Cox, et al., Published in Waste Management, 46: 338-351. December 2015

Implications of variable waste placement conditions for MSW landfills

Jason T. Cox [a,*], Nazli Yesiller [b], James L. Hanson [c]

[a] Golder Associates, Irvine, CA 92606, USA
[b] Global Waste Research Institute, California Polytechnic State University, San Luis Obispo, CA 93407, USA
[c] Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, CA 93407, USA

ARTICLE INFO

Keywords:
Municipal solid waste
Waste placement
Compaction
Moisture content
Unit weight
Settlement
Degradation
Decomposition
Field capacity

ABSTRACT

This investigation was conducted to evaluate the influence of waste placement practices on the engineering response of municipal solid waste (MSW) landfills. Waste placement conditions were varied by moisture addition to the wastes at the time of disposal. Tests were conducted at a California landfill in test plots (residential component of incoming wastes) and full-scale active face (all incoming wastes including residential, commercial, and self-delivered components). The short-term effects of moisture addition were assessed by investigating compaction characteristics and moisture distribution and the long-term effects by estimating settlement characteristics of the variably placed wastes. In addition, effects on engineering properties including hydraulic conductivity and shear strength, as well as economic aspects were investigated. The unit weight of the wastes increased with moisture addition to a maximum value and then decreased with further moisture addition. At the optimum moisture conditions, 68% more waste could be placed in the same landfill volume compared to the baseline conditions. Moisture addition raised the volumetric moisture content of the wastes to the range 33–42%, consistent with values at and above field capacity. Moisture transfer occurred between consecutive layers of compacted wastes and a moisture addition schedule of 2 days of as-received conditions and 1 day of moisture addition was recommended. Settlement of wastes was estimated to increase with moisture addition, with a 34% increase at optimum moisture compared to as-received conditions. Overall, moisture addition during compaction increased unit weight, the amount of incoming wastes disposed in a given landfill volume, biological activity potential, and predicted settlement. The combined effects have significant environmental and economic implications for landfill operations.

1. Introduction

Landfill disposal is the main means of management of residual wastes in the U.S. In 2012, municipal solid waste (MSW) disposal at a total of 1908 landfills amounted to 121 Mt, representing 54% of wastes generated in the U.S. (USEPA, 2014). The 54% disposal level had been steady over the last several years. Additional materials, such as construction and demolition wastes, municipal wastewater treatment sludges, and non-hazardous industrial wastes, not considered MSW, also are disposed of in landfills (USEPA, 2013). Siting, permitting, and construction of new landfill facilities have become increasingly difficult due to scarcity of suitable sites as well as public resistance. The MSW management infrastructure has consolidated considerably over recent decades with decreased number and increased size of operational facilities. Optimizing landfill capacity through development of efficient and economical waste placement strategies is significant for extending operational service life of existing facilities and reducing the need for construction of new landfills. The influence of variable waste placement conditions on short- and long-term engineering response of the wastes needs to be investigated to ensure stability and safe operation of landfill facilities.

Hanson et al. (2010) indicated that compaction of wastes at the time of disposal was the primary factor that controlled short-term density and placement efficiency of wastes in landfills. Maximizing waste density results in reduced disposal space requirements or extended facility lifetime (Ham et al., 1978). In similarity to soils, shear strength increases and compressibility decreases with increasing density (e.g., Bray et al., 2009; Bareither et al., 2012a). Transport of fluids (landfill gas and leachate) is affected by combined compaction density and moisture content characteristics of a waste mass (e.g., Yesiller et al., 2010). Even though waste placement practices affect properties and engineering response of wastes, field scale investigation of waste placement at MSW landfills is highly limited for conditions representative of current landfilling procedures in the U.S.

* Corresponding author.
E-mail addresses: jcox@golder.com (J.T. Cox), nyesille@calpoly.edu (N. Yesiller), jahanson@calpoly.edu (J.L. Hanson).

The effects of environmental (seasonal variation and temperature) and operational (moisture content, compactive effort, and compaction duration) conditions on compaction of MSW were studied systematically by Hanson et al. (2010). Tests were conducted in test plots on the residential component of incoming wastes at a U.S. MSW landfill with no modifications to size, shape, or composition of the wastes, and using typical compaction equipment and procedures. The test plots were approximately 200 m^2 in area and an average weight of wastes of 355 kN was used in the tests. The wastes were compacted using increasingly higher amounts of moisture to generate unit weight-moisture content relationships (i.e., compaction plots) similar to those used for soils. The measured compaction parameters with effort were $\gamma_{dmax\text{-}low}$ = 5.7 kN/m^3, $w_{opt\text{-}low}$ = 70%; $\gamma_{dmax\text{-}high}$ = 8.2 kN/m^3, $w_{opt\text{-}high}$ = 73%; and with season were $\gamma_{dmax\text{-}cold}$ = 8.2 kN/m^3, w_{cold} = 79.5%; $\gamma_{dmax\text{-}warm}$ = 6.1 kN/m^3, w_{warm} = 70.5%. The addition of moisture during compaction resulted in 24–165% increases in unit weights above the average and season-specific baseline conditions. Moisture addition was indicated to be more effective in winter than summer due to the combined effects of dry initial conditions and potential thawing and softening of wastes in winter. The average baseline unit weight was obtained with sufficient duration of compaction (⩾6 min) for variable moisture conditions. High compactive effort resulted in short durations (<6 min). The reported benefits of moisture addition to wastes at time of compaction included increased unit weight and associated reduced volume required for disposal as well as reduced time required for compaction. In addition, the volumetric moisture content of the wastes increased to 29–67% consistent with reported values of field capacity (Qian et al., 2002) in the compaction test plots (Hanson et al., 2010).

The factors that affect compaction of MSW including size of compactor, lift thickness, and number of passes were investigated by Surprenant and Lemke (1994). The study was conducted using a 12.4 m × 21.7 m test plot with a capacity to hold approximately 17,800 kN of waste at a U.S. MSW landfill. The incoming waste was composed of "pure" MSW free of construction and demolition waste and sludge. The data obtained from the investigation indicated that a 14% increase in density was achieved using a heavy compactor and a 25% increase in density was obtained using 0.3-m-thick lifts as compared to 0.8-m-thick lifts. In addition, the majority of the densification of the waste occurred within four passes with only 3% and 9% increase in density obtained with four additional passes for lift thicknesses of 0.3 and 0.8 m, respectively (Surprenant and Lemke, 1994). Overall, data have not been presented for full-scale analysis of field waste placement conditions at U.S. landfills. Factors that affect placement conditions and implications of the variable placement practices on resulting properties and behavior of placed wastes have not been investigated in a systematic manner.

A comprehensive test program was conducted to determine the engineering response of MSW as a function of placement conditions. Meso- and full-scale field compaction experiments were conducted to determine the effects of moisture addition at the time of compaction on characteristics and placement efficiency of MSW. The field scale compaction analyses from the test program are presented herein. Also, data obtained from field instrumentation and laboratory tests are presented to determine the effects of variable compaction conditions on the waste mass. In addition, financial analysis is presented for assessment of economic implications of waste compaction with moisture addition.

2. Experimental program and analysis

The field investigation was conducted to determine waste placement characteristics at a MSW landfill at two testing scales. Moisture was added to wastes at the time of compaction to investigate the effects of elevated moisture content on the properties of the wastes. Laboratory and field analyses of physical and engineering properties of the waste materials also were conducted to support the waste placement investigation. All of the moisture contents presented in the paper are provided on a dry gravimetric mass basis unless otherwise noted.

2.1. Field test site

The field investigation was conducted at Santa Maria Regional Landfill (SMRL) located in California, USA. The landfill is located in an area with a Csb climate (temperate, dry summer, warm summer) using the Koppen-Geiger climate classification system (Peel et al., 2007). SMRL is a Subtitle D landfill with a permitted disposal area of 100 ha and permitted disposal volume of 10.7 million m^3 (including daily and intermediate covers). The annual and daily waste disposal amounts at the site are approximately 735,000 kN (for 250 days of operation) and 2940 kN, respectively. The waste composition at the site by weight consists of approximately 38% residential waste, 39% commercial waste, and 23% self-delivered waste. Currently waste is placed in Cell 1 with an area of 15 ha, which has been the active disposal area since November 2002 and is expected to receive wastes through December 2021.

Waste was initially placed in a 9.3-m-thick lift over the entire 15 ha footprint of Cell 1 from November 2002 to August 2007. Since then MSW was placed in predetermined sub-cells with approximate dimensions of 15 m × 46 m. Waste was placed in each sub-cell to a height of approximately 4.6 m and typically over a 10–15 day period. Placement of a total of 5 lifts (Lifts I–V) is underway in Cell 1 with the 9.3-m-thick lift constituting the first lift and the second and third lifts currently being placed. As of late 2013, Lift I was 100% completed, Lift II was approximately 90% completed, Lift III was approximately 70% completed, and placement of Lifts IV and V had not yet started. Alternative daily cover (ADC) and tarps were used to cover the active face at the end of each working day. The ADC was generally comprised of wood chips and was only used on the slopes of the active face. For flat areas, tarps were rolled out over the active filling areas and were removed prior to commencement of the waste filling the next day. Once a sub-cell was filled to the desired lift height, a 0.6-m-thick layer of gravelly sand was placed over the wastes to serve as the intermediate cover.

