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# Evaluation of the geotechnical properties of MSW in two Brazilian landfills

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ABSTRACT

The characteristics of municipal solid waste (MSW) play a key role in many aspects of waste disposal facilities and landfills. Because most of a landfill is made up of MSW, the overall stability of the landfill slopes are governed by the strength parameters and physical properties of the MSW. These parameters are also important in interactions involving the waste body and the landfill structures: cover liner, leachate and gas collection systems. On the other hand, the composition of the waste, which affects the geotechnical behavior of the MSW, is dependent on a variety of factors such as climate, disposal technology, the culture and habits of the local community. It is therefore essential that the design and stability evaluations of landfills in each region be performed based on the local conditions and the geotechnical characteristic of the MSW. The Bandeirantes Landfill, BL, in São Paulo and the Metropolitan Center Landfill, MCL, in Salvador, are among the biggest landfills in Brazil. These two disposal facilities have been used for the development of research involving waste mechanics in recent years. Considerable work has been made in the laboratory and in the field to evaluate parameters such as water and organic contents, composition, permeability, and shear strength. This paper shows and analyzes the results of tests performed on these two landfills. The authors believe that these results could be a good reference for certain aspects and geotechnical properties of MSW materials in countries with similar conditions.



## 1. Introduction

The design of waste disposal centers has been a challenge for geotechnical engineers. The complicated behavior and the unknown aspects of the geotechnical properties of MSW have been the source of many problems in landfill sites. The behavior of the waste body is a controlling factor in the stability of engineered landfill structures. Large-scale displacements may lead to collapse and loss of integrity of lining components, affecting their serviceability. The geomembranes and the mineral barriers can be punctured/sheared and the geotextile protection layers and geocomposite drains can be damaged and/or become discontinuous (Dixon and Jones, 2005).

Landva and Clark (1986, 1990) were pioneers in waste mechanics and they carried out several research projects to form a sound engineering basis for stability analysis of landfills. Jessberger and Kockel (1993), Gabr and Valero (1995), Grisolia et al. (1995), Kölsch (1995), Kavazanjian et al. (1995), Grisolia and Napoleoni (1996), Manassero et al. (1996), Mahler et al. (1998), Mazzucato et al.(1999), Kavazanjian (1999), Carvalho (1999), Pelkey et al. (2001), Machado et al. (2002, 2008), Caicedo et al. (2002a,b), Mahler and De Lamare Netto (2003), Xiang-rong et al. (2003), Vilar and Carvalho (2004), Towhata et al. (2004), Zekkos (2005), Nascimento (2007), Reddy et al. (2009a,b), Karimpour-Fard (2009) and Shariatmadari et al. (2009), are among the researchers in the field of waste mechanics who have tried to provide a clearer vision of the mechanical behavior of MSW materials. In spite of these valuable contributions there remain a number of issues in waste mechanics for which complementary studies are required. In several cases poorly established aspects of MSW mechanical behavior have caused landfill failures. The landfills of Rumpke in USA (Stark et al. 2000; Zekkos, 2005), Dona Juana in Columbia (Caicedo et al. 2002a,b), Payatas in Philippines (Merry et al., 2005) and Leuwigajah dumpsite in Indonesia (Koelsch et al., 2005) are examples of such catastrophic events, which not only cost millions of dollars in losses but also create huge sources of environmental pollution.

In landfill design and stability analysis the characterization of the mechanical behavior of the MSW is necessary as well as other specific physical properties such as composition, unit weight, water and organic contents and permeability. The water and

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**Table 1**
The necessary parameters for landfill design (Dixon and Jones, 2005).

| Design case | Unit weight | Vertical compressibility | Shear strength | Lateral stiffness | Horizontal in situ stress | Hydraulic conductivity |
|---|---|---|---|---|---|---|
| Subgrade stability | x | | x | | x | |
| Subgrade integrity | x | | x | x | x | |
| Waste slope stability | x | x | x | | | x |
| Shallow slope liner stability | x | | x | | x | x |
| Shallow slope liner integrity | x | x | x | x | x | |
| Steep slope liner stability | x | | x | | x | x |
| Steep slope liner integrity | x | x | x | x | x | |
| Cover system integrity | x | x | x | | | |
| Drainage system integrity | x | | | | x | |
| Leachate/gas well integrity | x | x | x | x | x | x |

organic content have a direct effect on the long-term mechanical response of the MSW as they affect the processes of biodegradation.

Dixon and Jones (2005) describe the MSW properties required to perform stability and serviceability analysis in different approaches (Table 1). The authors also present a discussion about the modes of failure in landfills.

As MSW properties vary greatly from one region to another, the design of landfills and the improvement of the filling capacity of existing facilities should be supported by local measurement and evaluations. However, the existence of waste geotechnical characterization data, mainly data from similar places, could help engineers to obtain previous background data for the design and analysis of landfills and to help select alternatives for landfill extension.

## 2. Landfill sites

The Bandeirantes Landfill, BL, is located in the city of São Paulo on the Bandeirantes road (km 26.5 – Zone North). For several years this landfill was the main disposal center in São Paulo, receiving 10,000 Mg of waste materials daily. It started to function in 1979 and in 1999 it had occupied an area of around 100 ha. The height of the stored MSW varied from 30 to 100 m. In 1999 only two cells (AS4 and AS5) were in operation. To evaluate the geotechnical properties of the MSW in BL, the AS-2 area was selected. The age of the waste disposed in this cell was about 15 years. An area of about 450 $m^2$, was selected to perform the boreholes needed to collect the samples and to perform field tests to evaluate the density, permeability, and shear strength (SPT and CPT).

The second site, the Metropolitan Center Landfill, MCL, is located around 20 km from the center of Salvador. The daily input of MSW is about 2500 Mg. The used landfill area is about 25 ha and the filling process started in October, 1997. The initial estimated lifetime was 20 years but it is now estimated to be more than 30 years, as a result of several design modifications and improvements.

Since 2002 the company administrating the MCL (BATTRE) has been part of a technical and research cooperation program with the Geoenvironmental Laboratory at the Federal University of Bahia (UFBA). As a result of this program, a systematic monitoring of the geotechnical properties of MSW materials has been carried out, including several variables which could affect stability issues. In Fig. 1 aerial photographs of BL and MCL are presented.

## 3. Physical characterization of MSW

Since 2004 MSW samples of fresh waste have been collected each 6 months from MCL to observe any changes in the composition of the waste over time. To address the effect of aging on the key biodegradation parameters of MSW such as water and organic content, some complementary sampling campaigns were performed. Excavators were used for shallow sampling depths and drilling machines for higher depths. In BL, besides sampling of fresh waste, a drilling program was performed to collect 15-year old samples.

### 3.1. Water content determination

The MSW water content was determined using representative samples obtained after manual and machine assisted homogenization and quartering. The waste composition, wet basis, was measured immediately after sampling in a field laboratory. The waste was separated into the following component groups: paper/cardboard, plastic, rubber, metal, wood, glass, ceramic materials/stone, textile and paste fraction. The paste fraction includes organic materials that are easily degradable (food waste), moderately degradable (e.g., leaves) and other materials not easily separated.


**Fig. 1.** Aerial photographs of BL and MCL landfills.

After weighing each component the samples were placed in an oven at a temperature of 70 °C. The samples were kept in the oven until weight stabilization.

Fig. 2 compares the obtained water content values with some values reported in literature. As can be observed, the scattering in the case of MCL and BL is small comparing to the values presented by Landva and Clark (1986), Blight et al. (1992), Coumoulos et al. (1995) and Gabr and Valero (1995). Juca et al. (1997) presented relatively low moisture contents, but in this case the samples were 17 years old with an average organic content of only 10%.

This graph also shows that in the case of MCL and BL the water content of fresh MSW samples (collected before landfilling) is clearly higher than that of aged waste (collected from drilling operation). Fig. 2b shows the variation of the water content with age in these landfills.

### 3.2. Waste composition

Fig. 3 shows the average waste composition of fresh waste in BL and MCL. According to this figure the composition of waste materials in both landfills are comparable. The percentage of the main MSW components: paste, plastic and paper/cardboard are similar.

