moisture and volatiles, climate, self-weight, overburden, method of filling and mode of operation, etc., (Wall and Zeiss, 1995; Bareither *et al*., 2011).

Most landfill settlement models were developed for inorganic soils or peat. Sowers adopted a conventional soil mechanics approach to predict waste settlement. That

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is the total settlement is determined as the sum of primary and secondary consolidation settlements. From a limited number of data, Sowers showed that the primary and secondary compression indexes, C_c and C_a may be correlated to the initial void ratio, e_0 where $C_c = 0.15\text{-}0.55\ e_0$ and $C_a = 0.03\text{-}0.09\ e_0$. These correlations were however, based on measurements up to 15 month. Morris and Woods and Fassett *et al*. provided additional insights into the use of consolidation theory. The soil mechanics approach as discussed before requires precise determination of waste parameters. Uncertainty associated with material properties renders this approach less attractive for wastes when compared to soils. It is difficult to identify the magnitude of primary consolidation settlement as well as the time taken. Since, the wastes exhibit a highly compressible skeleton, primary and secondary consolidations occur simultaneously.

Furthermore, these models were developed considering the traditional operation of landfill where leachate resulting from degradation process was drown out the entire system (Edil *et al*., 1990).

Bjarngard and Edgers (1990) applied the same Sowers model with significant modification by subdividing secondary compression into two sub phases. On the other site empirical models were studied extensively to find the suitable model that should be applied in conventional landfills (McDonald, 2018).

In this study, the reasons for the simulation errors of the traditional models are revealed; based on soil mechanics based model, a new time model for total settlement process is proposed. At the same time, the new model may be useful to the design and reutilization of the MSW landfills in both sanitary and bioreactor landfills.

Modified model theory: The proposed model is a adaptation of a soil mechanics model with an important modification based on.

Changing in the densities of multi landfill stratums which produced differed stresses at the mid depth of each layer changing the primary compression and secondary compression indices of waste with time by taking into account the degree of decomposition and change of moisture content on the mentioned indices.

The model proposed consists of three elements at which the settlement component can be generally evaluated and represented by Eq. 1:

$$\varepsilon_t = \left(\varepsilon_p + \varepsilon_c + \varepsilon_b\right) \tag{1}$$

Where:

ε_t = Total strain

ε_p = Strain due to applied stress

ε_p can be determined using the formulation provided by Burlingame cited in (DeAbreu, 2003), the first element represented the change in the stiffness of waste in relation to the change of density and moisture content associated with the degree of degradation and this is reflected by the change modified coefficient of compression (C_c^*) which represents the relationship between stress and strain, that change does not stop after a period of time but continues as logarithmic function of time. Equation 2 for each layer of waste ε_p calculated from Eq. 3:

$$C_c = C_c^* * \log\left(\frac{t_3}{t_1}\right) \tag{2}$$

$$\varepsilon_p = C_c^* * \log\frac{(1/2)\gamma_i * H_i + \sum_{j=i+1}^{n}\left(\gamma_j H_j\right)}{\left((1/2)\gamma_i * H_i\right)} \log\left(\frac{t_3}{t_1}\right) \tag{3}$$

Where:

C_c = Compression index

C_c^* = Modified compression index

n = Number of layer

H_i = Initial thickness of layer i

γ = Unit weight of layer i

t_1 = Time for immediate compression completed

t_3 = Analysis time

At the early stages of decomposition, the strain can be instantaneous and dependent on the degree of saturation. The creep strain (ε_c) can be evaluated as equal to Eq. 4:

$$\varepsilon(t)_c = C_{cr} \log\left(\frac{t_2}{t_1}\right) \tag{4}$$

Where:

