J. Inst. Eng. India Ser. A (September 2020) 101(3):455–462
https://doi.org/10.1007/s40030-020-00456-2

ORIGINAL CONTRIBUTION

Laboratory Analysis and Prediction of Settlement of Municipal Solid Waste Under Anaerobic Condition

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Received: 13 December 2019 / Accepted: 8 July 2020 / Published online: 15 July 2020

Abstract The settlement of municipal solid waste under anaerobic condition is considered important for structural stability even after closure of the landfill. In this context, the settlement of waste was analyzed under constant loading in the anaerobic reactor. A settlement value of 29.9% was observed in the reactor immediately after load placement on the sample. Consolidation analysis of the collected municipal solid waste showed that the primary settlement of the waste completed after 48 h of load application. The total secondary settlement was observed to be 5.85% at the end of 202 days. From the results obtained for the biogas generation and settlement, the rate of degradation of waste was observed to be 0.477 day^{-1}. The settlement of landfill depends upon composition, moisture content, depth, density and compression characteristics of waste. The municipal solid waste thus needs analysis of biodegradation rate and also a mathematical model to predict the settlement. Thus, the mathematical modeling of predicting the settlement of landfill showed that initially the rate of settlement of the waste was high due to high degradation rate of organic contents. The settlement of 6.4% due to biodegradation and 10–18% was predicted due to mechanical compression in the landfill.

Keywords Municipal solid waste · Biodegradation · Compression · Landfill · Settlement · Anaerobic digestion

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Introduction

Waste disposal in landfill is the most common method adopted in both developing and developed countries and is still considered as cheapest and preferred means of disposing of waste. The continuous disposal of municipal solid waste leads to pollution, resulting in the landfill settlement. The municipal solid waste landfill requires additional consideration for analyzing the leachate generation, landfill gas emission, settlement and stability, depending upon the characteristics and properties of waste. However, the biodegradation and settlement rates of MSW are affected by moisture content and temperature because of the presence of micro-organisms in waste [1]. The degradation of waste changes the properties of municipal solid waste, and these changes are often used for assessing the geotechnical stability and other associated failures of the landfill [2]. The settlement of municipal solid waste (MSW) is due to high compressibility occurring under the influence of biodegradation of organic content and overburden load [3, 4]. The settlement of MSW that occurs due to fresh and degraded waste is required to be differentiated for predicting the long-term settlement [4–6]. The long-term settlement of the landfill is different for an old landfill and fresh landfill depending upon the fill age [7]. The waste dumped in the fresh landfill site decomposes due to the presence of significant amount of organic matter, thus causing considerable amount of settlement, whereas in older landfills, the presence of organic matters is almost negligible. However, in principle, the prediction of settlement is complex because of the heterogeneous nature of MSW, moisture content, variable density, unit weight, compression characteristics. The composition of MSW affects the void ratio, water content, unit weight and compressibility of the waste and is an important parameter for analyzing the landfill performance [8, 9]. Moisture content significantly affects the biodegradation process facilitating movement of microbes. The unit weight of MSW varies with depth having important consideration in engineering analysis [10] and for estimation of settlement of landfill [11, 12]. The settlement of MSW, however, occurs over a long period of time which can be up to 30–50% of the initial height of the waste and contributes to different settlements rates [7].

However, the settlement in landfill is due to (1) mechanical processes; (2) chemical processes; (3) dissolution processes; and (4) biological degradation of the waste [13, 14]. Settlement of the landfill causes immediate compression that occurs due to an external load applied or acting of self-weight. Primary compression of waste is due to expulsion of water and gas from voids occurring due to the overlying weight at particular point [15, 16]. However, the settlement of waste is due to biodegradation of organic waste which continues for many years. The degradation process of MSW is time-dependent process which alters the properties of the MSW during this process. The estimation of settlement due to biodegradation involves the determination using a suitable mathematical model. Different methods have been proposed to predict settlement of MSW landfill by many researchers [5, 6, 11, 17]. The anaerobic degradation of organic matters results in biodegradation settlement of MSW and methanogenesis of waste in the landfill. The estimation of settlement due to biodegradation involves the determination using mathematical approach and laboratory analysis depending upon the degradation conditions and also having important consideration for sustainable management of landfill. The settlement of waste after post-closure causes large settlement in landfill which leads to undue maintenance problems, crack development and failures in cover system.