For placement, incoming wastes were unloaded from the waste trucks and then pushed onto and spread over the active face using a Caterpillar (CAT) D6 bulldozer (weight of 390 kN). The waste was then compacted using a CAT 826D compactor with a weight of 360 kN. The wastes were compacted in thin lifts with a total waste thickness of approximately 0.5 m for a given day. The number of passes was not constant, rather was dependent on compactor operators and waste being placed and varied between 5 and 8 passes for a given waste lift. The operators adjusted the number of passes until densification of the wastes reached a practical limit. This limit was based on the operators' visual assessment of the waste lift height and the physical response of the compaction equipment together with the overall experience of the operators assessing the stiffness of the waste mass as the compactor navigated over the active face. In contrast, a consistent procedure was used for compaction coverage. In a 15 m × 46 m active face area, the compactors operated in alternating directions. Initially, wastes were compacted with the compactor moving along a given direction (e.g., north–south). Next, wastes were compacted along the transverse direction (e.g., east–west). Finally, the third and final coverage included compaction along the original direction (e.g., north–south).

The compaction characteristics of the wastes at the site, unit weight and moisture content, were determined to establish baseline conditions. The unit weight was determined as the quotient of the weight of the incoming waste and the volume of space occupied by the compacted waste. Historic scale-house records were used to determine weight of incoming wastes and topographic surveys of the waste mass were used to determine volume of the wastes. Data obtained over the period between November 2002 and July 2011 were used for the calculation of unit weight. Moisture content was determined by the research team using samples of incoming wastes collected subsequent to unloading at the active face and prior to compaction. The samples were oven dried in a convection oven, located in a designated area at SMRL, in accordance with the procedures described in ASTM D2216. However, instead of oven drying the samples at 105 °C, the samples were oven dried at 75 °C for approximately 24 h to ensure all of the moisture was removed while avoiding charring of some constituents (e.g., Reddy et al., 2009). The mass of samples obtained for baseline moisture content analysis varied between 0.8 and 4.2 kg with an average mass of 2.0 kg. The moisture content samples were collected over a one-year period (June 2012 to May 2013) to establish baseline conditions.

2.2. Meso-scale field tests

Meso-scale field tests were conducted in dedicated test plots at the site using the residential component of the incoming waste stream. The main components (approximately 70% by weight) of the residential waste (RMSW) were food and yard waste; plastic garbage bags; plastic bottles and containers; glass bottles and containers; and paper and paperboard materials. Miscellaneous waste items such as diapers, shoes, textiles, and other household items also were observed in the RMSW. A total of two test plots were constructed each with dimensions of 31 m (L) and 11 m (W) resulting in an aerial footprint of 341 m^2 for a given test plot. The test plots were located in Cell 1 in an area with an intermediate cover underlain by Lift I. First, a bulldozer was used to remove the top 0.5 m of the intermediate cover soil and create a flat base for the test plots. Then, each test plot was divided in half using survey stakes and spray paint and each half was designated as a test pad. First, Test Plot 1 (TP1) was constructed and subdivided into Test Pads A and B. Then, Test Plot 2 (TP2) was constructed and subdivided into Test Pads C and D. Approximately 450 kN of waste was placed in each pad totaling 900 kN for each test plot for a given day of testing. The total thickness of the compacted wastes in each test plot was approximately 4.6 m.

The RMSW was unloaded, spread, sprayed with water (when applicable), and compacted in the test plots with the same equipment used for waste placement at the site. Incoming moisture content was determined using samples of wastes collected from incoming loads of RMSW. Moisture was added to the wastes to raise the moisture content above the as-received conditions to target levels over a broad range of moisture contents based on previous MSW compaction analysis (Hanson et al., 2010). Non-potable water, obtained from a nearby groundwater well, was used. The amount of moisture to be added was calculated based on the amount of wastes placed in a given test pad and the average moisture content of the incoming RMSW. An on-site water truck (capacity of 15,000 L) with a turret nozzle sprayed the pre-determined amounts of water to the wastes in the test pads to raise the moisture content to the target values (Fig. 1). The unit weight of the wastes in the test pads was calculated using weights (from scale-house records and amount of added water, if any) and volumes (from topographic surveys using a Trimble GPS system).

A compaction procedure similar to the normal operations at the active face was adopted. An orthogonal pattern of compaction coverage was implemented to provide highly controlled conditions. In each orthogonal direction, the compactor made 8 trips over the test plot footprint. A preliminary analysis was conducted in TP1 to establish the compaction schedule. A total of 4 elevated moisture contents were targeted in the test program. The initial moisture addition plan included 3 consecutive days of moisture addition for a given target moisture content. This schedule was to be used for the first 3 elevated moisture contents and 1 day of compaction was planned for the 4th and last (highest) elevated moisture content to be used in the test program. However, preliminary testing in Test Pad A indicated that moisture became excessive by the time the 2nd level of elevated moisture content tests were conducted and significant difficulties were encountered in operation of the compaction equipment. Therefore, the compaction schedule was modified to a 2-to-1-placement method where the wastes were placed at as-received conditions without moisture addition for two days followed by one day of placement at the target elevated moisture contents. The meso-scale tests were conducted between February and April 2013.

2.3. Full-scale field tests

Subsequent to completion of the meso-scale compaction investigation, full-scale compaction tests were conducted to determine the compaction characteristics of MSW and the effects of moisture addition on the normal daily waste placement procedures at the test site. The tests were conducted at the active face of SMRL with an area of approximately 15 m × 46 m within Lift III in Cell 1. The composition of incoming waste delivered to the active face included by weight 38% residential waste (composition described in Section 2.2), 39% commercial waste, and 23% self-delivered waste. Commercial wastes were mainly comprised of significant amounts of paper, cardboard, plastics, and food, whereas self-delivered wastes were mainly comprised of bulky items such as furniture, mattresses, construction demolition waste, appliances, etc.

The full stream of incoming municipal solid wastes at the site were unloaded, spread, sprayed with water (when applicable), and compacted in the active face with the same equipment and procedures used for normal waste placement at the site. Incoming moisture content was determined using the samples of wastes collected from incoming loads of the MSW over the one-year monitoring period (Section 2.1). Moisture was added to the wastes to raise the moisture content above the as-received conditions to target levels over a broad range of moisture contents based on previous MSW compaction analysis (Hanson et al., 2010). Non-potable water, obtained from a nearby groundwater well was used. The amount of moisture to be added was calculated based on the average amount of wastes placed at the active face in a given day (i.e., 2940 kN) and the average moisture content of the incoming MSW. The on-site water truck with a turret nozzle sprayed the pre-determined amounts of water to the wastes in the active face to raise the moisture content to the target values (Fig. 2). The unit weight of the wastes in the active face was calculated using weights (from scale-house records and amount of added water, if any) and volumes (from daily topographic surveys using a Trimble GPS system).

The compaction schedule established in the meso-scale tests was used for the full-scale tests. The 2-to-1-placement method included placement of the wastes at as-received conditions without moisture addition for two days followed by one day of placement at the target elevated moisture contents. A total of 3 elevated moisture contents were targeted in the full-scale compaction test program. An additional 2 days were allowed between the middle and highest added moisture levels in a diversion from the 2-to-1-placement method to ensure that excessive moisture

Fig. 1. Meso-scale test program moisture addition to the wastes during meso-scale tests.

Fig. 2. Full-scale test program moisture addition to the wastes during full-scale tests.

was not present in the waste mass that could interfere with equipment operation. The full-scale tests were conducted between July and August 2013.

2.4. Post-compaction moisture distribution

The moisture contents of the waste masses included in the test program were evaluated subsequent to compaction for both the meso- and full-scale tests. For meso-scale tests, test pits extending to depths of 1.3 m were excavated in the test plots on the morning following compaction, approximately 12–15 h after the end of a day with moisture addition using a CAT D8 dozer. Each test pit extended through 3 lifts of compacted RMSW. Samples were collected from the surface and at 0.45 m depth intervals to a maximum depth of 1.3 m in the test pits. A total of four samples were collected from each test pit. The mass of the samples was in the range of 2.6–5.7 kg. A total of 3 test pits were excavated in the meso-scale test program with two test pits located in TP1 and one test pit located in TP2.

For full-scale tests, two test pits extending to depths of 1.2 m were excavated in the active face the following morning, approximately 12–15 h after the end of a day with moisture addition using a CAT D8 dozer. Duplicate samples were obtained from each sampling depth including the surface and at specific depths of 0.6 m and 1.2 m in a test pit. The sample mass ranged from approximately 1.0 to 2.5 kg. In addition to the test pits, a detailed surface moisture distribution analysis was conducted in the full-scale test program. An equally spaced 5×10 grid-pattern was established over the surface of the active face ($15\ m \times 46\ m$) and a moisture content sample was obtained at each intersection point on the grid (i.e., moisture samples taken on $3\ m \times 5\ m$ spacing). The analysis was conducted at the as-received moisture content and also at a target elevated moisture content. Samples with masses between 1 and 2 kg were obtained from the compacted waste mass at the end of the test days. A total of 50 samples were obtained for the as-received moisture condition and similarly 50 samples were obtained for the target elevated moisture condition.