C_{cr} = Creep compression index

t_2 = Time duration for which "creep" compression is to be evaluated

As the moisture content increases and the growth of microorganisms increases, the deformation moves to the next stage where it is ruled by the decomposition phase. The organisms are fully functional where biodegradable waste mass are rapidly dehydrated, separated, fermented and metabolized into their final compounds such as methane, carbon dioxide and soluble compounds. This "biological" strain component can be represented as Eq. 5:

$$\varepsilon(t)_b = C_\beta \log\left(\frac{t_3}{t_2}\right) \tag{5}$$

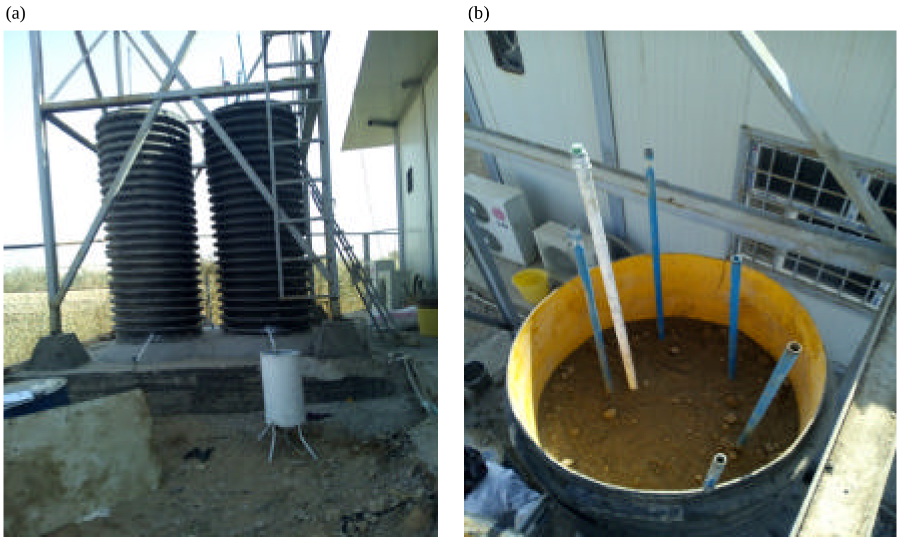

Fig. 1: a, b) Pilot scale lysimeters construction and filling

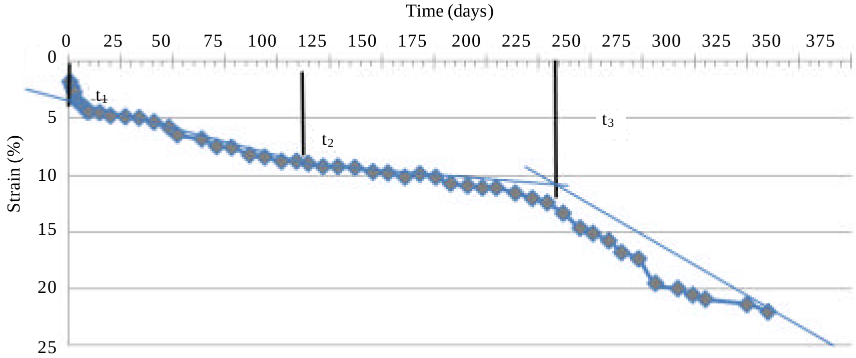

Fig. 2: Long term settlement for sanitary landfill lysimeter

where, C_β is biological compression index. In addition to compressibility parameters. The time factors in this model are t_1, t_2 and t_3. These will be evaluated from a pilot scale lysimeters total settlement curves. Linearization of the three sections of the settlement curve as proposed by Fei and Zekkos (2012) was used, a straight line is fitted to each section of the curve. Intersection points of the three straight lines are defined as t_2 and t_3 in Fig. 1 and 2 for sanitary and bioreactor landfills, respectively. The model will be verified based on bioreactor and sanitary landfills data. Finally, the settlement model can be presented by Eq. 6:

$$\varepsilon_t = C_c^* * \log\frac{(1/2)\gamma_i * H_i + \sum_{j=i+1}^{n}\left(\gamma_j H_j\right)}{\left((1/2)\gamma_i * H_i\right)}\log\left(\frac{t_3}{t_1}\right) + C_{cr}\log\left(\frac{t_2}{t_1}\right) + C_\beta\log\left(\frac{t_3}{t_2}\right) \quad (6)$$

MATERIALS AND METHODS

Pilot scale lysimeters: Two Pilot Lysimeters (PL) were constructed in the back yard of College of Engineering, University of Al Qadessiya to simulate two types of landfill, one for simulation sanitary landfill (PLS) where the other for simulation bioreactor landfill with leachate recirculation (PLB). Both pilot lysimeters were made of thick multi layer High Density Polyethylene (HDPE) having a cylindrical shape with diameter of (100 cm) and height of (3 m) with a total volume of (2.35 m^3), standing on constructed (4*4 m) concrete base with (1 m) height above ground level, the concrete base was necessary for leachate collection as shown in Fig. 1. The waste mass introduced into the pilot lysimeter was divided into five layers, separated by settlement plates to monitor settlement and volume deformation at each layer. All lysimeters were provided with five side ports one in each layer for sampling.