In this context, to estimate the rate and magnitude of settlement over a period of time due to mechanical compression and biodegradation of MSW, a laboratory setup was developed. The effect of both degradation and physical processes was monitored to determine the settlement. The prediction of settlement was done using mathematical model proposed by Chakma and Mathur [12]. The moisture content, pH and compression characteristics of waste were evaluated using consolidation testing of MSW, and settlement is predicted using these parameters. The mechanical compression of MSW was determined with variation in density of MSW. However, the results from empirical methods are to be compared with laboratory analysis; thus, a laboratory setup is prepared for comparison of analysis. However, in the study area, waste is dumped in open land but requires the analysis of settlement of waste because of increasing waste generation with rapid industrialization, urbanization and population growth.

MSW Sample Collection and Characterization

The fresh waste samples (approximately 2 weeks old) were collected from the dump site. The collection of samples from the dump site was done as per guidelines of ASTM-D-5231-92 [18]. The MSW samples were collected from vehicles unloading waste from residential, commercial and institutional sectors at the dump site. The sampling was done randomly for 10 days ($n = 10$) for each season to obtain a representative sample using the quartile method. The waste collection was done on a plastic sheet while unloading trucks to avoid mixing of soil and dust particles [19]. The collected samples were determined for physico-chemical characterization.

Compression Reactor Setup and Operational Procedure

A reactor of dimension (600 × 600 × 400) mm was prepared using perspex sheet attached to the load delivery system to apply the constant surcharge load on waste. The load was applied through a system comprised of hydraulic jack 65 mm diameter which was connected to the perforated plate to evenly distribute the load on waste sample (Fig. 1). The perforations were made in the plate to allow the leachate to pass through the waste. The bulk unit of landfill was approximately 7.15 kN/m^3; load corresponding to 10 m of the overburden of waste can be simulated in reactor [16].

A 15-cm-thick gravel (max. particle size 20 mm) and tire derived aggregate (TDA) drainage layer (longest dimension 20–25 mm) was placed on the bottom of the reactor. The drainage layer was overlain by polypropylene geotextile filter layer of size 2 × 2 mm square mesh to prevent the migration of solid particles into the drainage layer. The waste sample collected from the landfill site was dried at 60 °C to obtain constant weight and then placed in the reactor at height of 400 mm. The sample was placed in 5–7 successive layers, properly compacted with the wooden tamper to give a uniform density throughout. Drainage layer (5 cm thickness) was placed on top of waste separated with geotextile to allow the even distribution of leachate into waste sample.

The reactor was equipped with thermocouple for monitoring the temperature, linear variable displacement transducer (LVDT) for displacement monitoring, gas sensors for measuring the biogas generation in reactor (mainly methane, CH_4 and CO_2) and leachate recirculation system. The reactor is completely sealed and was purged with nitrogen gas to remove the oxygen from waste and gravels and headspace of reactor. The reactor was operated at