According to Machado et al. (2002, 2008), the mechanical response of MSW materials under static loading is governed mainly by the fibrous elements and the paste, which acts as a medium to hold the fibrous part, generating a reinforcement reaction. The plastic component is usually referred to as the MSW fibrous elements and it is responsible for the upward concavity of the MSW shear stress-strain curves. The average percentage of plastics in both landfills is about 20%, which could be considered high compared to the reported values in literature. If textiles and rubber are also considered reinforcement elements, the fiber content of the waste reaches about 25% in both landfills.

### 3.3. Particle size distribution

Sieve analysis was performed with opening sizes from 0.075 to 101 mm using the waste components after drying. Larger elements were measured manually. Fig. 4 presents the size distribution of different waste samples. As can be seen, the greater the age of the sample, the lower the particle size of the waste elements.

This is probably due to the effect of the biodegradation progress, which acts by disintegrating the MSW particles and making the MSW a finer material over time. In fresh waste samples, 50% of the elements are smaller than 30 mm. This percentage increases to 65, 73 and 85 for 1-, 4- and 15-year old samples, respectively. Also presented in this figure are the boundary limits for the size distribution of MSW materials suggested by Jessberger (1994). As can be seen, older samples tend to be finer than suggested by Jessberger (1994).

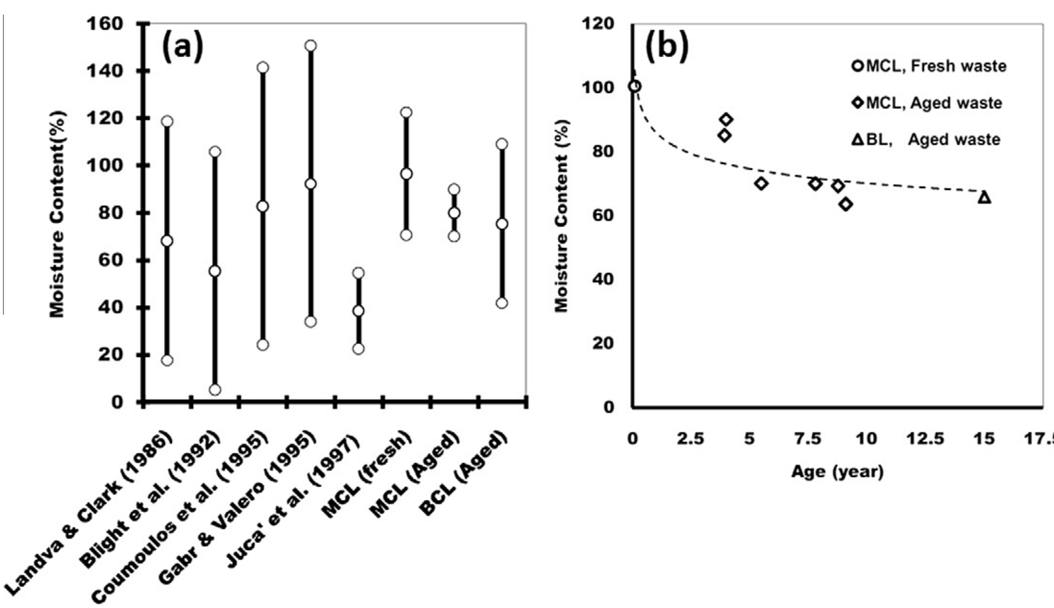


**Fig. 2.** MSW moisture content values (a) comparison with reported values in literature (b) variation with age.

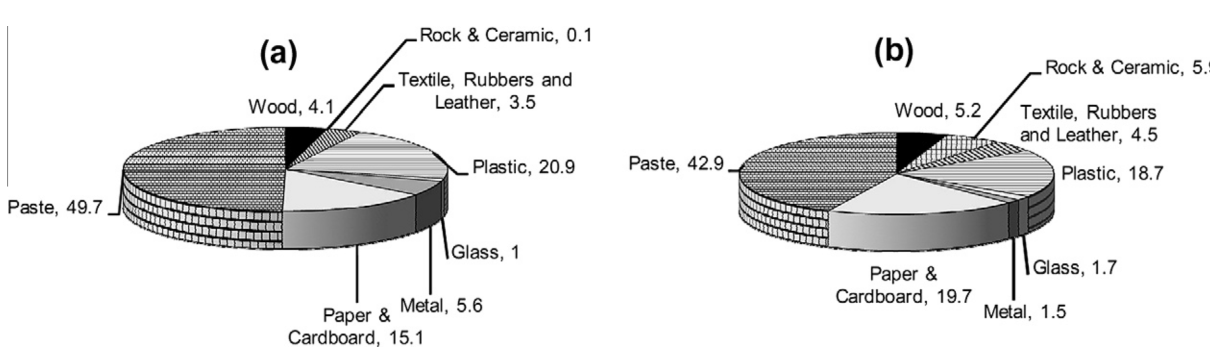


**Fig. 3.** Average fresh waste composition (a) BL and (b) MCL.

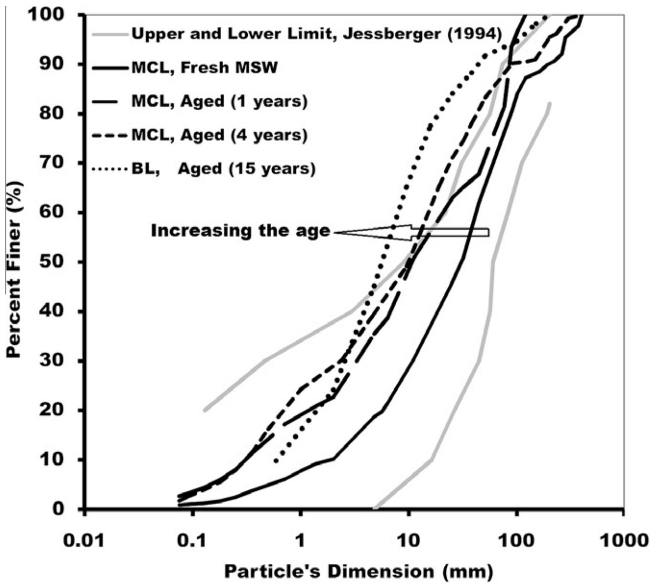


**Fig. 4.** Particles size distribution of waste samples.

### 3.4. Total volatile solids

Paste total volatile solids (TVS) were obtained after waste sieving. The paste fraction was quartered to a mass of about 1000 g and ground into particles for size reduction and to increase the specific surface. Waste samples of 20 g were placed into crucibles and dried in an oven at 70 °C for 1 h. The samples were then combusted in muffle at 600 °C for 2 h. The volatile content was computed using the ratio between the loss of mass and the dry mass before combustion. Fig. 5 presents the variation of TVS with the age of the MSW samples.

There is a sharp decrease in the paste TVS over the first 4 years. In the case of the BL waste, which is 15 years old, slightly higher values of TVS were found compared to the MCL samples. This is probably due to the differences in the climate between in Sao Paulo and Salvador. As Salvador has daily average temperatures of above 20 °C practically all year round, higher amounts of rainfall and higher air humidity compared to São Paulo, it is to be expected that the biodegradation process in Salvador occurs at a higher rate than in São Paulo.