3. Results and discussion

3.1. Compaction analyses

The compaction data obtained in the field tests were analyzed using three distinct unit weights (Eqs. (1)–(3)): dry unit weight (γ_d), total unit weight (γ_t), and operational unit weight (γ_{oper}). The dry and total unit weights have the same definitions as those used in geotechnical engineering, whereas the operational unit weight was introduced by Hanson et al. (2010) for waste. The dry and total unit weights are calculated using weight of solids in a waste mass and weight of incoming wastes plus any added water for dry unit weight and total unit weight, respectively. The operational unit weight is calculated by using solely the weight of incoming wastes without including the weight of added water (if used). For as-received conditions without moisture addition, the total and operational unit weights have equivalent values. The total and dry unit weights are applicable to engineering calculations, whereas operational unit weight was introduced to evaluate landfill capacity and for practical economic calculations. The weight of incoming wastes is highly relevant for landfill operations as financial determinations are made based on the tipping fees charged for the wastes by weight upon entry to a landfill. A new parameter is introduced herein to further assess the economics of landfill capacity based on waste placement conditions. The operational waste placement factor (OWPF) is used to evaluate

the additional weight of wastes that can be placed into a given volume of airspace due to the addition of moisture (Eq. (4)). An OWPF > 1 indicates that more incoming waste can be placed in the same landfill volume at the given moisture content than at the baseline condition (i.e., as-received moisture content), whereas OWPF < 1 indicates that less incoming waste can be placed in the same landfill volume at the given moisture content than at the as-received moisture content.

$$\gamma_d = \frac{\text{Weight of Solids}}{\text{Total Compacted Volume}} \tag{1}$$

$$\gamma_t = \frac{\text{Weight of Incoming Waste} + \text{Additional Water (if used)}}{\text{Total Compacted Volume}} \tag{2}$$

$$\gamma_{\text{oper}} = \frac{\text{Weight of Incoming Waste}}{\text{Total Compacted Volume}} \tag{3}$$

$$OWPF = \frac{\gamma_{oper\text{-}MC}}{\gamma_{oper\text{-}AR}} \tag{4}$$

where $\gamma_{oper\text{-}MC}$ is the operational unit weight at a moisture content when moisture was added to the waste mass during placement and $\gamma_{oper\text{-}AR}$ is the operational unit weight at the as-received moisture content (i.e., no moisture addition to the incoming waste mass).

The results of the meso-scale compaction tests on residential wastes are presented in Table 1 and Fig. 3. The average as-received moisture content for RMSW was determined to be 55% using the samples obtained from the incoming wastes. The target moisture contents for the meso-scale tests were set at 65%, 80%, 95%, and 120%. The wide range of target moisture contents was selected based on previous research that indicated variation of compacted moisture content-unit weight over such large ranges for municipal solid waste (Hanson et al., 2010). Significant increases occurred in unit weight of the RMSW due to moisture addition at time of compaction (Table 1). The average dry unit weight of RMSW compacted and placed at moisture contents of 65%, 80%, and 95% increased by approximately 31%, 65%, and 36%, respectively, as compared to the average dry unit weight of the waste compacted at the as-received moisture content (i.e., 55%). The average operational unit weight of RMSW compacted at moisture contents of 65%, 80%, and 95% increased by 33%, 66%, and 37%, respectively, as compared to the operational unit weight of the waste compacted at the as-received moisture content. The average dry and operational unit weights of RMSW compacted at 120% moisture content decreased by approximately 23% and 17%, respectively, compared to the dry and operational unit weights of waste compacted at 55% moisture. At elevated moisture contents, water replaced the waste solids decreasing the effectiveness of the compaction process.

The compaction curves were bell shaped with unit weight increasing with moisture content up to a maximum level and then unit weight decreasing with increasing moisture content beyond this maximum in similarity to data presented for RMSW compacted in test plots (Hanson et al., 2010). Based on the compaction curves provided in Fig. 3, the maximum dry unit weight ($\gamma_{d\text{-}max}$) for RMSW was determined to be 8.5 kN/m^3 with a corresponding optimum water content (w_{opt}) of 78.5% and the maximum operational unit weight to be 13.3 kN/m^3 with a corresponding optimum water content ($w_{oper\text{-}opt}$) of 79.5%. The operational waste placement factors varied between 0.83 and 1.66 in the meso-scale test program (Table 1). The OWPF increased with moisture addition at time of compaction with values >1 for moisture contents of 65%, 80%, and 95%. Similar to unit weight, the OWPF decreased with further increase of moisture content to 120%. The maximum OWPF (1.66) was obtained at 80% compaction moisture content, which aligned well with the optimum moisture content in the tests (w_{opt} = 78.5% and $w_{oper\text{-}opt}$ = 79.5%). Approximately 1.66 times more residential MSW can be placed into a given landfill volume when compacted at or near 80% moisture content as compared to baseline moisture conditions (i.e., 55% moisture content).

The results of the full-scale compaction tests on MSW at the active face of SMRL are presented in Table 2 and Fig. 4. The average as-received moisture content for MSW was determined to be approximately 45% using the samples obtained from the incoming wastes at the test site. The target moisture contents for the full-scale tests were set at 70%, 90%, and 110% to extend to moisture levels beyond optimum compaction conditions. The wide range of target moisture contents was selected based on previous research that indicated variation of compacted moisture content-unit weight over such large ranges for municipal solid waste (Hanson et al., 2010). Significant increases occurred in unit weight of the MSW due to moisture addition at time of compaction

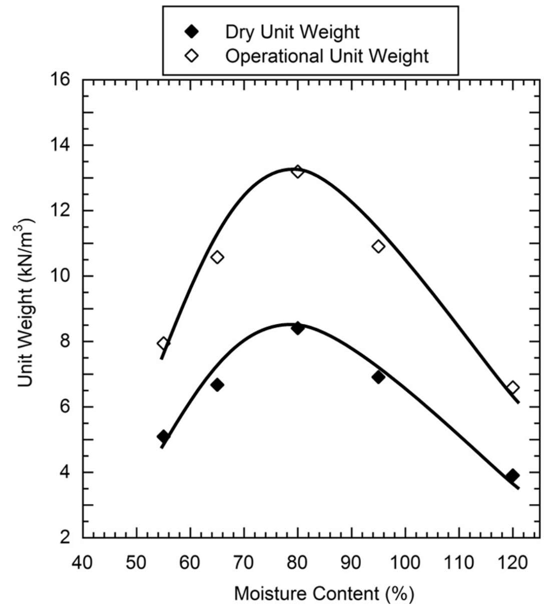


Fig. 3. Compaction curves based on meso-scale tests.

Table 1
Results of meso-scale test program.

Moisture content (%)	γ_t (kN/m^3)	γ_d (kN/m^3)	γ_{oper} (kN/m^3)	Operational waste placement factor (OWPF)
55	7.95	5.10	7.95	1
65	11.31	6.68	10.58	1.33
80	15.33	8.41	13.20	1.66
95	13.49	6.92	10.91	1.37
120	8.66	3.91	6.60	0.83

Table 2
Results of full-scale test program.

Moisture content (%)	γ_t (kN/m^3)	γ_d (kN/m^3)	γ_{oper} (kN/m^3)	Operational waste placement factor (OWPF)
45	5.70	3.93	5.70	1.00
70	9.36	5.50	7.94	1.39
90	12.88	6.78	9.60	1.68
110	8.10	3.86	5.52	0.97

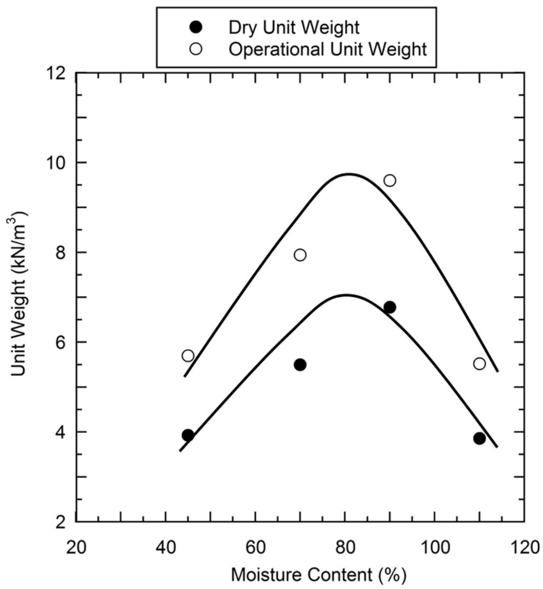


Fig. 4. Compaction curves based on full-scale tests.

(Table 2). The average dry unit weight of MSW compacted at moisture contents of 70% and 90% increased by approximately 40% and 73%, respectively, as compared to the average dry unit weight of the waste compacted at the as-received moisture content (i.e., 45%). The average operational unit weight of the MSW compacted at moisture contents of 70% and 90% increased by 39% and 68%, respectively, as compared to the operational unit weight of the waste compacted at the as-received conditions. The average dry and operational unit weights of MSW compacted at 110% moisture content decreased by approximately 2% and 3%, respectively, compared to the dry and operational unit weights of waste compacted at baseline conditions (i.e., 45% moisture). At elevated moisture contents, water replaced the waste solids decreasing the effectiveness of the compaction process. The specific gravity of fresh compacted MSW was determined to be 1.258 at SMRL (Yesiller et al., 2014).

Similar to meso-scale tests, the compaction curves for the full-scale tests were bell shaped with unit weight increasing with moisture content up to a maximum level and then decreasing with increasing moisture content beyond this maximum. Based on the compaction curves provided in Fig. 4, the maximum dry unit weight ($\gamma_{d\text{-}max}$) for MSW was determined to be 7.0 kN/m^3 with a corresponding optimum water content (w_{opt}) of 80.5% and the maximum operational unit weight to be 9.8 kN/m^3 with a corresponding optimum water content ($w_{oper\text{-}opt}$) of 81.0%. The operational waste placement factors varied between 0.97 and 1.68 in the full-scale test program (Table 2). The OWPF increased with moisture addition at time of compaction with values >1 for moisture contents of 70% and 90%. Similar to unit weight, the OWPF decreased with further increase of moisture content (to 110%). The maximum OWPF (1.68) was obtained at 90% compaction moisture content, which was in line with the optimum moisture content in the tests (w_{opt} = 80.5% and $w_{oper\text{-}opt}$ = 81.0%). Approximately 1.68 times more MSW can be placed into a given landfill volume when compacted at or near a moisture content of 90% as compared to baseline moisture conditions (i.e., 45% moisture content).