Table 1: Details of pilot scale lysimeters filling

Filling date 6/11/2017	Pilot scale lysimeter									
Substrate (%)	Food	Paper	Plastic		Metal	Glass	Textile		Other	Total
	61	4.3	5.8		5.5	3.1	2.3		18	100
	Operation mechanism									
Filling of system	Sanitary					Bioreactor				
No. of layer	1	2	3	4	5	1	2	3	4	5
Height (m)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Quantity (kg)	178	193	202	181	179	177	173	180	200	208
Density (kg/m^3)	505	546	573	512	508	500	490	510	567	588
Cover	Sanitary						Bioreactor			
Component	Sand			Clay			Sand			Clay
Height (m)	0.05			0.1			0.05			0.1
Quantity (kg)	62			168			64			166
Density (kg/m^3)	1600			2140			1641			2128
Liner	Sanitary						Bioreactor			
Component	Gravel			Clay			Gravel			Clay
Height (m)	0.1			0.25			0.1			0.25

Table 1 shows the physical composition of MSW used in filling the pilot lysimetrs, liner, cover and principal of operation. Layers of compacted, gravel and geotextile sheet were provided at the bottom of lysimeter to prevent a clogging at the outlet by of suspended solids while sand and compacted clay was applied at the top of lysimeters for regular distribution of rainfall and/or leachate recirculated and for protecting the outdoor environment from lysimeter effects such as odour or other pathogen effects.

In the PLS simulator landfill the generated leachate was drained out of the system through a draining pipe contracted at the bottom of it. While leachate generated from PLB simulator landfill was used recirculation through sprinkler constructed at the top of it. The long term effects of leachate drained or recirculation on settlement and volume deformation was performed.

Sample preparation: Refuse samples representing various stages of decomposition were extracted from two pilot-scale lysimeters. The refuse was sampled in Initial adjustment phase (lag phase), acid phase and the accelerated methane production phase as follow.

About 500 g of MSW samples were drawn from the sampling holes (openings) on the pilot lysimeters side wall. Samples were kept in covered plastic container to be transferred later to the laboratory. After that samples were shredded to the desired size, particles of length equal to no more than half the diameter of oedometer test cell were using high quality grinder (Ririhong Hi-speed multifunctional grinder).

Moisture content and organic content: Moisture content was determined in accordance with the standard procedure ASTM D2216, using Eq. 7 but the samples were dried at a lower constant temperature of 60°C (to avoid possible burning of any organic constituents) until the mass remained constant Eq. 7:

$$w\% = \frac{w_w - w_d}{w_w} * 100 \tag{7}$$

Where:

w_w = Wet weight of sample (g)
w_d = Dry weight of sample (g)
w = Water content

The organic content which is a representation of volatile solids in the synthetic MSW was measured as per ASTM D2974 (heated at 750°C for 2 h to achieve constant mass). Degree of Decomposition (DOD) was calculated using Eq. 8 depending on organic content, to express the extent of biodegradation (Andersland *et al.*, 1981) Eq. 8:

$$DOD = \left(1 - \frac{x_f}{x_i}\right) * \left(\frac{1}{1 - x_f}\right) * 100 \tag{8}$$

Where:

DOD = Degree of Decomposition
x_i = initial organic fraction
x_f = Organic fraction after partial decomposition