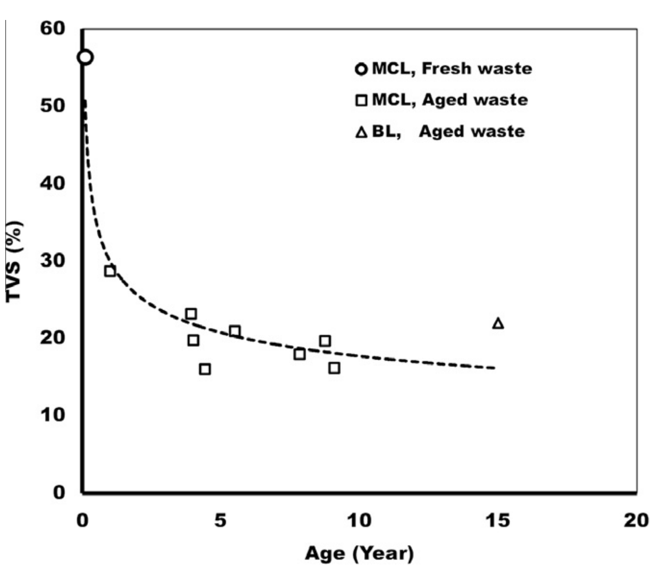


**Fig. 5.** Variation in organic content with age.

## 4. Results and discussions

### 4.1. Permeability tests

The permeability of MSW materials must be estimated for the design of the landfill containment systems (Sharma and Reddy, 2004). This parameter is important because of its influence on leachate pressure distributions in the waste body and hence on the magnitude and distribution of effective stresses and therefore on shear strength (Dixon and Jones, 2005). According to recent regulation for designing of landfills, leachate produced inside the landfill body must be collected and therefore the installation of leachate collection and removal systems is necessary. The MSW permeability is an important parameter in the design of adequate drainage systems (Reddy et al., 2009c).

Furthermore, in the case of bioreactor landfills in which leachate recirculation is used to increase the biodegradation rate and accelerate settlement stabilization, the MSW permeability is a key parameter. Incorrect estimation of the MSW permeability may lead to leachate accumulation in some parts of the landfill, resulting in a non-uniform degradation of the waste which can cause differential settlement and structural failure of the landfill components (Penmethsa, 2007).

The permeability of MSW not only varies significantly with the factors such as waste composition, compaction and overburden stress applied to the waste fill but also with the extension of the degradation process, which results in significant changes in the composition and size distribution of the waste components (Reddy et al., 2009c).

Besides all the aforementioned parameters, the plastic fragments have a considerable effect on the permeability of MSW materials. In the case of saturated flow, the virtually impermeable plastic fragments embedded in the material obstruct the flow of fluids. The larger the amount and size of the plastic fragments, the greater the influence on permeability (Xie et al., 2006).

Because of all the factors which can affect this parameter and as it is difficult to reproduce all the landfill conditions in laboratory tests, field measurement are normally considered the most reliable approach to estimate the permeability of MSW materials. However, only limited results have been reported in the literature regarding field evaluation of MSW permeability (Landva and Clark, 1986; Ettala, 1987; Oweis et al., 1990; Shank, 1993; Jain et al., 2006).

Fig. 6a presents the results of infiltration tests performed in two boreholes in BL. The scattering of the obtained values can be attributed to a large extent to heterogeneity of the MSW and to the blocking effect of the plastic components. It can be said, however, that increasing the depth and therefore the overburden stress, a decrease in waste permeability can be observed. The obtained values ranged from $10^{-5}$ to $10^{-8}$ m/s.

Fig. 6b shows the results of field measurements of MSW density, obtained after drilling of 40 cm diameter boreholes near the location of the infiltration tests. The MSW density ranged from 13 to 17.5 kN/m$^3$ and no clear tendency of variation with depth was found. This figure also presents a comparison between the measured values and the values estimated using the chart for MSW unit weight proposed by Zekkos et al. (2006). As can be observed, the proposed chart is compatible with the average trend line of the field measurements.

Fig. 7 presents laboratory results of permeability tests performed using a triaxial cell and MCL fresh waste samples with dimensions of 20 × 40 cm. The field results obtained in BL are also presented in this figure. In order to compare field and triaxial lab

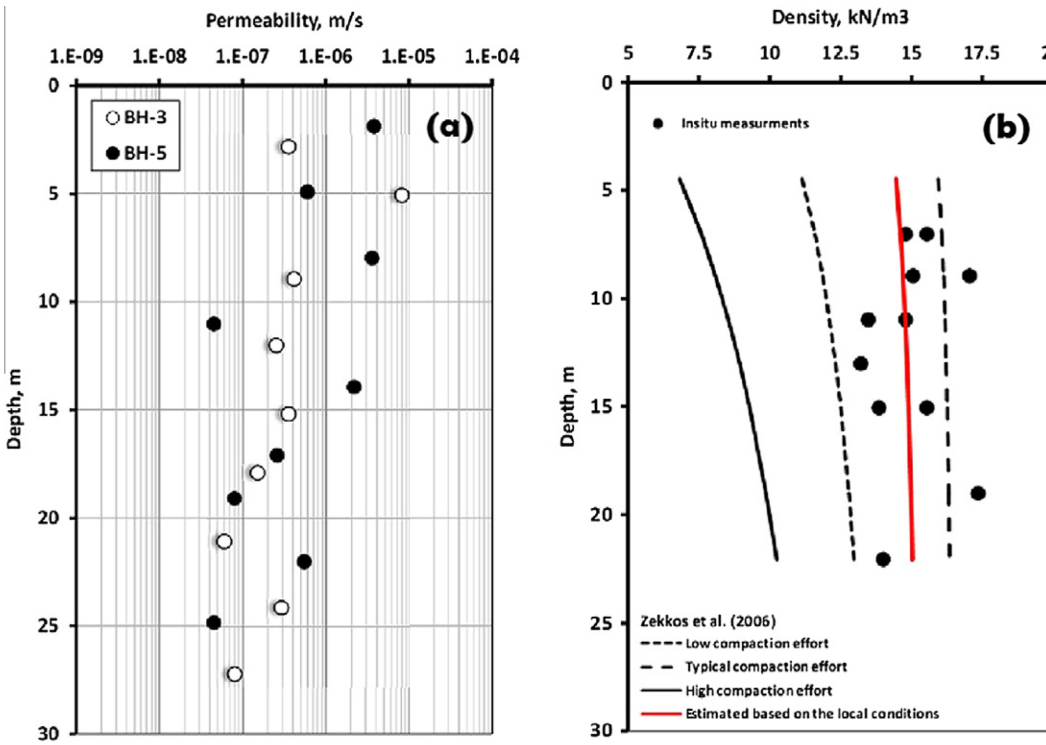


**Fig. 6.** (a) MSW permeability, BL field tests (b) BL values of MSW unit weight.

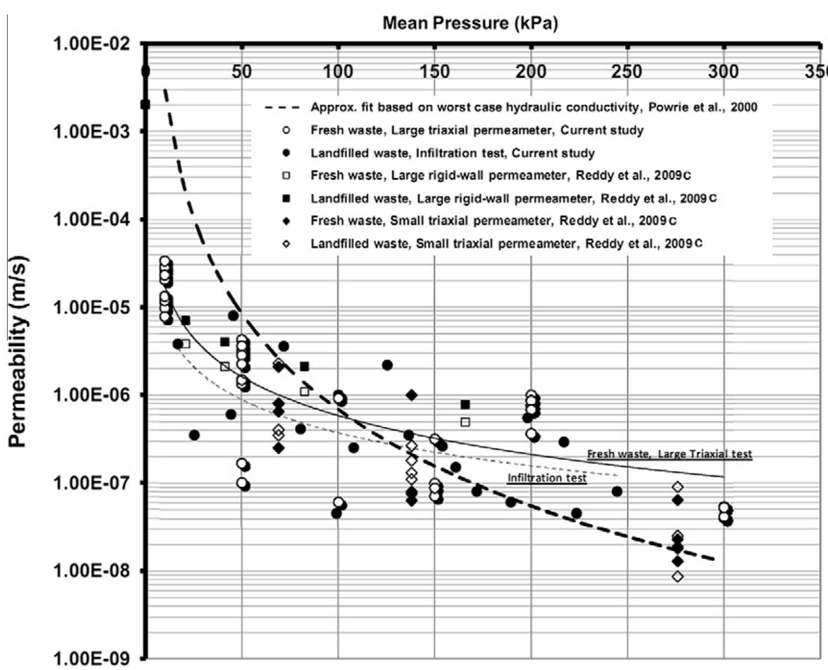


**Fig. 7.** Comparison between MCL and BL values of permeability and those reported in literature.

results an at rest pressure coefficient, $K_0$, equal to 0.4 (Singh and Fleming, 2008) was assumed. Fig. 7 also compares the experimental values of permeability obtained in MCL and BL with those presented in technical literature.