The unit weights were somewhat lower in the full-scale tests on MSW compared to the meso-scale tests on RMSW. This difference was mainly attributed to the presence of bulkier items in the MSW such as furniture, appliances, and large quantities of plastic packaging materials, which were not present in the RMSW. A tighter packing arrangement was possible with the predominately smaller items present in the RMSW than with the mixture including larger and bulkier items present in the full MSW stream.

A composite plot based on data obtained in this investigation and field and laboratory data reported by Hanson et al. (2010) is presented in Fig. 5. Compaction curves for fresh MSW (i.e., waste disposed of in landfills) have higher maximum dry unit weight and steeper dry- and wet-of-optimum slopes as compared to compaction curves for manufactured MSW prepared in a controlled laboratory environment. The difference between field and laboratory MSW compaction curves was attributed to the difference in the waste constituent matrix/structure and the compaction effort applied. The relative uniformity of a given constituent component, relatively small particle sizes, and highly controlled procedures of compaction testing in the laboratory yielded somewhat idealized compaction curves for MSW. In addition, the distribution of compaction effort was different between field and laboratory conditions. While the 4X modified compaction effort in the laboratory was considered representative of field conditions overall, the forces associated with application of this effort in the field and in the laboratory differed significantly between the 390 kN compactor with kneading compaction versus the 40 N hammer with impact compaction. Compaction results in rearrangement of the solids fraction (decreasing the interparticle voids) as well as influences the structure of the solids fraction (exposing intraparticle voids). Field scale compaction permits significant breakdown and densification of the constituent components of the wastes. Larger differences in unit weight can occur in the field with the significant crushing/rearrangement of the large items as well as small components in fresh MSW compared to more incremental increases in unit weight of manufactured MSW due to less crushing/rearrangement of the particles in the laboratory (Hanson et al., 2010).

3.2. Moisture conditions

Results of the detailed moisture content data obtained for baseline conditions at SMRL are presented in Figs. 6 and 7. Monthly

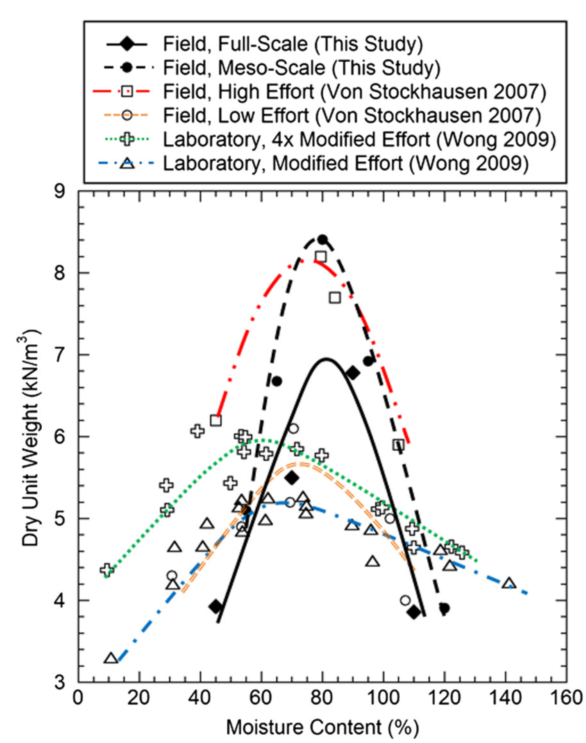


Fig. 5. Compaction curves for MSW.

average moisture content for the MSW at the site varied between 37.3% in August and 46.3% in June with an overall average of approximately 45% for a one-year period. The moisture content did not vary significantly with season during the study period. Higher seasonal variation was expected at the site. However, precipitation during the designated wet season (October 2012–April 2013) was unusually low (156 mm for study period as compared to 356 mm for 30-year average) with one of the driest seasons on record during a prolonged drought. This low precipitation resulted in the low variation in moisture content during the study period with slightly elevated conditions in June due to a high amount of agricultural discards. Moisture contents for the three main individual categories of the waste stream: residential, commercial, and self-delivered, are presented in Fig. 7. The highest moisture content was measured for residential municipal solid waste (average 58%), followed by commercial waste (average 46%), and the lowest moisture contents were obtained for self-delivered wastes (average 12%).

The results of the post-compaction moisture content analysis for the meso-scale tests are presented in Fig. 8 for tests conducted on compacted layers with moisture contents of 45%, 65%, and 80%. The measured moisture contents were higher than the target moisture contents. Moisture transfer was observed between the waste layers. In consecutive days of moisture addition, the moisture content of the waste layers increased progressively (Fig. 8a). Moisture moved downward (Fig. 8a through c) due gravity-induced infiltration as well as upward due to pumping effects. Free moisture was observed in the surface layer of Test Pit 2 (Fig. 8a and b). Difficulties occurred in operation of the compaction equipment on the third day of 80% target moisture addition in Test Pad A during preliminary testing. The 2-to-1-placement method (2 dry: 1 wet) resulted in somewhat less variation between the target and measured moisture contents as observed in Test Pit 3 (Fig. 8c). In addition to moisture transfer between waste layers, potentially higher moisture contents of incoming wastes than the measured average baseline moisture content of the RMSW or lower weight of the incoming wastes than the targeted average value also may have contributed to the elevated measured moisture contents compared to the target values.

The results of the post-compaction moisture content analysis from the test pits in the full-scale tests are presented in Fig. 9.

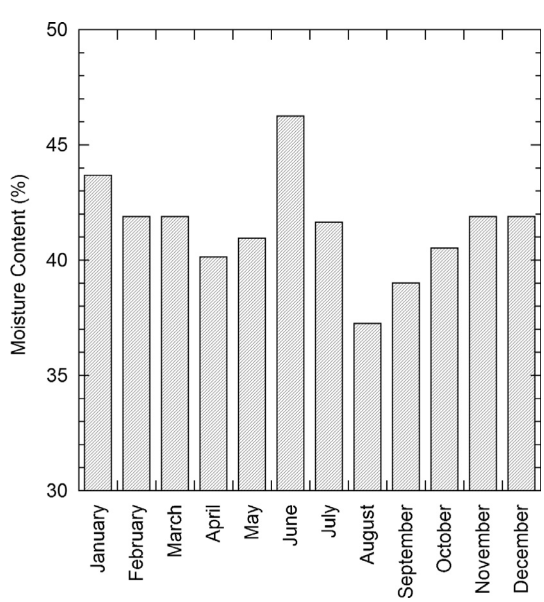


Fig. 6. Baseline moisture conditions at the test site.

Similar to meso-scale tests, the measured moisture contents were higher than the target moisture contents. Downward movement of moisture occurred in the full-scale tests.

The results of the surface moisture content analysis in the full-scale tests are presented in Fig. 10. Ponding of the added moisture on the waste surface, in particular over low areas created by the wheels of the waste compactor, was observed during sampling from surface of the compacted wastes. Pumping of moisture from below the surface likely contributed to the ponding. The added day between the tests at elevated moisture contents was implemented to ensure penetration of the surface water throughout the compacted waste lift thickness to prevent adverse interactions in the compaction of the next layer. The average moisture contents were 34.0 ± 16.1% and 133.9 ± 27.9% for as-received and target 90% moisture content, respectively (Fig. 10). The amount of incoming wastes on the 90% target moisture content test day was determined to be 2211 kN based on the scale house data obtained at the end of the test day, which was lower than the average incoming daily waste weight of 2940 kN. Using the scale house data (that became available after the compaction tests), the moisture content of the waste mass was calculated to be 103%. This calculated value was more in line with the measured moisture contents presented in Fig. 10.

Degree of saturation (S) and volumetric moisture content (θ) also were evaluated in the test program. The degree of saturation is defined as the quotient of the volume of water and the volume of voids. The volumetric moisture content is defined as the quotient of the volume of water and the total volume. In meso-scale tests, the S and θ ranged from 44% to 53% and 29% to 39%, respectively, based on the data obtained from the test pit moisture measurements. In full-scale tests, the S and θ ranged from 46% to 59% and 33% to 42%, respectively, based on the data obtained from the test pit moisture measurements. The field capacity of MSW expressed as volumetric moisture content was reported to range from 22% to 71% with the great majority of the data in the 30–55% range (Qian et al., 2002). Anaerobic decomposition of wastes is optimized at moisture contents at and above field capacity (San and Onay, 2001). The volumetric moisture contents of the compacted wastes at elevated moisture contents were in the 30–55% range for the majority of the conditions tested herein. Gravimetric moisture contents on wet basis (w_{wet}), higher than 25% and up to 40–70%, were reported to represent optimum conditions without complete saturation in bioreactor landfill applications (Baker and Eith, 2000; Phaneuf, 2000). The w_{wet} was determined to be 35–52% in meso-scale tests and 31–52% in full-scale tests providing conditions within the range of values presented in the literature (Baker and Eith, 2000; Phaneuf, 2000; Qian et al., 2002) associated with enhanced waste decomposition.