Compressibility test: Confined compressibility testing was carried out in an oedometer to determine compressibility characteristics of samples in different stage of decomposition. Shredded specimens were compacted directly into a 50 mm diameter by 20 mm height circular stainless steel ring with a dowel. Tests were performed in conformance with ASTM Test Method (D2435-90). The compacted samples had initial density of 530 kg/m^3. The testing procedure involved subjecting the specimen to a constant vertical stress of 50 kPa. Subsequently, the vertical stress was increased to 100, 200, 400 and 800 kPa and compression was monitored for 24 h. Based on the total compression under each normal stress, axial strain versus normal pressure was plotted and primary compression ratio was calculated. Long term

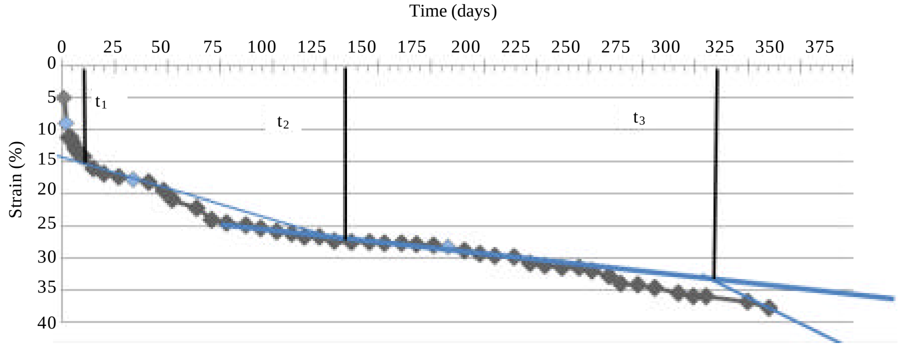

Fig. 3: Long term settlement for bioreactor landfill

compressibility was tested for the second phase sample by following the same procedure until 400 kPa pressure had been reached, vertical pressure was maintained constant and compression was measured with time for 15 days to provide adequate data to assess secondary compression behaviour. Modified compression index C_c^* and modified secondary compression indices C_{cr} and $C_{\hat{a}}$ were calculated.

Model parameters: The two important sets of parameters were required for the settlement model: the first is the compressibility parameters (primary, creep and biological) and the second is the critical time factor (t_1, t_2 and t_3) that define the change of degradation state.

The time factor required for the model was determined from pilot scale lysimeters total settlement curves. Linearization of the three sections of the settlement curve as proposed by Fei and Zekkos (2012), a straight line is fitted to each section of the curve. Intersection points of the three straight lines are defined as t_1, t_2 and t_3 in Fig. 2 and 3 for sanitary and bioreactor landfills, respectively.

Time factor for completion of initial compression, t_1: Initial compression takes place immediately once the load is applied. The settlement monitoring results showed the initial compression time it takes (7-10 days) in both sanitary and bioreactor simulated landfills

Time factor for creep compression, t_2: After completion of immediate compression, settlement continues due to time dependent physical mechanisms such as particle reorientation and movement, ravelling, delayed compression of deformable particles as a result of stress distribution and potential softening of waste constituents due to the introduction of moisture in the waste mass (Bareither *et al*., 2011). It takes (120-135) days in both sanitary and bioreactor simulated landfills.

Time factor for biological compression, t_3: Continual presence of moisture, MSW settlement continues, the active biodegradation phase occurs when most microbial species reach their maximum growth rates and thus, a strong microbial community has been established (Bareither *et al*., 2011). t_3 estimated to be continuing to the end of experiment time.

RESULTS AND DISCUSSION

Water content and degree of decomposition: The water content and degree of decomposition for fresh, first phase, second phase and third phase of sampled refuse presented in Table 2.

From Table 2 it can be noted that the moisture content in PLS decrease with time, opposing with PLB where the moisture content increase with time. While DOD in both simulator was increased with time. The DOD was much higher than those in PLS for the same phases. However, leachate recirculation seems to improve both of DOD and water content in PLB simulator lysimeter. From this standpoint, increase water content can be considered as indicator for enhancing the degree of decomposition.