The comparison between laboratory and field tests shows fair compatibility, however, since the infiltration tests were performed on older waste, the average values of permeability are lower. This is in agreement with Reddy et al. (2009c) who stated that the decrease in permeability in aged MSW is attributed to the increase in the smaller particles resulting from degradation. Hossain et al. (2006) also concluded that with degradation the MSW structure will change and the MSW particles break down leading to a decrease in the MSW void ratio and thus a decrease in the MSW permeability.

This graph also presents the results of two other pieces of research on the permeability of MSW materials, however, there are only a few results reported in literature which directly evaluate the effect of the stress state on the permeability of MSW.

Powrie et al. (2000), using a large consolidation cell of 2 m in diameter and 3 m in height, conducted several constant head flow tests to determine the permeability of different types of household waste: raw, pulverized and aged up to 20 years. In Fig. 7, the best fit based on the worst estimation of permeability is shown. As can be seen, the proposed curve overestimates the obtained values of MSW permeability for low values of mean pressure, while the opposite occurs for high stress levels.

Reddy et al. (2009c) carried out research to evaluate permeability of fresh and landfilled MSW using a small and large-scale rigid-wall permeameter and a small-scale triaxial permeameter. Part of the reported results of this research are illustrated in Fig. 7. The results of the permeability tests (large scale) performed on fresh waste showed that the permeability changes from $2 \times 10^{-3}$ m/s under zero applied vertical stress to $4.9 \times 10^{-7}$ m/s under 276 kPa of vertical stress (166 kPa of mean pressure using a $K_o$ of 0.4). For aged waste the permeability values ranged from $2 \times 10^{-3}$ to $7.8 \times 10^{-7}$. In the case of the small-scale triaxial tests, the permeability decreased from $10^{-6}$ to $10^{-8}$ m/s when the confining pressure was increased from 69 to 276 kPa.

The results of current research at low confining stresses are comparable with data published by Landva and Clark (1986), Chen and Chynoweth (1995), Gabr and Valero (1995), Moore et al. (1997), Landva and Clark (1990), Jang et al. (2002) and Durmusoglu et al. (2006).

### 4.2. CPT and SPT tests

The standard penetration test (SPT) and the cone penetration test (CPT), are common methods to evaluate the geotechnical properties of Geo-materials and are widely used in geotechnical practices. The importance of these methods is based on their ability to overcome the problems concerning sampling and errors related to laboratory testing. So far, extensive work has been done to relate the output of these methods to the geotechnical characteristics of soil materials.

Fig. 8 shows some typical results of SPT tests performed at various landfills such as Liossia in Greece (Coumoulos et al., 1995), Meruelo in Spain (Sanchez-Alciturri et al., 1993), Muribeca in Brazil (Juca et al., 1997) and Georgia in USA (Sowers, 1968).

According to Sowers (1968) and Juca et al. (1997) the number of blows in SPT tests rarely exceeded 10. Coumoulos et al. (1995) and Sanchez-Alciturri et al. (1993) reported that the number of blows increases with depth, which indicates that the confining pressure

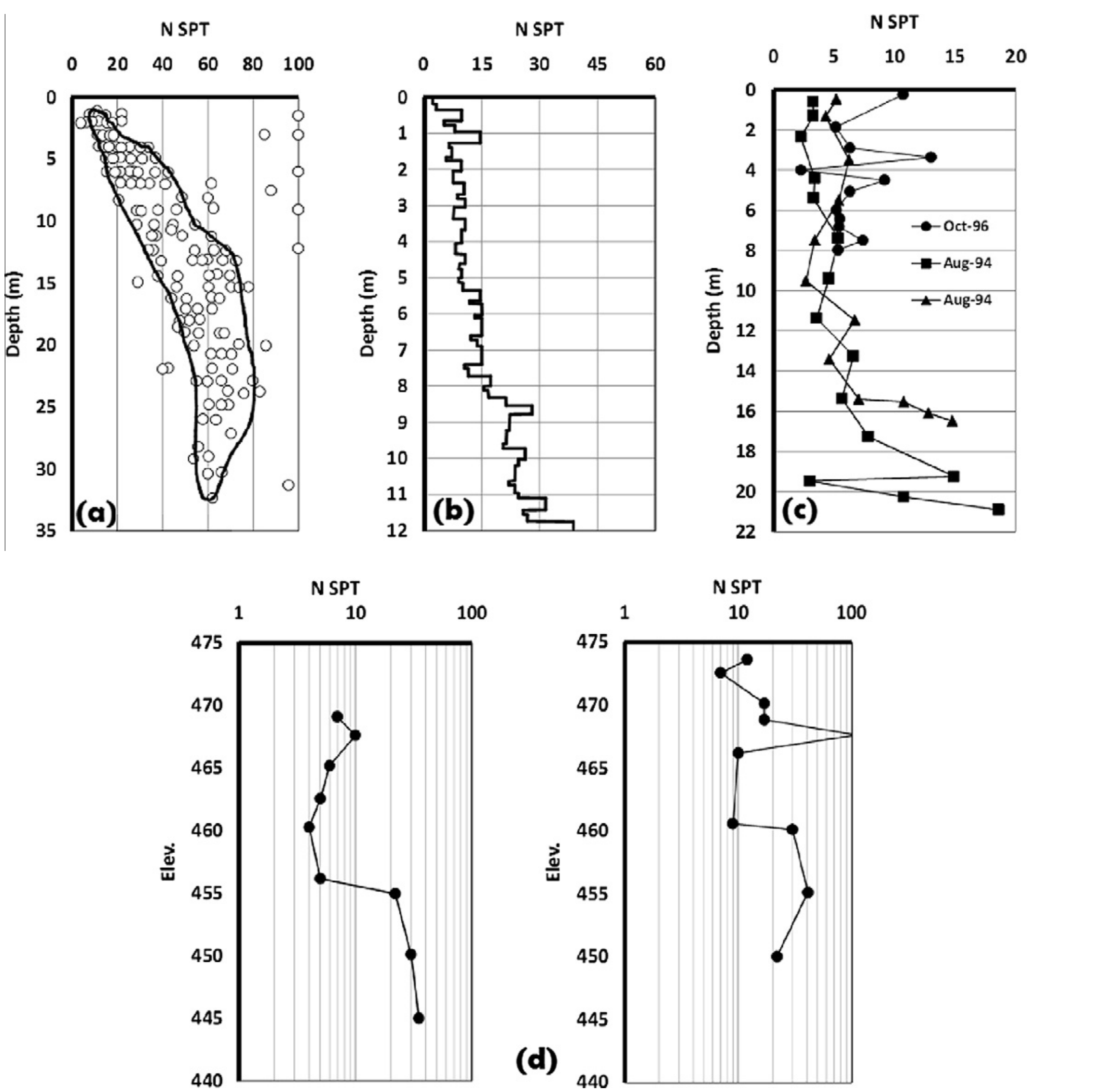


**Fig. 8.** Typical SPT results from various landfills (a) Coumoulos et al. (1995), (b) Sanchez-Alciturri et al. (1993), (c) Juca et al. (1997) and (d) Sowers (1968).

has some effect on the MSW field behavior. It can also be noted that the values reported by Juca et al. (1997) are considerably lower than values reported by Coumoulos et al. (1995) and Sanchez-Alciturri et al. (1993).

Siegel et al. (1990), Manassero et al. (1996) and Knochenmus et al. (1998) suggest that the cone penetration tests (CPT) could be used to locate regions with lower resistance inside the waste fills and also to evaluate the aging effect on the shear strength of MSW materials. Fig. 9 shows typical results of CPT tests carried out in several landfills (Cartier and Baldit, 1983; Siegel et al., 1990; Bouazza et al., 1996).

Despite the scattering of the CPT results, probably due to the high contact pressure between cone tips and the particles of stone, metal, glass and others, it may be said that the cone resistance increases with depth (Manassero et al., 1996).