4. Practical implications

To assess practical implications of moisture addition during compaction, analyses are provided to demonstrate the effects of compaction at variable moisture conditions on engineering properties of wastes. Settlement was predicted for landfilling conditions similar to the full-scale test program. Hydraulic conductivity and shear strength tests on wastes as a function of compaction water content are summarized. Financial aspects (both costs and revenues) were analyzed for a simulated landfill similar to the test site to investigate the feasibility of moisture addition at time of compaction from a facility operation perspective in addition to the analysis of potential implications on the engineering response of the waste mass. Furthermore, financial analysis is provided to compare moisture addition at time of compaction to the

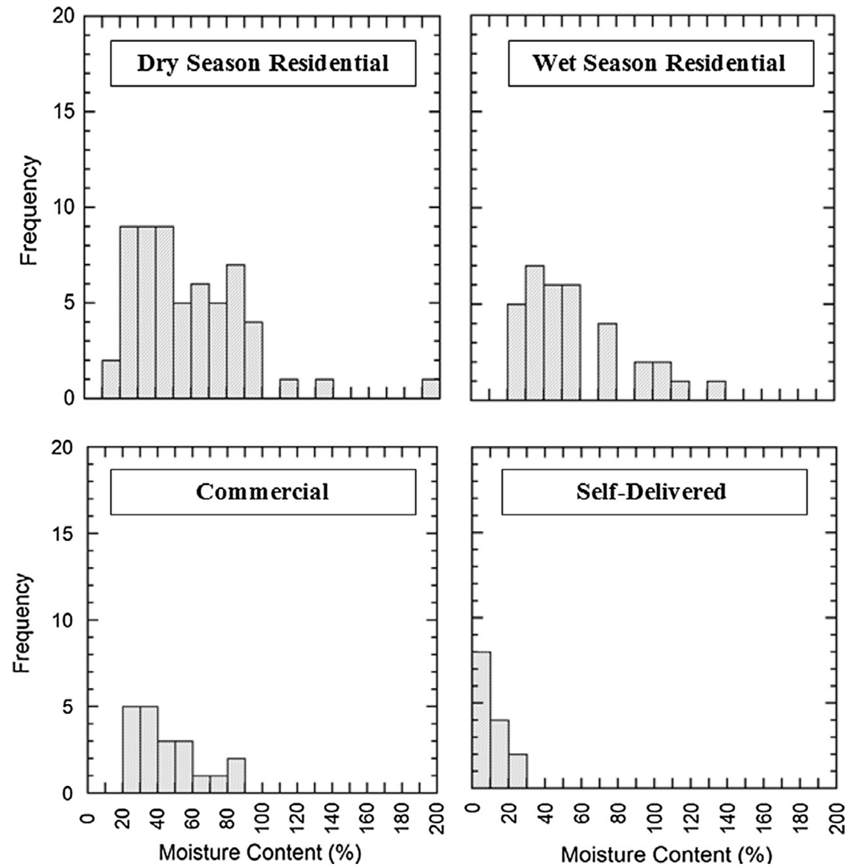


Fig. 7. Baseline moisture contents of waste constituents at the test site.

alternative approach of moisture addition to a waste mass through a bioreactor application.

4.1. Settlement analysis

Potential long-term effects of the moisture addition at the time of compaction were assessed by evaluating the settlement characteristics of the variably compacted wastes. Compressibility of wastes is directly influenced by the unit weight of wastes. In addition, compressibility is influenced by potential changes in degradation processes in the landfill. Predicted settlement was calculated as the summation of initial compression and secondary compression. The initial compression of MSW was estimated using the waste compressibility index (*WCI*) developed by Bareither et al. (2012a). The *WCI* was used to predict C_c' for MSW based on moisture content, dry unit weight, and organic content. The secondary compression was estimated using the approach provided by Sowers (1973). The combined effects of mechanical creep and biological degradation induced settlement were estimated using the modified secondary compression index (C_α') in this formulation. More sophisticated models with decoupled effects of creep and degradation were not included due to lack of data on creep- or biodegradation-dependent compression behavior of variably compacted wastes.

The initial compression was calculated using Eqs. (5) through (7). The moisture contents and dry unit weights from the full-scale tests were used in the analysis. The average organic content of the fresh wastes at the site was determined in the laboratory tests to be 77% in accordance with ASTM D2974 (Yesiller et al., 2014).

$$WCI = w \cdot \left(\frac{\gamma_w}{\gamma_d}\right) \cdot \left(\frac{OC}{100 - OC}\right) \quad (5)$$

$$C_c' = 0.26 + 0.058 \cdot \log(WCI) \quad (6)$$

$$S_i = H \cdot C_c' \cdot \log\left(\frac{\sigma'_{vo} + \Delta\sigma'_v}{\sigma'_{vo}}\right) \quad (7)$$

where w is the moisture content of waste, γ_w is the unit weight of water, γ_d is the dry unit weight of waste, OC is the organic content of waste, C_c' is the modified compression index, S_i is the initial settlement of a given waste lift, H is the initial thickness of a given waste lift, σ'_{vo} is the initial vertical effective stress at the midheight of a waste lift, and $\Delta\sigma'_v$ is the induced change in vertical effective stress at the midheight of a waste lift.

The modified secondary compression index (C_α') for the as-received moisture conditions was determined to be 0.029 based on settlement data obtained from magnet extensometer arrays placed at 8 locations within the waste mass to depths between 3.6 and 22.3 m. An example schematic of the measurement system and settlement data obtained at this location are provided in Fig. 11. The C_α' values were determined over the entire thickness of Lift II and Lift I (assuming constant liner elevation) to be 0.019 and 0.031, respectively (Fig. 11b). Data presented in the literature (Lamothe and Edgers, 1994; Hossain et al., 2003; Benson et al., 2007; Bareither et al., 2010, 2012b; Gourc et al., 2010) were used for estimating C_α' for elevated moisture contents (i.e., optimum and wet of optimum). The modified secondary compression index (C_α') was assumed to be the summation of the weighted average of mechanical creep compression rate (30%) and biochemical

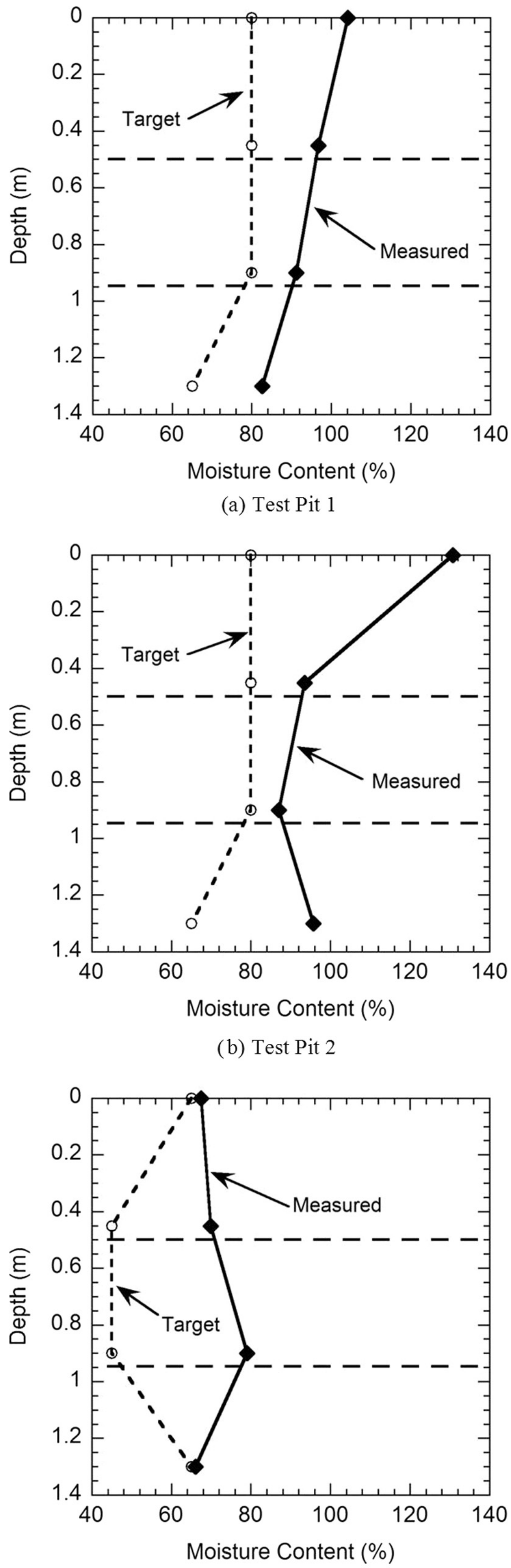


Fig. 8. Variation of moisture content of compacted wastes with depth in the meso-scale tests.