Compression parameters: The compressibility parameters obtained from oedometer test are presented in Table 3. As seen, the value of primary compression index C_C^* were calculated at different stage of decomposition for sanitary and bioreactor landfills during different times of operation whil evalues for secondary compression index was calculated at an intermediate time of operation when the 't' value is 120 day to study the biodegradation effects more clearly. Values of modified primary compression indices C_C^* for sanitary landfill samples were similar to the trend bioreactor landfill samples, both increases with time. Generally, the reported modified primary compression indices C_C^* lie in the range of 0.15-0.3 and are much close with the C_C^* values range of 0.17-0.36 reported by

Table 2: Water content and degree of decomposition of waste at different phases

Day of sampling	Phases	Principle of operation	Water content (%)	Loss of ignition (%)	Degree of decomposition (%)
1	Fresh	Sanitary	68	72	0
		Bioreactor	66	74	0
34	First phase	Sanitary	66	71	5
		Bioreactor	62	73.2	4
120	Second phase	Sanitary	53	58	46
		Bioreactor	61	55	57
240	Third phase	Sanitary	32	44	69
		Bioreactor	67	36	80

Table 3: Values of primary and secondary modified compression indecies

Day of sampling	phases	Principle of operation	C_C^*	C_{cr}	C_β
1	Fresh	Sanitary	0.15	-	-
		Bioreactor	0.16	-	-
34	First phase,	Sanitary	0.18	-	-
		Bioreactor	0.21	-	-
120	Second phase	Sanitary	0.20	0.033	0.07
		Bioreactor	0.23	0.035	0.11
240	Third phase	Sanitary	0.24	-	-
		Bioreactor	0.30	-	-

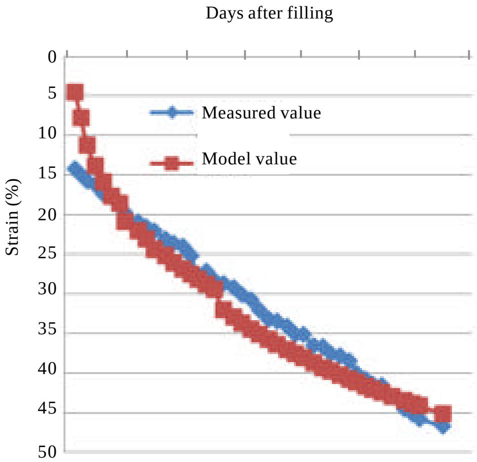

Fig. 4: Measured and model value for layer 1 in bioreactor landfill

Qian *et al*. (2002). In this study, the value of compressibility indices for bioreactor landfill were slightly higher than those of sanitary landfill with a general trend of increasing compressibility indices with increase in degradation. The more thoroughly decomposed samples (higher DOD) had a weakened structural matrix, leading to an increase in initial settlement under the same applied stress. Overall these findings are in accordance with findings reported by Hossain and Gabr (2005), Reddy *et al*. (2015) and Wall and Zeiss (1995) but contradicts the correlation found by Reddy *et al*. (2011) for synthetic MSW which showed decreasing compression ratio with increase in degradation. There are wide range in the published values of these parameters, this wide range is could be attributed to the large variations in compositions of wastes involved, the various ages of the landfills and the stresses to which wastes have been subjected. In general, the results of this study are comparable with other published values (Fig. 4-8).