Sanchez-Alciturri et al. (1993) carried out CPT tests in Meruelo landfill in Spain and reported that the CPT resistance varies from 1 to 3 MPa and the friction ratio rarely exceeds 2% with a minimum of 1%. Using the Schmertmann profiling chart (Schmertmann, 1978), they concluded that CPT results in MSW materials are consistent with those obtained in sands and clayey sand and silts. In the case of the reported results by other researchers such as Hinkle (1990) and Siegel et al. (1990), the MSW materials are rather consistent with clayey sands and silts and sandy and silty clays and exhibit more sleeve friction. Taking into account the results cited above, Sanchez-Alciturri et al. (1993) concluded that the MSW cone resistance is normally lower than 4 MPa and its friction ratio goes up to 4%. Zhan et al. (2008) shows some CPT results obtained in a landfill in China. A range from 4% to 6% was observed to the friction ratio. They also stated that the relative value of both tip resistance and sleeve friction in CPT tests is higher in the case of older wastes, however did not present an explanation for this observation.

#### 4.2.1. Standard penetration test results

Fig. 10a shows the results of SPT tests carried out at the Metropolitan Center Landfill. The results of 5 boreholes, reported by Oliveira (2002) and Fucale (2005) are shown in this graph. Fig. 10b shows the results of five SPT tests performed in BL.

The three SPT tests reported by Fucale (2005) were performed in a less than 1-year-old MCL cell. The two SPT tests performed by Oliveira (2002) used 3-year old MSW materials. In the BL tests the average age of the waste was about 15 years.

According to these graphs the $N_{SPT}$ values tend to increase with depth, corroborating the findings of Coumoulos et al. (1995) and Sanchez-Alciturri et al. (1993). This means that these materials act as frictional materials.

Fig. 11 shows the results of a statistical analysis of $N_{SPT}$ values in the 10 SPT tests in the form of a histogram-frequency graph. According to this graph the cumulative frequency of $N_{SPT}$ values in the range from 5 to 20 blows per 30 cm is a minimum of 70%. This graph also shows that the $N_{SPT}$ values barely exceed 20.

A comparison using the average values of $N_{SPT}$ with different ages (Fig. 12) shows that the $N_{SPT}$ values tend to decrease with the time elapsed. These findings are compatible with the results of Landva and Clark (1986) regarding the decrease in the shear strength of waste materials with time.

According to Machado et al. (2008, 2009), however, in regions like Brazil, because of the high water and organic contents and appropriate climate conditions from the point of view of decomposition, the high rate of biodegradation causes a considerable loss of mass over a relatively short period. At the same time, the fiber (plastic) material, which is poorly degradable, tends to increase relatively, and as a result the MSW shear strength should increase. This is corroborated by experimental results obtained from triaxial tests performed on waste samples of different ages.

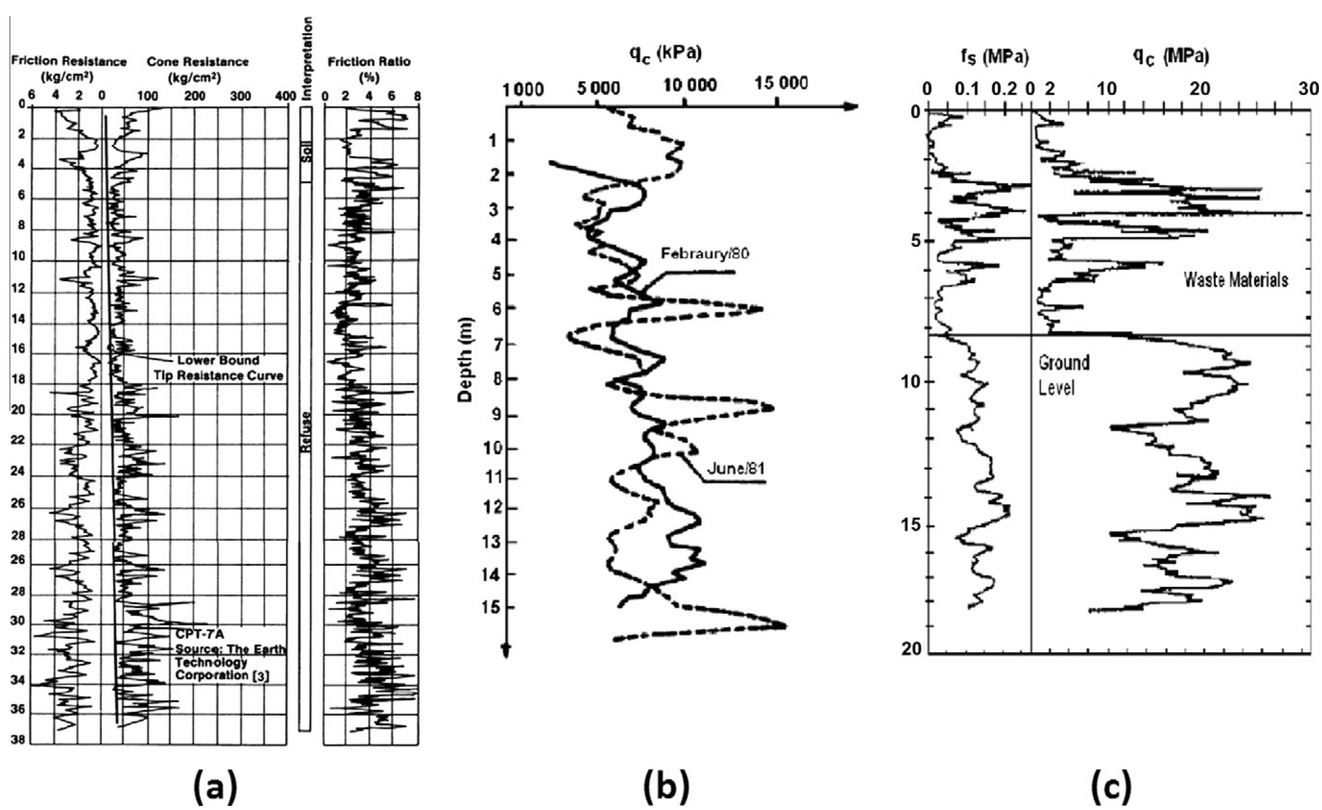


**Fig. 9.** Typical CPT results from various landfills (a) Siegel et al. (1990), (b) Cartier and Baldit (1983) and (c) Bouazza et al. (1996).