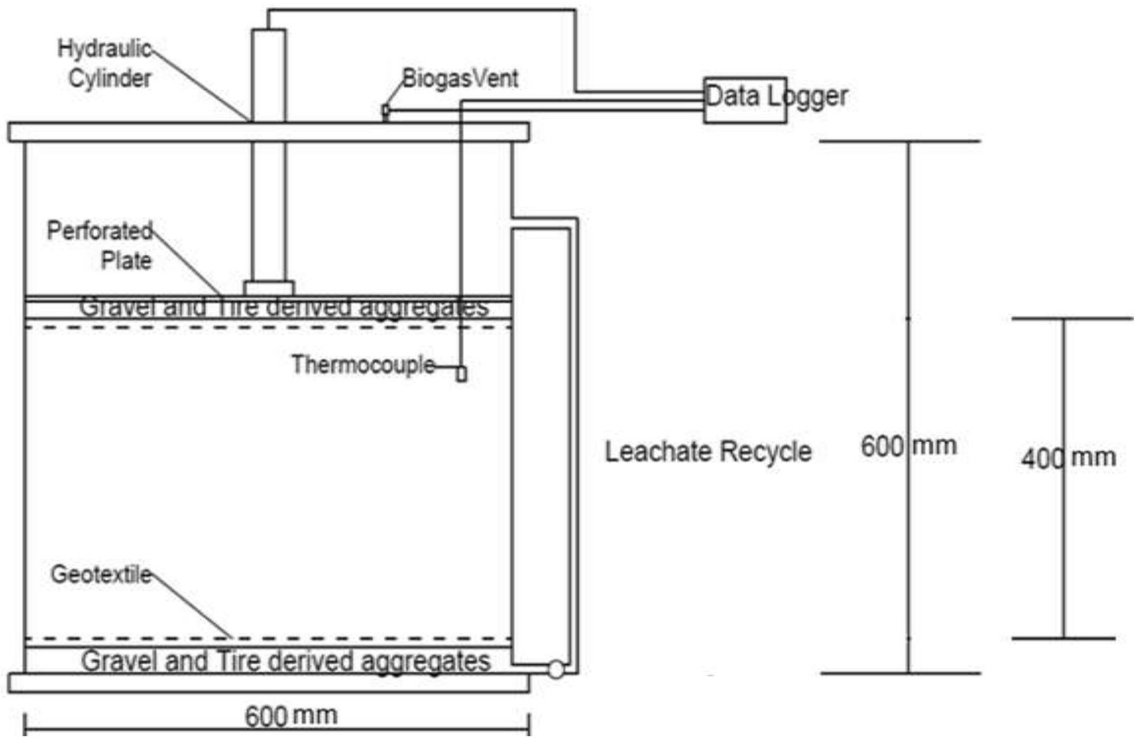

Fig. 1 Schematic of laboratory setup for the anaerobic digestion

constant mesophilic temperature of (27 ± 3) °C during the operation period of experiment. The reactor was operated, and settlement, biogas generation was continuously monitored for a period of 202 days.

Settlement Analysis

Settlement of fresh waste was determined in three different stages: (1) immediate settlement, (2) primary settlement and (3) secondary settlement. The immediate compression of waste is stress dependent and due to self-weight of overlying MSW which increases the vertical stress instantaneously after placement of waste. Immediate settlement completed within hours and caused strain [20]. After completion of immediate settlement, MSWs settle under consolidation effect. Thus, primary settlement was evaluated using Terzaghi's one-dimensional consolidation, and the time factor for completion of primary consolidation was evaluated using equation given by [21]:

$$T = \frac{c_v t}{d^2} \sim 1 \quad (1)$$

where T the time factor, c_v the consolidation coefficient, t the elapsed time after loading, d max the drainage path length, $d = h/2$.

The coefficient of consolidation c_v was evaluated graphically using time square root method (Table 1). c_v can be determined by using equation given by [21], depending upon the standard interpretation based on best fit straight line drawn through initial data points and horizontal asymptote representing the ultimate settlement intersecting at time $\sqrt{t_x}$, where

$$c_v = \frac{3d^2}{4t_x} \quad (2)$$

Table 1 Physical characterization of fresh waste sample

Sr. no.	Component	Percentage (%)
1	Organic content	56.1
2	Paper	12.2
3	Plastic	10.3
4	Glass	1.0
5	Metal	1.2
6	Inert	10.5
7	Others	8.7

Further, degradation of waste results in large differential settlements, gas emissions and leachate generation. However, the settlement of landfill is primarily due to biodegradation and mechanical compression that affects the post-closure settlement [4, 17]. In this context, a model developed by Chakma and Mathur [12] was used for predicting the settlement. However, the model considered the effect of biodegradation, moisture content, temperature and variation in density.

Settlement was predicted using the equations developed by Chakma and Mathur [12], thereby considering the combined effects of biodegradation and mechanical compression. The strain due to biodegradation settlement was estimated depending upon the moisture content (θ), temperature (T), pH and fraction of waste, volume of waste layer. The strain (ε_b) due to biodegradation is determined using Eq. (3):

$$\varepsilon_{b,i}(t) = \sum_{i=1}^{i=N} \frac{V_{i,N} - V_{S,N}(t)}{V_{i,N}} \quad (3)$$

where $V_{i,N}$ denotes the initial volume of every layer.