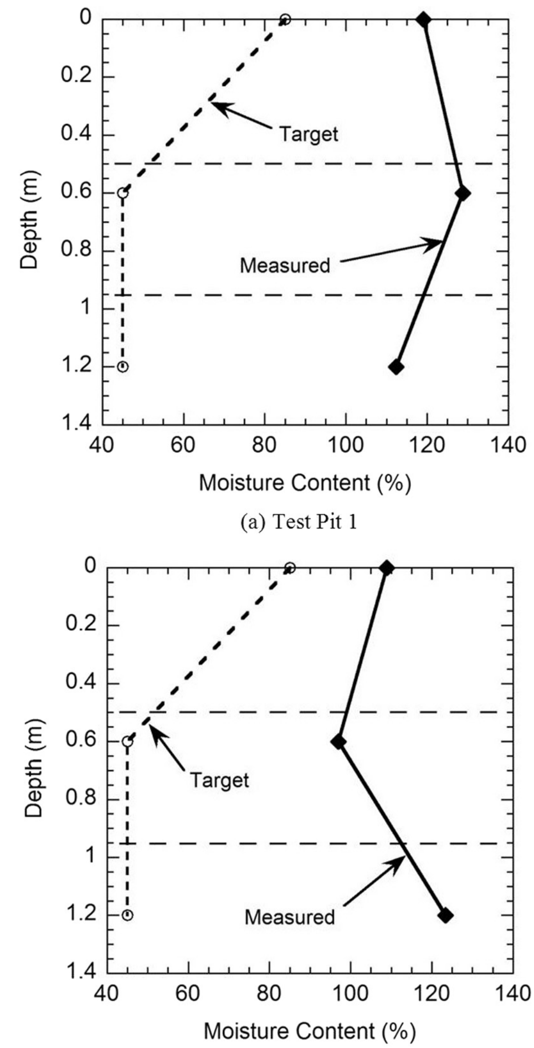


Fig. 9. Variation of moisture content of compacted wastes with depth in the full-scale tests.

compression rate (70%). The mechanical creep compression rate was set to the same value for optimum and wet of optimum conditions, whereas the biochemical compression rate was increased for increasing moisture contents using data provided in the literature for bioreactor landfills (Lamothe and Edgers, 1994; Hossain et al., 2003; Benson et al., 2007; Bareither et al., 2010, 2012b; Gourc et al., 2010). The mechanical creep compression rate used in the analysis was 0.036 representing an average of values reported in literature. Values of biochemical compression rate reported in literature were averaged to obtain a rate for optimum compaction conditions (0.215), whereas the high reported values were used for biochemical compression rate for wet of optimum conditions (0.36). Details of the analysis are presented in Cox (2013). Secondary settlement was calculated using Eq. (8).

$$S_s = H' \cdot C'_\alpha \cdot \log\left(\frac{t_f}{t_i}\right) \tag{8}$$

where S_s is the secondary compression of a given waste lift (combination of mechanical creep and biochemical compression), H' is the

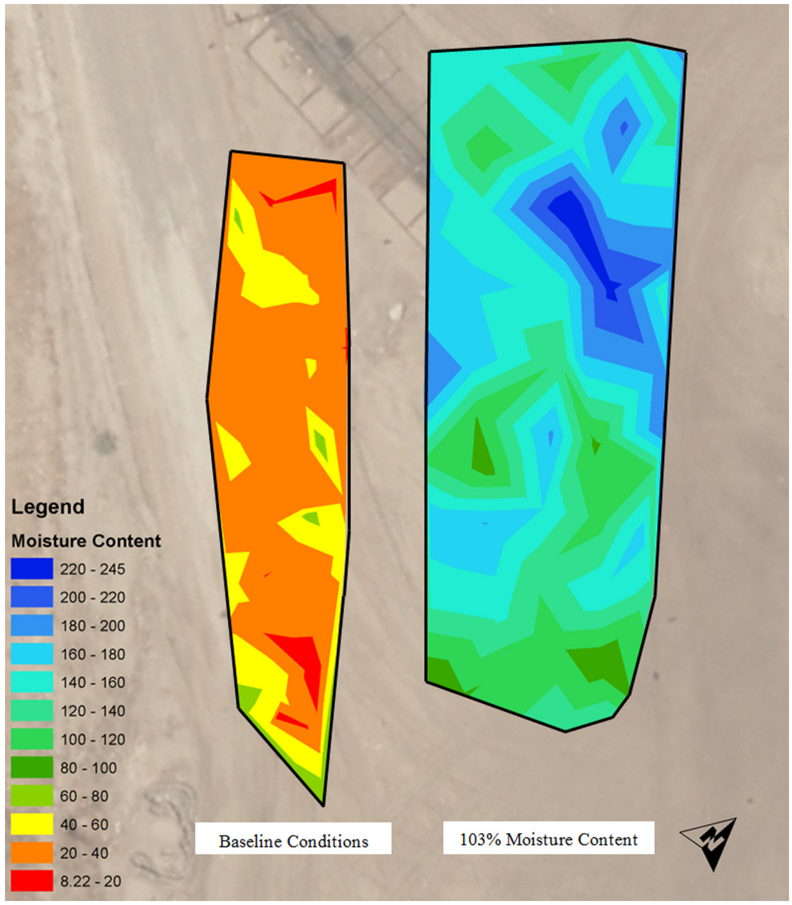


Fig. 10. Distribution of moisture content in the active face.

thickness of the waste lift after initial compression, C'_{α} is the modified secondary compression index, t_f is time associated with end of secondary compression phase being investigated, and t_i is time associated with onset of secondary compression (i.e., end of initial compression phase).

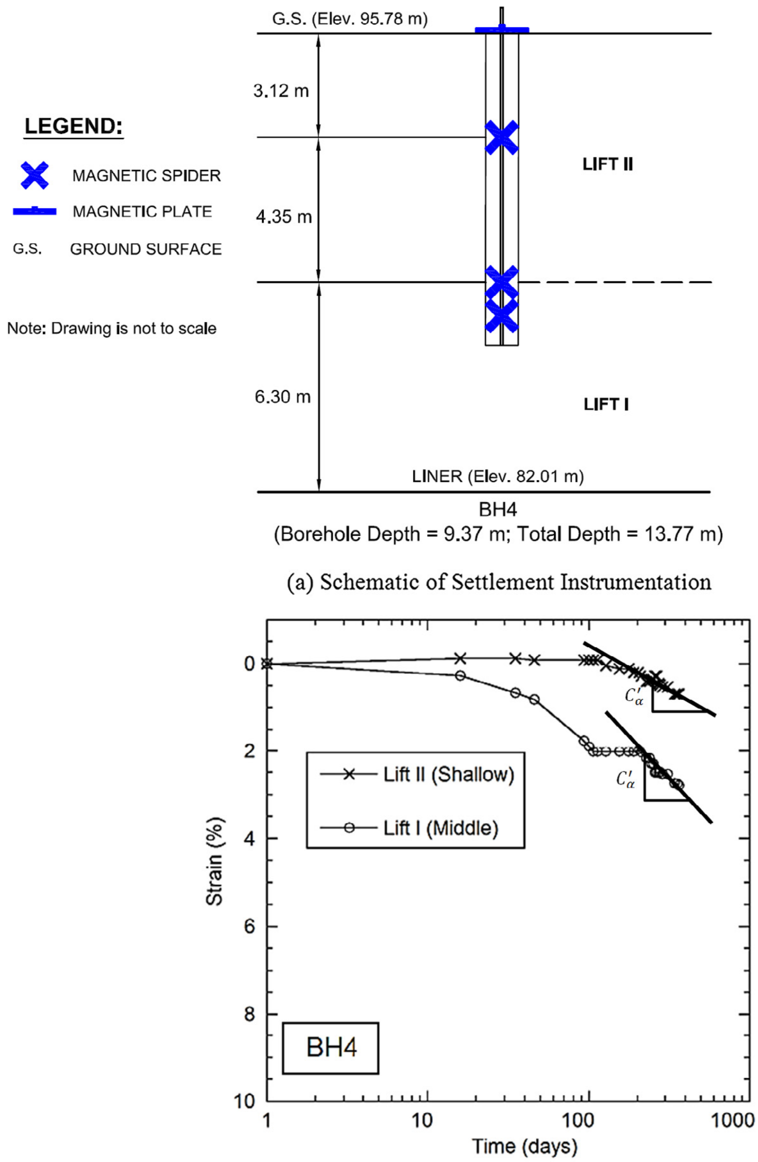
Analysis was conducted for three cases: as-received moisture (45%), optimum moisture (80.5%), and wet of optimum moisture content (110%) conditions to estimate the trends in settlement characteristics of MSW as a function of placement conditions. Settlement was calculated for a waste layer with a thickness of 10 m. The waste was assumed to be overlain by another waste layer with an initial thickness of 10 m (unit weight of 9.81 kN/m^3) and an intermediate soil cover with a thickness of 0.5 m (unit weight of 18.9 kN/m^3). The secondary compression analysis was conducted for a duration of 10 years to represent a practical timeline to predict recovery of airspace prior to final cover placement.

Results of the settlement analysis are presented in Table 3. The initial compression was similar for as-received and optimum moisture content conditions and was slightly higher for wet of optimum moisture content. The magnitude of secondary settlement was higher than that of initial settlement for all cases and the secondary settlement increased with moisture content. In line with the trend for secondary settlement, total settlement also increased with increasing moisture content. For the 10-m-thick waste layer, the estimated total settlements were 2.5, 3.8, and 5.6 m for 45%, 80.5%, and 110% moisture contents, respectively at the end of the 10-year analysis period.

4.2. Hydraulic conductivity and shear strength

Hydraulic conductivity and shear strength of wastes were analyzed as a function of compaction conditions using laboratory testing. Hydraulic conductivity tests were conducted on manufactured MSW samples compacted using static compaction to match dry unit weights associated with 4X modified effort (Fig. 5). Large-scale (350 mm diameter) dual-ring rigid wall hydraulic conductivity tests were used to determine the variation of k for variably compacted wastes as the moisture content increased from dry of optimum to optimum to wet of optimum conditions. The hydraulic conductivity for wastes was determined to be highly sensitive to moisture content at time of compaction, where the k ranged from 1.28×10^{-4} m/s (for the driest specimen) to 7.99×10^{-7} m/s (for w_{opt} specimen). The k values decreased sharply at moisture contents approaching w_{opt}. At moisture contents greater than w_{opt}, the k values remained nearly constant (Fig. 12).