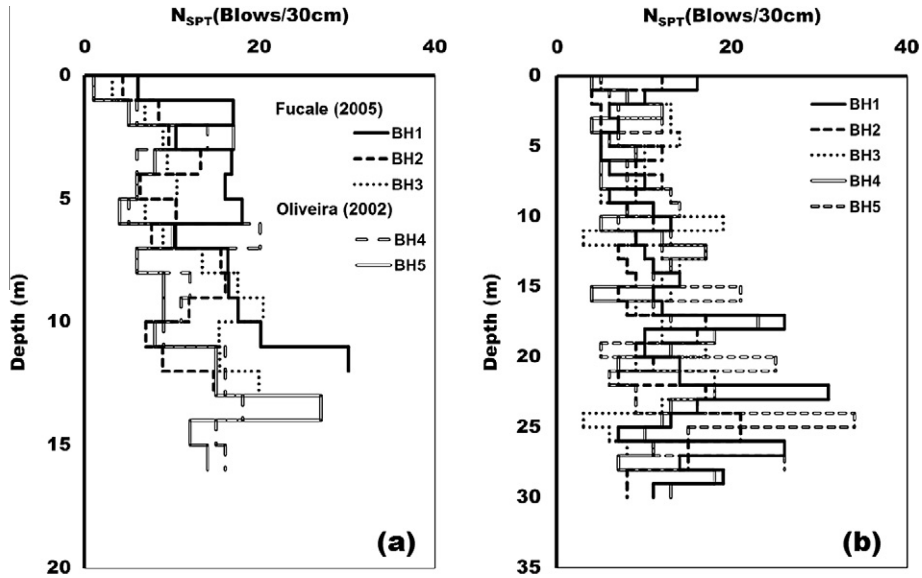


**Fig. 10.** SPT tests performed in (a) MCL and (b) BL.

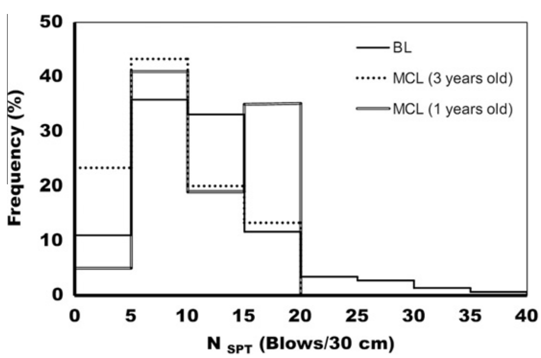


**Fig. 11.** Histogram of measured $N_{SPT}$ values.

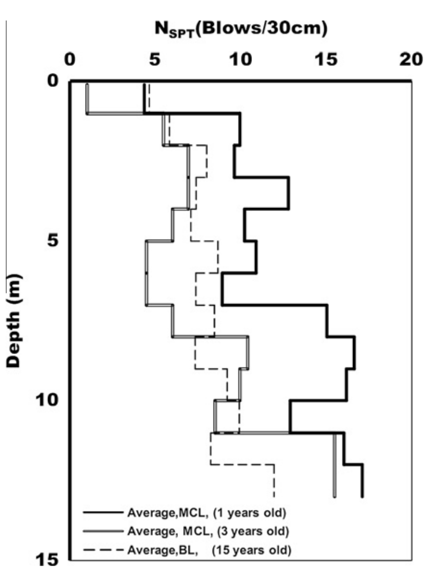


**Fig. 12.** Average $N_{SPT}$ values for MSW with different ages.

One of the probable explanations for such discrepancies in the obtained results may be the clogging of the SPT sampler or its contact with elements bigger than the opening of the SPT sampler (5.08 cm). According to Fig. 4, the percentage of elements bigger than 5.08 cm is 35%, 29%, 17% and 7% for fresh, 1-, 4- and 15-year old waste, respectively.

The $N_{SPT}$ values obtained in MCL using 3-year old waste are similar to those obtained in BL using in 15-year old waste. On examination of Fig. 5, which shows the variation in the organic content of MSW materials in these two landfills, it can be observed that the organic content of the 15-year old waste materials in BL is almost the same as the 3-year old MCL waste. This means that the composition of the MSW in these two fills should be compatible and this could explain the similar strength obtained during the SPT tests.

#### *4.2.2. Cone penetration tests*

The results of five CPT tests were analyzed. Two of them were performed in BL and the other three were performed in MCL by Oliveira (2002). The results of all the CPT tests were plotted by using the geometrical mean values every 1 m from the top surface. According to Eslami and Fellenius (1997), this is the best way to treat values with a high range of variations, because its bias, unlike the arithmetic mean, arises from ratios of values instead from their absolute magnitudes.

Fig. 13a shows the CPT records in BL performed in a waste fill with 15-year old waste. Fig. 13b shows the results of the CPT tests carried out on 3-year old waste.

According to the results of the statistical analysis performed (Fig. 14) it can be said that in MCL (younger waste) almost all the tip resistance values are lower than 5 MPa, but in BL the frequency of values higher than 5 MPa is 47%. Still considering the BL waste, around 40% of the tip resistance is located between 5 and 10 MPa.

In MCL the values for sleeve friction barely exceed 100 kPa, but in BL the most sleeve friction values ranges from 100 to 600 kPa and they are concentrated between 100 and 300 kPa with a frequency of around 70%.

These results show that the CPT values are higher in the BL waste which is older than the MCL waste. The opposite is observed in the SPT results. Fig. 15 compares the average values of tip resistance and sleeve friction in MCL and BL.

The differences observed when comparing SPT and CPT results could arise from the differences in the mechanism of penetration and in the shape of the penetrating element in SPT and CPT tests.

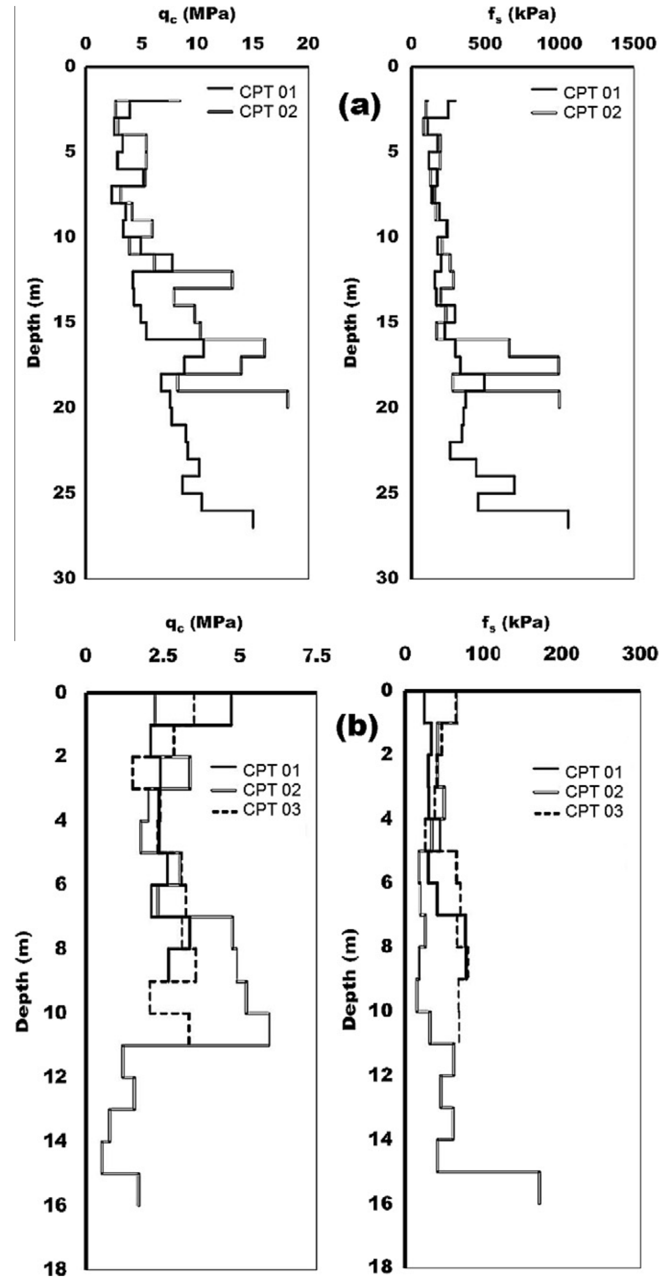


**Fig. 13.** Obtained CPT results (a) BL and (b) MCL.

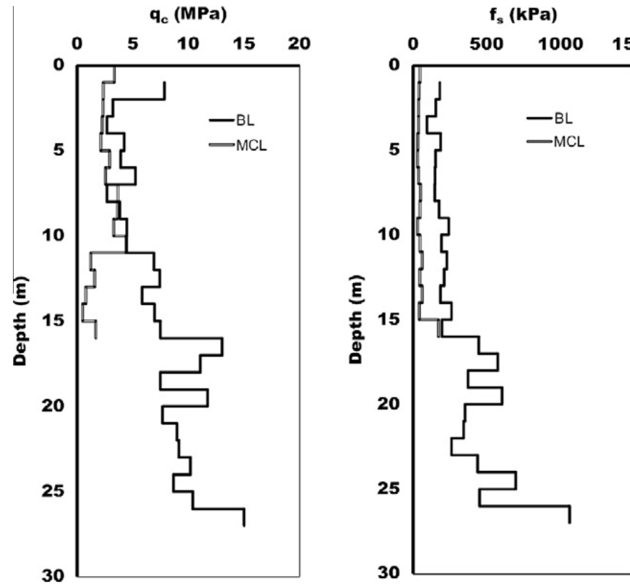


**Fig. 15.** Average CPT values in BL and MCL.

The CPT uses a cone shaped penetrating element with a sharp tip which is driven statically into the soil. This could facilitate the penetration and the puncture of planar elements considerably comparing the sampler used in the SPT apparatus.