Finally, the settlement at any time (t) due to biodegradation is then computed by Eq. (4), in which (H_i) is the initial thickness of each layer:

$$S_b(t) = \sum_{i=1}^{i=N} H_i \varepsilon_{b,i}(t) \quad (4)$$

The mechanical compression in landfill occurs due to overburden load and addition of new waste layer causing additional weight on the underlying layer. Thus, strain in each layer of fill can be estimated by equation given by [11]

$$\varepsilon_{mi}(t) = C'_m \log\left[\frac{\gamma_i H_i + \sum_{j=j+1}^{N} \Delta\gamma_j H_j}{\gamma_i H_i}\right] \quad (5)$$

where $\varepsilon_{mi}(t)$ the strain attributable to mechanical compression, C_m the coefficient of compressibility for mechanical compression, H_i the initial height of compacted lift, $\Delta\gamma_j$ the increment of unit weight imposed by lift j on lift i.

The mechanical compression is obtained by

$$S_m(t) = \Delta H \varepsilon_{mi}(t) \quad (6)$$

ΔH is initial height after closure.

Results and Discussion

Characterization of MSW

The physical characterization of MSW (Table 1) showed that waste collected from the dump site is rich in organic content (56%) contributing majorly to the total generated MSW. The fraction of paper and plastic was also observed to be higher in the waste [22].

In particular, the gradation influences the decomposition and mechanical behavior of the waste and due to large particles, the gradation is often difficult to determine. Thus, the large particles of waste were found to be unsuitable, so representative samples should be obtained after shredding

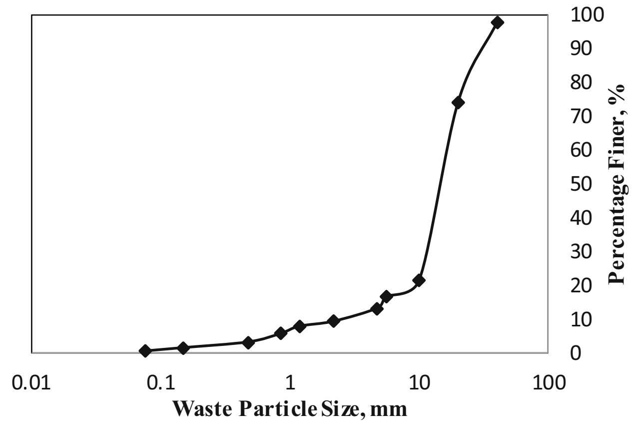

Fig. 2 Gradation of fresh waste sample

the waste to average size of 0.75–40 mm. The gradation of waste sample collected from site was done as per ASTM D 422 [23]. The MSW was sieved through sieves of size 100 mm, 50 mm, 20 mm, and 57%, 14.5%, 10% of fresh was retained on sieves. The gradation curves for fresh sample are presented in Fig. 2.

Settlement Analysis

Settlement of MSW was observed for a period of 202 days under a constant loading of 50 kPa and plotted against the log-time scale. Addition of synthetic leachate was done in order to enhance the microbial activities in the reactor. The initial settlement was observed to be 1.87% after leachate addition. In comparison with literature, settlement of about 3% was reported by [16] for the fresh waste. Settlement of fresh waste was determined in three different stages: (1) immediate settlement, (2) primary settlement and (3) secondary settlement.

Immediate Settlement

The immediate settlement of waste occurs due to increase in vertical stress instantaneously after the placement of waste in the reactor. The observed results showed that approximately 29.9% (117.59 mm) of settlement occurred immediately after the application of load. The higher settlement observed in the reactor at initial loading stage may be due to higher organic fraction and initial trapped gases and difference in compaction of the waste.

Primary Settlement

After completion of the immediate settlement, municipal solid waste settles under the effect of consolidation. The time for the completion of primary settlement was determined using the time root square method and was

Table 2 Result of consolidation analysis using time square root method

Parameters	Values
d (m)	0.2
$\sqrt{t_x}$	5.8
t_x (s)	121,104
$c_v = \frac{3d^2}{4t_x}$ (m^2/s)	2.47×10^{-7}
T (after 48 h)	0.773

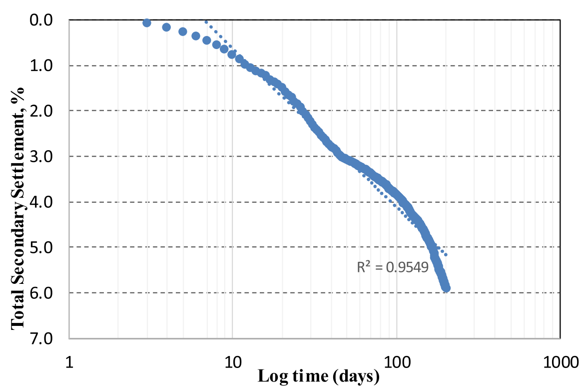

Fig. 3 Secondary settlement at 50-kPa load for raw waste in reactor

estimated approximately to be 48 h. The results of the consolidation analysis are shown in Table 2.