Shear strength analysis was conducted using large scale (300 mm × 300 mm) direct shear tests on manufactured waste prepared using static compaction to match dry unit weights associated with 4X modified effort (Fig. 5). The normal stress used in the tests was 200 kPa. The shear strength of wastes was determined to be sensitive to moisture content at time of compaction. Shear strength varied significantly with compaction conditions, where the secant internal angle of friction (with an assumption of zero cohesion) decreased from approximately 40° to 30° for a change in moisture content from 11% to 110% (Fig. 12). Additional details regarding the hydraulic conductivity and shear strength



(a) Schematic of Settlement Instrumentation

(b) Settlement Data Used to Determine C'_α for Baseline Moisture Conditions

Fig. 11. Example field settlement analysis.

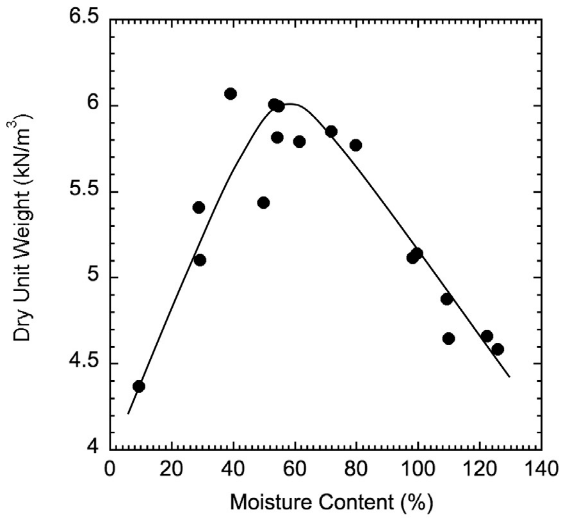
Table 3
Settlement analyses.

Placement condition	*WCI*	γ_t (kN/m^3)	H_o (m)	σ'_{vo} (kPa)	$\Delta\sigma'_v$ (kPa)	C'_c	H' (m)	t_i (days)	t_f (days)	C'_α	S_i (m)	S_s (m)	Total settlement (m)
Dry of optimum (as-received)	3.81	5.7	10	28.5	108	0.294	8.0	60	3650	0.029	2.0	0.4	2.4
Optimum	3.85	12.7	10	63.4	108	0.294	8.7	60	3650	0.161	1.3	2.5	3.8
Wet of optimum	9.49	8.1	10	40.5	108	0.317	8.2	60	3650	0.263	1.8	3.9	5.6

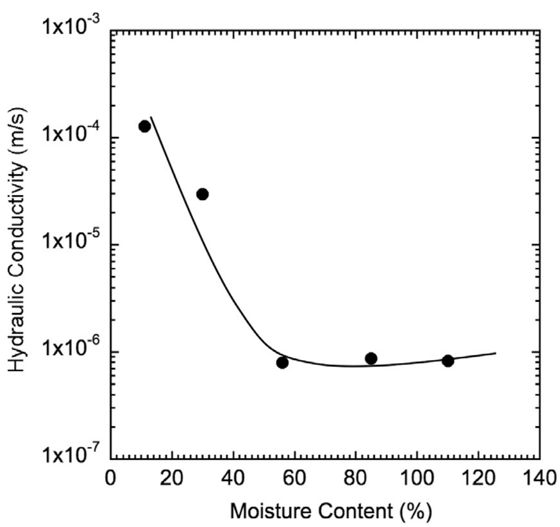
tests are provided in Wong (2009), Yesiller et al. (2010), and Hanson et al. (2012). Applying the trends observed in the laboratory tests to field conditions, significant changes can be expected in hydraulic conductivity and shear strength characteristics of wastes compacted with moisture addition in the field as the water content varies from dry of optimum to optimum to wet of optimum conditions. The ponding and pumping of water in field compaction tests demonstrated evidence of reduced hydraulic conductivity at elevated moisture content. The difficulty with operation of compactors demonstrated evidence of reduced shear strength at elevated moisture content.

4.3. Financial analysis

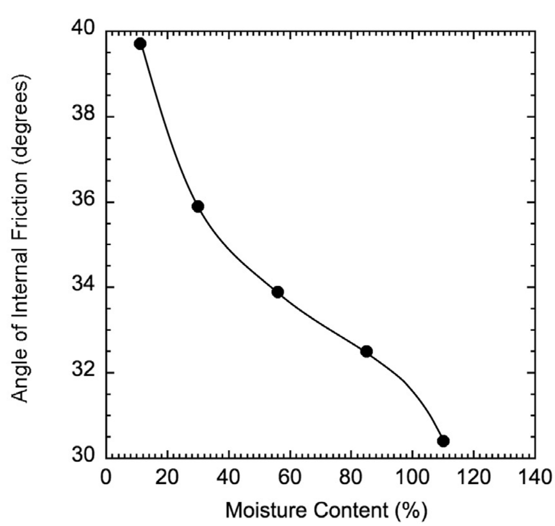
A financial analysis was conducted to compare addition of moisture to MSW at the time of waste placement to moisture addition



(a) Compaction Curve for 4X Modified Effort



(b) Hydraulic Conductivity



(c) Shear Strength

Fig. 12. Variation of engineering properties with compaction.

through delivery systems (piping networks or pervious blankets) installed through wastes that have reached semi-permanent heights (typically used for bioreactor applications). The costs associated with compaction moisture addition included cost of water; water truck operation and maintenance costs; and leachate management costs. The revenues associated with moisture addition during compaction included those resulting from airspace gain at the time of compaction; airspace gain due to settlement of compacted wastes; and revenues from enhanced gas production. The costs associated with bioreactor application included construction/installation of a moisture delivery system; operation and maintenance of the system; and leachate management costs. The revenues associated with bioreactor application included those resulting from airspace gain due to settlement of wastes and revenues from enhanced gas production. Data from the full-scale compaction analysis were used in the financial calculations. The following assumptions and parameters were incorporated into the financial comparison of a simulated landfill using the compaction moisture addition approach and a bioreactor landfill (additional details of the financial analysis are provided in Cox (2013)):

- both the simulated landfill and the bioreactor landfill had a cell footprint of 10 ha;
- 735,000 kN of waste was placed in each ha;
- the tipping fee was $7.1/kN;
- the financial analysis was conducted for a 5-year-period;
- the costs and revenues associated with as-received conditions were considered baseline;
- The operational unit weight of waste was 5.7 kN/m^3 both for the baseline conditions at the simulated landfill and for the bioreactor landfill;
- For the simulated landfill, two placement scenarios in addition to baseline conditions were analyzed: optimum moisture, γ_{oper} = 9.8 kN/m^3; wet of optimum moisture, γ_{oper} = 5.5 kN/m^3;
- for the simulated landfill, 83 days of moisture addition was applied in a given year based on the 2-to-1-placement method and 250 days of operation at the facility;
- for the simulated landfill, the amount of leachate generated for optimum and wet of optimum conditions were conservatively assumed to be 10% and 20% higher than as-received conditions, respectively. The conservative assumption was based on field records demonstrating no increase in measured leachate volume during the test program or in the year following the test program (Clarin, 2014);
- leachate treatment costs of $0.024/L, provided by Berge et al. (2009) were used for both cases;
- construction costs for a gas collection system, leachate recirculation system, and air injection system for the bioreactor landfill were based on data provided by Berge et al. (2009);
- construction costs for a gas collection system for the simulated landfill was assumed to be equal to the costs associated with construction of the gas collection system for a bioreactor landfill;
- settlement over a 5-year duration at the simulated landfill was calculated as the summation of initial settlement and secondary settlement based on the approach described in Section 4.1;
- the bioreactor landfill underwent a total settlement of 20% of the original height over the 5-year-period subsequent to active waste filling based on estimates provided by Berge et al. (2009); and
- for the simulated landfill, potential gas recovery revenues at elevated moisture contents were conservatively estimated to remain the same as conventional landfill levels (Berge et al. (2009) indicated a 23% increase in gas recovery revenues in bioreactor landfills compared to conventional facilities).

The results of the financial analysis are presented in Table 4. The financial comparison between the compaction moisture addition

Table 4
Financial analysis for a 5-year period.

Financial parameters	Optimum ($w = 81\%$)	Wet of optimum ($w = 110\%$)	Bioreactor landfill[a]
Costs			
Gas collection system ($/ha)	33,000	33,000	33,000
Leachate recirculation system ($/ha)	N/A	N/A	95,350
Air injection system ($/ha)	N/A	N/A	80,400
Moisture addition during compaction ($/ha)	14,000	26,100	N/A
Leachate treatment costs ($/ha)	126,500	138,000	561,000
Total costs ($/ha)	173,500	197,100	769,750
Revenue			
Settlement induced ($/5-year)	1,832,900	2,523,600	1,043,700
Moisture addition during compaction ($/ha)	561,000	−291,700	N/A
Gas recovery ($/ha)	687,480	687,480	845,600
Total revenue ($/ha)	1,431,770	648,140	949,970
Net revenue ($/ha)	1,255,270	451,040	180,220
Net revenue for 10 hectare footprint	$ 12,582,700	$ 4,510,400	$ 1,802,200

N/A = Not Applicable.
[a] Data for financial analysis of bioreactor landfills is provided by Berge et al. (2009).

and the bioreactor operation indicated that compaction at optimum conditions with moisture addition resulted in higher net revenues than the bioreactor operation. The bioreactor landfill required significant construction costs as compared to the waste placement practices implemented in this test program. Moisture addition at time of compaction provided increased waste placement amounts at the time of compaction (OWPF > 1) and increased net revenues compared to bioreactor conditions.