Another possible explanation is that the biodegradation process, as shown in Fig. 4, leads to a reduction in MSW particles. According to the CPT-based classification chart represented by Robertson et al. (1986), fine grained soils exhibits higher values of fiction ratio or sleeve friction values. This could be the main reason why the values of sleeve friction in BL are clearly higher than those in MCL.

The results of the CPT tests in MCL and BL were used for MSW classification purposes, using the classification charts proposed by Robertson et al. (1986) and Eslami and Fellenius (2004). Fig. 16 presents the obtained results. Although more similar to MSW than other soil types, peat and organic soils do not present similar CPT values.

According to Robertson et al.'s (1986) classification chart, the MSW from MCL can be classified in the groups 4, 5, 6 and 7 which means that the range of penetration resistance is similar to silty clay to sandy silt soils. In the case of the BL waste, this range is wider and varies from clay to sandy silt soils characteristics. These results are consistent with Hinkle (1990) and Siegel et al. (1990).

In the case of the Eslami and Fellenius (2004) classification chart, the MSW in both waste fills is mainly classified in the groups III, silty clay to clayey silt, and IV, sandy silt to silty sand.

It can be concluded that, common CPT-based classification approaches are not appropriate for classifying MSW materials and

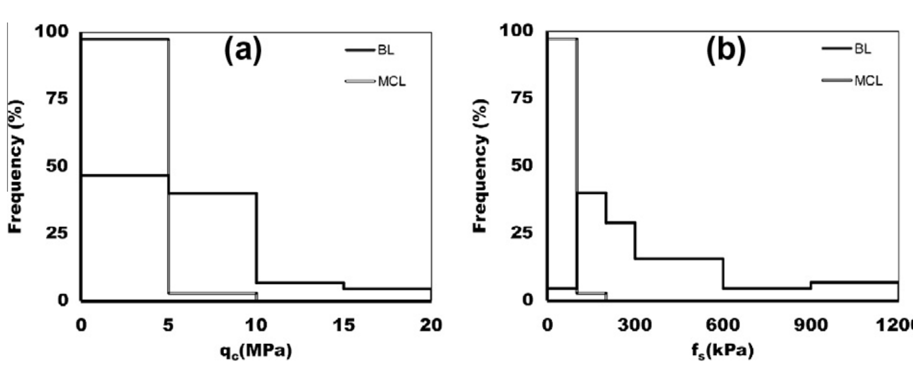


**Fig. 14.** Obtained histograms of $q_c$ (a) and $f_s$ (b).

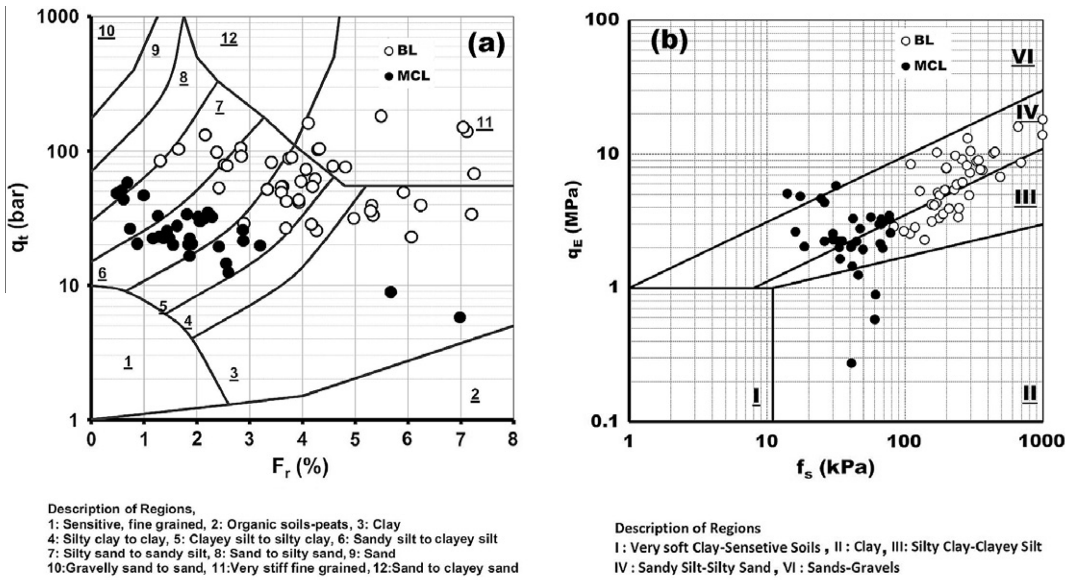


**Fig. 16.** MSW classification using CPT results. (a) Chart proposed by Robertson et al. (1986), (b) chart proposed by Eslami and Fellenius (2004).

are not a sound method to explore waste strata in underground surveying programs. This means that a CPT test should always be supported and coupled with traditional sampling or other direct investigation methods.

In the field tests program in BL, to compare the results of CPT and SPT tests a SPT test was performed close to each CPT borehole. In MCL, SPT04 and SPT05 were executed close to CPT03. Fig. 17 shows a correlation between results of the SPT and CPT tests.

Assuming a zero intercepts in linear fitting, in BL a clear trend could be observed between the $N_{SPT}$ values and the penetration resistance parameters in CPT: as the $N_{SPT}$ values increase both the tip resistance and sleeve friction increases. In the case of MCL this is not pronounced and it seems that with an increase in the $N_{SPT}$ value, both the tip resistance and sleeve friction remain almost constant.

Jefferies and Davies (1993) suggested another approach to convert the results of the CPT test to equivalent $N_{SPT}$ values

$$(q_c/p_a)/N_{60} = 8.5(1 - I_c/4.6) \tag{1}$$

where $q_c$, $p_a$, $N_{60}$ and $I_c$ are the cone resistance, atmospheric pressure, SPT number of blows and the soil behavior type index, respectively. The $I_c$ factor may be calculated using the following equation:

$$I_c = ((3.47 - \log\ Q_t)^2 + (\log F_r + 1.22)^2)^{0.5} \tag{2}$$

where $Q_t$ and $F_r$ are the cone resistance and the friction ratio normalized by the overburden stress. The right side of Eq. (1) could be referred to as a conversion coefficient which is dependent on the penetration resistance achieved from the CPT. The analysis of the CPT results using the above mentioned approach is presented in Fig. 18.

The $I_c$ factor in BL changes from 1.33 to 1.85 with a geometric average of 1.6. According to this approach, all the $I_c$ values are in the range of clean sand to sandy silt which is different from the results of Robertson et al. (1986) and Eslami and Fellenius (2004) classification charts but is consistent with the results reported by Sanchez-Alciturri et al. (1993). The $q_c$–$N$ conversion coefficient in BL varies from 0.5 to 0.6 with a geometric average of 0.55 which is almost equal to the coefficient represented in Fig. 17.

In the case of MCL this factor has a wider range and varies from 1.5 to 2.65 with a geometric average of 1.92. In this case, the range of $I_c$ is wider and based on the calculated values, part of the waste materials in MCL waste fill are classified as silty sand to sandy silt. The $q_c$–$N$ conversion coefficient value in MCL also exhibits a wider range compared to BL, changing from 0.36 to 0.57 with an average of 0.49 which shows a considerable difference with the results in Fig. 17.