The settlement observed in the reactor after the completion of immediate settlement was about 10.14% (38.8 mm). The time factor for the completion of primary settlement was evaluated to be 48 h, and the total settlement at the end of 48 h was reported to be 40.04% which may be attributed to heterogeneity of sample and difference in compaction of waste. In the study reported by [16], the primary settlement of 33–48% was observed for raw waste at the end of 24 h.

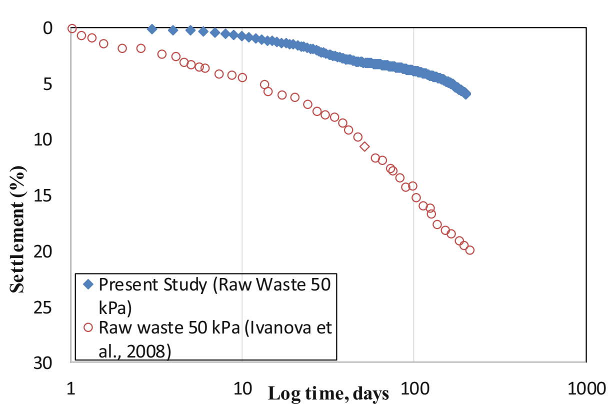

Fig. 4 Comparison of secondary settlement at 50-kPa load

Secondary Settlement

The long-term secondary settlement attributed to biodegradation and creep-induced settlement was plotted against log time as shown in Fig. 3. The secondary settlement starts in the reactor after completion of primary settlement, and after 202 days in the reactor, the settlement rate was recorded to be 5.85% Similarly, the long-term secondary settlement observed by [16] was 25% at the end of 919 days of experiment.

The long-term secondary settlement at 50 kPa in reactor was obtained and compared with literature as shown in Fig. 4. The rate of biodegradation of waste was estimated to be about 0.477 day^{-1} using nonlinear regression analysis, and from the obtained result, concentration of biogas (CH_4) generated from waste over duration of experiment was also determined to be very high of about 32,000 ppm (Fig. 5).

The results depict that the rate of secondary settlement of waste was slow in comparison with earlier reported literature [16, 24] which may be due to the composition of MSW and bulk density of waste and the test conditions for the experiments. The rate of degradation obtained for the present study was higher than the reported literature which may show the presence of easily digestible food waste, organic/biodegradable content having high rate of degradation. In contrast to the previous studies, despite higher k value, the settlement is slower which may be attributed to the operating conditions of the experiment [7, 16].

The experimental analysis revealed that the settlement of waste during the initial stage was higher due to nature and heterogeneity of waste, lack of compaction. However, the study carried out by [16] showed the primary settlement of 33.4% and long-term secondary settlement of 25% for raw waste. The obtained results of consolidation from the laboratory experiment are presented in Table 3.

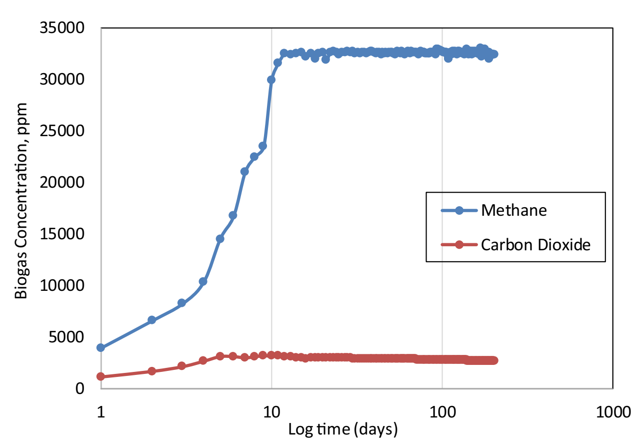

Fig. 5 Biogas generation in reactor

Table 3 Results of the consolidation analysis

Parameter	Height of sample (mm)	Settlement (mm)	Remarks
Initial height of sample	400	0	–
Height after leachate addition	392.5	7.5	–
Height immediately after application of load (50 kPa)	274.91	117.59	Immediate settlement
After 48 h of load application	235.11	39.8	Primary settlement (U = 90%)
Height after 202 days	212.12	22.99	Long-term secondary settlement

The biogas generation and temperature were monitored throughout the testing period of MSW. As the test was conducted at room temperature, the variation in temperature was due to anaerobic condition developed inside the reactor. The temperature initially raised from 23 to (28 ± 2 °C) and remained almost constant for 202 days indicating the biodegradation of waste. The total settlement (immediate, primary and secondary) in reactors was estimated to be 45.9% after the application of load in reactor at the end of 202 days of experiment (Fig. 6).