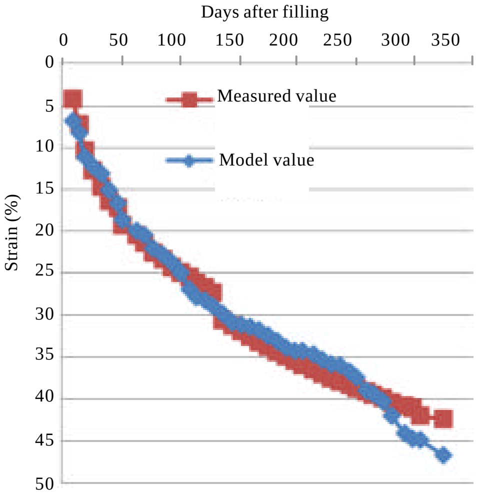

Fig. 5: Measured and model value for layer 2 in bioreactor landfill

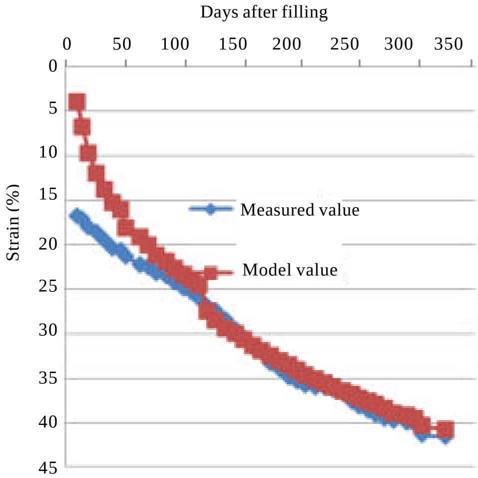

Fig. 6: Measured and model value for layer 1 in sanitary landfill

Model validation and result of model prediction: The developed model validation is an important part of the model development process. Utilizing the model, the predicted MSW settlement was compared with the observed field settlement from different layers in pilot sanitary and bioreactor landfills. The settlement data have

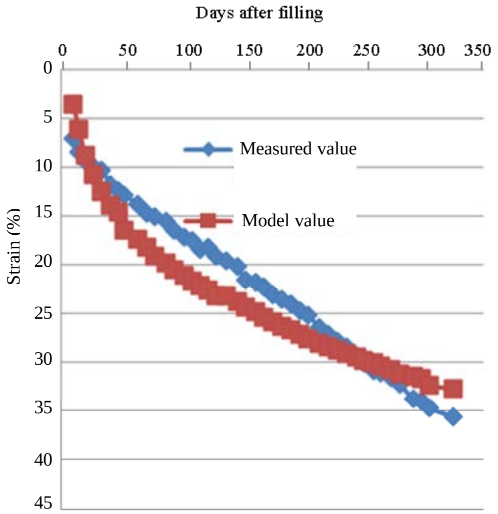

Fig. 7: Measured and model value for layer 2 in sanitary landfill

been collected from monitoring settlement in sanitary and bioreactor lysimeters during 335 day. The model parameter t_1 and t_2 in sanitary landfill had been taken as 7 and 120 days, respectively, while in bioreactor landfill their values were 10 and 135 day. Using these time factors and compressibility parameters obtained from experimental results, the computed settlement had been compared with the observed settlement data in Fig. 4-8 for bioreactor and sanitary landfills layers, respectively. The predicted results matched quite well with the measured field data. With a very good agreement between the measured and model data, coefficient of correlation close to 1.0.

CONCLUSION

Most settlement models were applied to solid waste developed for inorganic soils or peat. It is important to mentioned that these models were not developed considering the all the factors effect on settlement. Besides these model were conducted the settlement in conventional landfill only (sanitary landfills). In case of bioreactor landfills, waste settlement will include creep as well as the biological components due to the accelerated degradability of waste as leachate is recycled. A settlement model was developed to incorporate the changes in waste properties that take place during the decomposition of the waste matrix. Work in this study was utilized data from laboratory oedometer tests to illustrate compressibility parameters for refuse at different degrees of decomposition and to define the time factors required for modelling. Based on the experimental results in this study it can be concluded that:

Primary compression ratio values varied from 0.15-0.3 and found to be within the range of previous published studies. The primary compression ratio shows a slightly increasing trend with degree of degradation and moisture content which needs further investigation by testing the samples with the same composition in a large-scale setup.

The Creep index (C_{rc}) had been estimated as 0.03 for both sanitary and bioreactor landfill samples. The magnitude of the biological indices was yielded the highest values (C_β = 0.11) in bioreactor landfill were samples actively decomposing. For the model prediction, C_{rc} and C_β have been taken as 0.03 and 0.07 for sanitary landfill and 0.03 and 0.07 for bioreactor landfill, respectively.

The time factors (t_1, t_2, and t_3) vary depend on the mode of operation. Time factor t_2 is the time when accelerated creep settlement. The time factor t_2 as observed in most of the field studies can be considered as between 120 and 135 days. More work is needed to define the time factors, especially consideration for time factor t_2.

The settlement prediction matches well with the settlement measured data, the model settlement prediction considers all the aspects of biological decomposition, creep and matrix stiffness change as decomposition takes place with time.

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