5. Summary and conclusions

This investigation was conducted to evaluate the influence of waste placement practices on the engineering response of municipal solid waste (MSW) landfills. Waste placement conditions were varied by altering the moisture content of the wastes at the time of initial disposal. Tests were conducted at a landfill located in California, USA in test plots (residential component of incoming MSW stream) and full-scale active face (all incoming MSW including residential, commercial, and self-delivered components). The short-term effects of moisture addition were assessed by investigating compacted unit weight and moisture characteristics of the wastes. The long-term effects of moisture addition were assessed by estimating settlement characteristics of the variably placed wastes. Effects on engineering properties including hydraulic conductivity and shear strength also were assessed. In addition, economic implications of the moisture addition at time of compaction were evaluated. Based on this investigation, the following conclusions were drawn:

1. The unit weight of the wastes increased with moisture addition to a maximum value and then decreased with further moisture addition. The compaction characteristics in the test plots were γ_{dmax} = 8.5 kN/m^3 and w_{opt} = 78.5%; $\gamma_{oper\text{-}max}$ = 13.3 kN/m^3 and $w_{oper\text{-}opt}$ = 79.5%. The compaction characteristics in the full-scale tests were γ_{dmax} = 7.0 kN/m^3 and w_{opt} = 80.5%; $\gamma_{oper\text{-}max}$ = 9.8 kN/m^3 and $w_{oper\text{-}opt}$ = 81.0%. The baseline conditions at the landfill without moisture addition were γ_d = 3.9 kN/m^3 and w = 45%.
2. The OWPF increased with moisture addition for moisture contents of 70% and 90% with values >1 and then decreased to <1 with further moisture addition at 110%. At the optimum moisture conditions, approximately 68% more waste could be placed in the same landfill volume compared to the baseline conditions.
3. Moisture addition raised the volumetric moisture content of the wastes to the range 33–42%, consistent with values at and above field capacity and raised the gravimetric moisture content on wet basis to 31–52% in the range of optimum conditions without complete saturation as targeted in bioreactor landfill applications.
4. Ponding of water on the surface of the compacted layers and moisture transfer occurred between consecutive layers of compacted wastes. A moisture addition schedule of 2 days of as-received conditions and 1 day of moisture addition was recommended.
5. Settlement of wastes was estimated to increase with moisture addition, with a 34% increase at optimum moisture compared to as-received conditions.
6. Hydraulic conductivity and shear strength of wastes also can be influenced by variable compaction conditions as indicated in laboratory tests and observed in the field.
7. For waste placement at optimum moisture content conditions, financial analysis indicated that significant added revenues were possible at the test site and also higher net financial gains were possible for the waste placement approach described in this paper compared to bioreactor applications.
8. Overall, moisture addition during compaction increased unit weight, the amount of incoming wastes disposed, biological activity potential, settlement, and landfill revenues. The combined effects have significant environmental and economic implications for landfill operations.

Acknowledgements

Funding for the investigation was provided by the City of Santa Maria, California and the Global Waste Research Institute at California Polytechnic State University. The assistance of Mr. Jeffrey Clarin (Solid Waste Manager, City of Santa Maria), Mr. Douglas Shearer (Solid Waste Landfill Supervisor, City of Santa Maria), Mr. Lance Llodes (Landfill Lead Heavy Equipment Operator, City of Santa Maria), and the staff at Santa Maria Regional Landfill were greatly appreciated. Ms. Danielle Noce assisted with the test program. Ms. Noce was supported by funds provided by the U.S. National Science Foundation under REU Site Grant: EEC-1263337.

References

ASTM D2216, 2010. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, Annual Book of ASTM Standards. American Society for Testing and Materials, West Conshohocken, PA.
ASTM D2974, 2012. Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils. Annual Book of ASTM Standards. American Society for Testing and Materials, West Conshohocken, PA.
Baker, J.A., Eith, A.W., 2000. The bioreactor landfill: perspectives from an owner/operator. In: Proceedings of the 14th GRI Conference, Hot Topics in Geosynthetics-I. Geosynthetic Institute (GSI), Folsom, PA, pp. 27–39.
Bareither, C.A., Benson, C.H., Barlaz, M.H., Edil, T.B., Tolaymat, T.M., 2010. Performance of North American bioreactor landfills. I: Leachate hydrology and waste settlement. J. Environ. Eng., ASCE 136 (8), 824–838.
Bareither, C.A., Benson, C.H., Edil, T.B., 2012a. Compression behavior of municipal solid waste: immediate compression. J. Geotechn. Geoenviron. Eng., ASCE 138 (9), 1047–1062.
Bareither, C.A., Benson, C.H., Edil, T.B., Barlaz, M.A., 2012b. Abiotic and biotic compression of municipal solid waste. J. Geotechn. Geoenviron. Eng., ASCE 138 (8), 877–888.
Benson, C.H., Barlaz, M.A., Lane, D.T., Rawe, J.M., 2007. Practice review of five

bioreactor/recirculation landfills. Waste Manage. 27, 13–29.
Berge, N.D., Reinhart, D.R., Batarseh, E.S., 2009. An assessment of bioreactor landfill costs and benefits. Waste Manage. 29, 1158–1567.
Bray, J.D., Zekkos, D., Kavazanjian, E., Athanasopoulos, G.A., Riemer, M.F., 2009. Shear strength of municipal solid waste. J. Geotechn. Geoenviron. Eng., ASCE 135 (6), 709–722.
Clarin, J., 2014. Personal Communication, Solid Waste Manager at Santa Maria Regional Landfill. City of Santa Maria California.
Cox, J.T., 2013. Effects of Waste Placement Practices on the Engineering Response of Municipal Solid Waste, M.S. Civil and Environmental Engineering Department, California Polytechnic State University, San Luis Obispo, California.
Gourc, J.-P., Staub, M.J., Conte, M., 2010. Decoupling MSW settlement into mechanical and biochemical processes – modelling and validation on large-scale setups. Waste Manage. 30, 1556–1568.
Ham, R.K., Reinhardt, J.J., Sevick, G.W., 1978. Density of milled and unprocessed refuse. J. Environ. Eng. Div., ASCE 104 (EE1), 109–125.
Hanson, J.L., Yesiller, N., Von Stockhausen, S.A., Wong, W.W., 2010. Compaction characteristics of municipal solid waste. J. Geotechn. Geoenviron. Eng., ASCE 136 (8), 1095–1102.
Hanson, J.L., Wong, W.W., Yesiller, N., 2012. Shear strength of municipal solid waste as a function of placement conditions. In: Proceedings, 2012 Global Waste Management Symposium, pp. 1–4.
Hossain, M.S., Gabr, M.A., Barlaz, M.A., 2003. Relationship of compressibility parameters to municipal solid waste decomposition. J. Geotechn. Geoenviron. Eng., ASCE 129 (12), 1151–1158.
Lamothe, D., Edgers, L., 1994. The effects of environmental parameters on the laboratory compression of refuse. In: Proceedings of the Seventeenth International Madison Waste Conference. Department of Engineering Professional Development, University of Wisconsin-Madison, Madison, WI.
Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Koppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.
Phaneuf, R.J., 2000. Bioreactor landfills: regulatory issues. In: Proceedings of the 14th GRI Conference, Hot Topics in Geosynthetics-I. Geosynthetic Institute (GSI), Folsom, PA, pp. 9–26.
Qian, X., Koerner, R.M., Gray, D.H., 2002. Geotechnical Aspects of Landfill Design and Construction. Prentice-Hall, Inc., Upper Saddle River, New Jersey.
Reddy, K.R., Gangathulasi, J., Parakalla, N.S., Hettiarachichi, H., Bogner, J., Lagier, T., 2009. Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations. Waste Manage. Res., SAGE 27 (6), 578–587.
San, I., Onay, T.T., 2001. Impact of various leachate recirculation regimes on municipal solid waste degradation. J. Hazard. Mater. B87, 259–271.
Sowers, G.F., 1973. Settlement of waste disposal fills. In: Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, vol. 1, pp. 207–210.
Surprenant, G., Lemke, J., 1994. Landfill compaction: setting a density standard. Waste Age 25 (8), 42–52.
USEPA, 2013. Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2011: Full Report, EPA530-R-13-001.
USEPA, 2014. Municipal Solid Waste in the United States: 2012 Facts and Figures, EPA530-F-14-001, Office of Solid Waste. <http://www.epa.gov/osw/nonhaz/municipal/pubs/2012_msw_fs.pdf> (accessed 28.07.14).
Wong, W.W., 2009. Investigation of Geotechnical Properties of Municipal Solid Waste, M.S. Thesis. California Polytechnic State University, San Luis Obispo, California.
Yesiller, N., Wong, W.W., Hanson, J.L., 2010. Hydraulic conductivity of municipal solid waste as a function of placement conditions. In: Datta, M., Srivastava, R.K., Ramana, G.V., Shahu, J.T. (Eds.), Proceedings of the 6th International Congress on Environmental Geotechnics, vol. 1. McGraw Hill, pp. 457–462.
Yesiller, N., Hanson, J.L., Cox, J.T., Noce, D.E., 2014. Determination of specific gravity of municipal solid waste. Waste Manage. 34 (5), 848–858.