Prediction of Settlement

Biodegradation Settlement The modeling of biodegradation settlement of MSW depends upon the characteristics of waste, composition, moisture content, density, pH, temperature and compression characteristics. The settlement of MSW landfill of 10 m height was estimated depending upon the variation in moisture content, pH and temperature. The variation in different parameters was observed, and settlement attributed to biodegradation was estimated depending upon the actual and predicted conditions of pH of waste, moisture condition and temperature (Figs. 7, 8, 9).

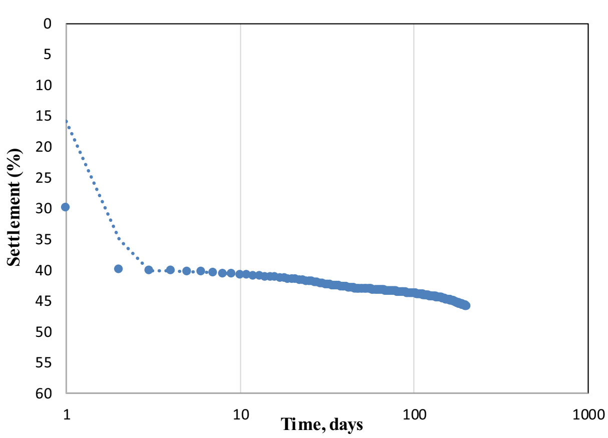

Fig. 6 Total settlement in reactor at the end of 202 days

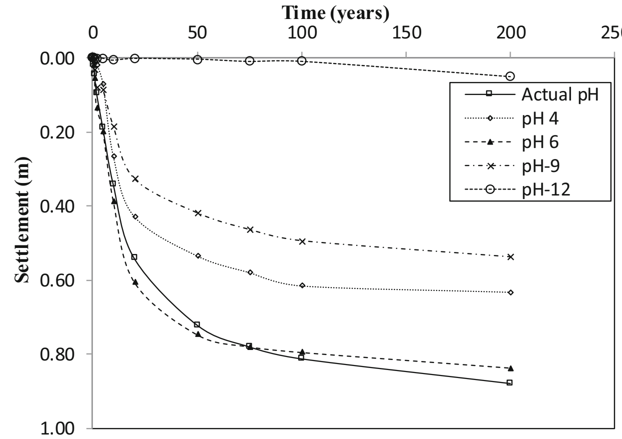

Fig. 7 Variation in settlement with varying pH

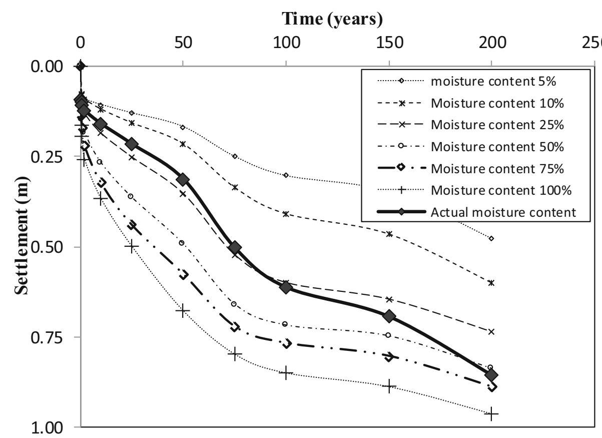

Fig. 8 Variation in settlement with varying moisture content

It was observed that with the increase in the temperature, the settlement increases. However, the variation in pH of waste showed higher settlement at pH-6 and actual pH of waste sample. It was observed that increase in acidic and alkaline nature of waste reduces the biodegradation, thereby reducing the settlement. The moisture plays an important role in biodegradation of waste. The spatial and temporal variation in moisture content in landfill was considered with increasing depth.

The long-term biodegradation settlement in landfill of height 10 m was estimated to be 0.85 m at the end of 100 years for obtained biodegradation parameter. However, the predicted range of temperature and moisture

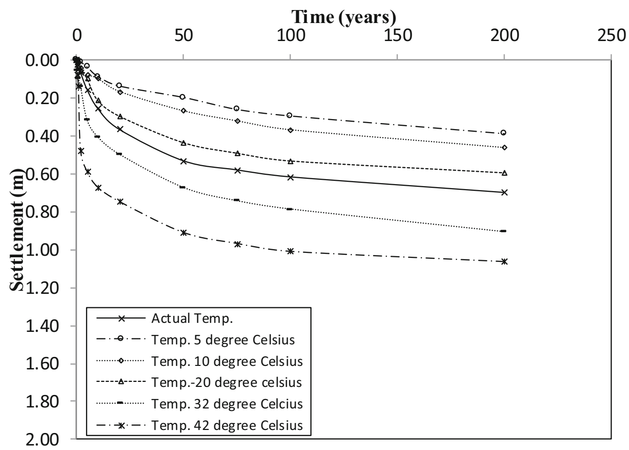

Fig. 9 Variation in settlement with varying temperature

content depict that with the increase in the temperature and moisture content, the settlement in landfill increases about 15–25%. The biodegradation settlement varies from 0.85 to 1.06 m at the end of 100 years considering the variation in temperature and moisture content.

Mechanical Compression The observed mechanical compression for 10 m landfill height was determined to be 1.15 m for $C = 0.02$ and 1.72 m for $C = 0.03$ at the end of 100 years. It was observed from the results that increase of 0.01 in value results in increase of 0.57 m in the settlement. Thus, it was clear that mechanical compression is important for analyzing the settlement of landfill as a very small change in C value results in large settlement variation.

The obtained results from the laboratory analysis showed 5.85% secondary settlement at the end of 202 days. The modeled parameters also showed about 6.4% of biodegradation settlement for landfill height of 10 m for initial 202 days. The mechanical compression due to overburden of waste was predicted to be 10–18%. The model and laboratory results can be accurately predicted after evaluating the creep-induced settlement for the raw waste. Further, the investigation can be done on predicting the settlement depending upon the creep and biodegradation-induced settlement by analyzing the settlement behavior of MSW. However, the laboratory scale experiment showed the limitation for analyzing the biodegradation and creep settlement individually due to limited resources available for testing of MSW, thus needing further investigation for determining the secondary settlement.

Conclusion

The long-term settlement is mainly associated with volume reduction due to biodegradation of organic fraction of waste and physical creep compression. It was observed from the study that biodegradation of waste gets affected by moisture, temperature, composition, pH and microbes present in the waste. At initial stage, immediate settlement of 29.9% occurred during application of load on the waste sample. The high rate of settlement observed can be accounted to poor compaction, higher organic/biodegradable fraction present in the waste. The consolidation results obtained from the experiment were determined, and primary settlement of 10.14% was observed in the reactor. The test was carried out at normal temperature conditions, and total settlement of 40.04% was recorded at the end of primary settlement. The total secondary settlement of 5.85% was observed for 202 days after completion of primary settlement of waste sample and continues for a longer period of time. The total settlement in the reactor was estimated to be 45.9% at the end of 202 days of the testing period. The settlement of waste sample was predicted using a model depending upon the obtained parameters from the laboratory analysis. However, the effect of waste degradation and compression on sample depicts settlement of 6.4% and 10–18%, respectively, in landfill over a period of 202 days. The obtained results revealed that settlement of waste in landfill is highly dependent on the organic fraction of waste, temperature, moisture, pH and rate of degradation of waste. The mechanical compression of waste sample depicts that the overburden pressure and increasing unit weight of waste are important parameters for evaluating the settlement. The observed parameters from the study predicted the long-term settlement of the waste and analyzed the post-closure settlement in landfill. The waste degradation due to combined effect of biodegradation and mechanical compression poses the structural and operational problems in landfill. In this context, settlement analysis helps in determining waste degradation rate and rate of settlement of landfill.

Acknowledgements The authors would like to thank Vice Chancellor and administration of Jaypee University of Information Technology, Waknaghat, for providing financial support and considerable input for development of anaerobic reactor.

Compliance with Ethical Standards

Conflict of interest The author confirms that there are no known conflicts of interest associated with this publication.

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