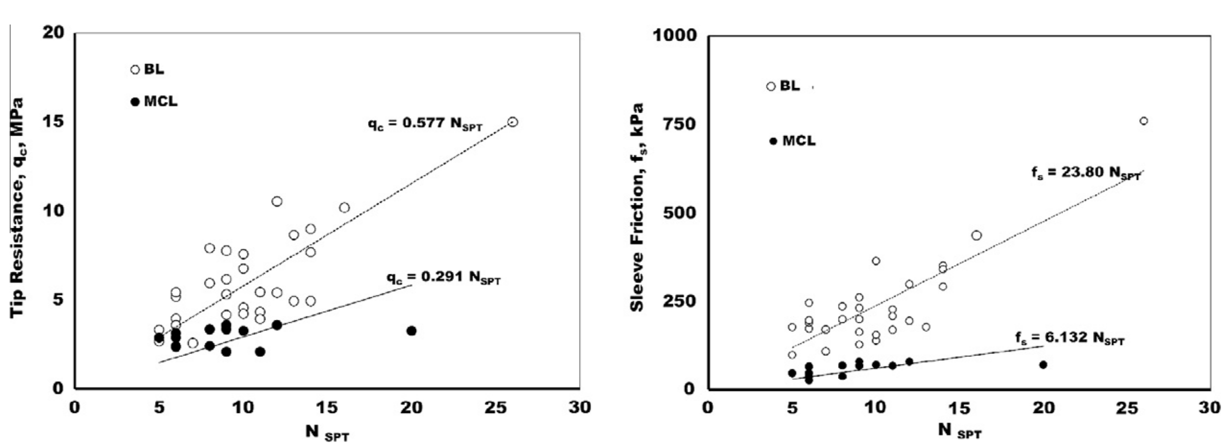


**Fig. 17.** Relationship between $N_{SPT}$ values and (a) $q_c$ and (b) $f_s$.

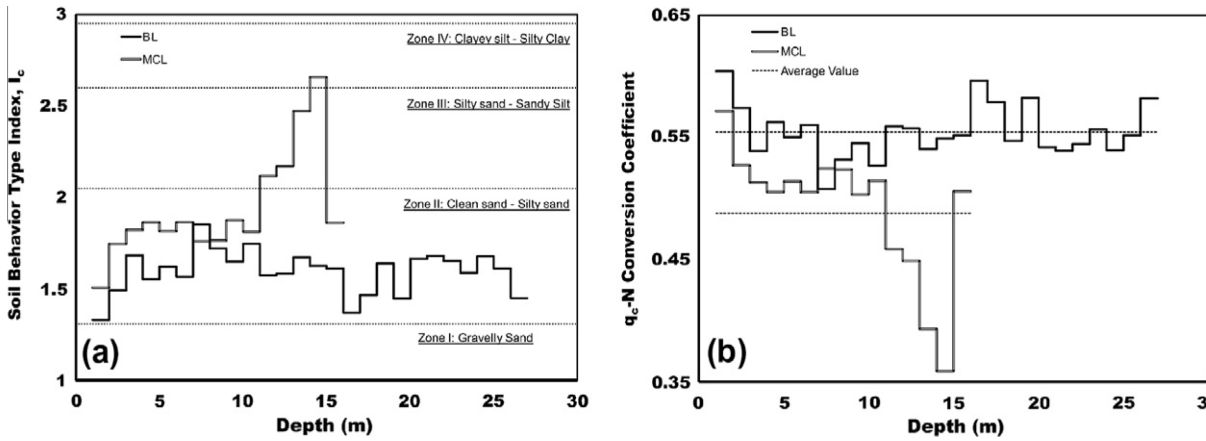


**Fig. 18.** Variation of (a) $I_c$ and (b) $q_c$–$N$ conversion Coefficient with depth in BL and MCL.

These results had been expected as MSW aging appears to have different effects on the SPT and CPT results. An increase in the age of the waste causes a reduction in the MSW particle size and an increase in waste homogeneity, which makes older MSW closer to soil materials and could explain, at least in part, the better compatibility between the SPT and CPT results in the case of the BL waste.

## 5. Conclusions

This paper shows the results of a field research program focusing on some geotechnical properties of MSW materials which has been carried out over several years in the Bandeirantes Landfill, São Paulo and the Metropolitan Center Landfill, Salvador, Brazil.

Evaluation of the physical properties of the MSW at these two sites shows that the waste disposed presents high levels of moisture and organic contents which together with the tropical climatic conditions leads to a very conducive environment for long-term compression, mainly due to mass loss of the waste. However, as Salvador presents daily average temperatures above 20 °C practically all year round, with higher rainfall and higher air humidity compared to São Paulo, the biodegradation process in Salvador occurs at a faster rate than in São Paulo.

A high percentage of fiber content (about 25%) is common in BL and MCL fresh waste which is considered high compared to the reported values in literature. Furthermore, almost 50% of fresh waste includes easily degradable organic material which is the main source of short and long-term deformation in both landfills. According to Machado et al. (2002, 2008), this large amount of easily degradable organic material tends to reduce the shear strength of the fresh waste samples. As the decomposition process continues, the MSW fiber content increases and tends to increase the MSW shear strength.

The results of field infiltration tests in BL showed a decrease in the permeability of the MSW with depth indicating the effect of overburden stress on this factor. The permeability ranged from $10^{-5}$ to $10^{-8}$ m/s. A comparison between the results of field BL and laboratory MCL tests using triaxial samples showed the aged waste from BL exhibits relatively lower permeability compared to the fresh MCL waste. The results of this research were in agreement with results reported by Powrie et al. (2000) and Reddy et al. (2009c).

The SPT tests showed that the $N_{SPT}$ values are rarely higher than 20 blows and, despite the high scattering observed, there is an increase with depth. The results showed that $N_{SPT}$ values measured in fresh waste fill are higher compared with aged waste fills. As biodegradation progresses, the size of the particles reduce, and therefore the probability of the artificial increase in the value of $N_{SPT}$ due to clogging of the sampler or due to its contact with large particles is smaller.

The CPT records in MCL showed the that maximum tip resistance is limited to 5 MPa, but in BL the frequency of values higher than 5 MPa is 47%. Still considering the BL waste, around 40% of the tip resistance is located between 5 and 10 MPa. In MCL the values for sleeve friction barely exceed 100 kPa, but in BL most of the sleeve friction values ranges from 100 to 600 kPa and they are concentrated between 100 and 300 kPa with a frequency of around 70%.

CPT and SPT results in BL showed a clear relationship between them: by increasing the $N_{SPT}$ values both the tip resistance and sleeve friction increases. In the case of MCL this trend is not pronounced and it seems that with the increasing $N_{SPT}$ value, both the tip resistance and sleeve friction remain almost constant.

In the case of BL, the angular coefficient obtained from linear fitting using CPT and $N_{SPT}$ results was consistent with the results of the Jefferies and Davies (1993) correlation to convert the CPT tip resistance results into equivalent SPT number of blows. This was not observed in the case of MCL.

As discussed in the text, this behavior must be related to the reduction in the waste texture over time (BL waste, 15 years old), which makes MSW more similar to soil materials.

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## References

Blight, G.E., Ball, J.M., Blight, J.J., 1992. Moisture and suction in sanitary landfills in semiarid areas. Journal of Environmental Engineering 118 (6), 865–877.

Bouazza, A., Van Impe, W.F., Haegeman, W., 1996. Quality control of dynamic compaction in municipal solid waste fills. In: Proceedings of the Second International Congress on Environmental Geotechnics, Osaka, Japan, vol. 2, pp. 635–640.

Caicedo, B., Yamin, L., Giraldo, E., Coronado, O., 2002a. Geomechanical properties of municipal solid waste in Dona Juana sanitary landfill. In: Proceedings of the Fourth International Congress on Environmental Geotechnics, Brazil, vol. 1, pp. 177–182.

Caicedo, B., Giraldo, E., Yamin, L., Soler, N., 2002b. The landslide of Dona Juana landfill in Bogota, a case study. In: Proceeding of the Fourth International Congress on Environmental Geotechnics, Brazil, vol. 1, pp. 171–175.

Cartier, G., Baldit, R., 1983. Comportement géotechnique des décharges de résidus urbains. Bulletin de Liaison des Laboratoires des Ponts et Chaussés, No. 128, Paris-França, pp. 55–64.

Carvalho, M.F., 1999. Mechanical Behavior of Municipal Solid Waste. Ph.D thesis, University of Sao Paulo, Sao Carlos, SP, Brazil (in Portuguese).

Chen, H.T., Chynoweth, D.P., 1995. Hydraulic conductivity of compacted municipal solid waste. Bioresource Technology 51, 205–212.

Coumoulos, D.G., Koryalos, T.P., Metaxas, I.L., Gioka, D.A., 1995. Geotechnical investigation at the main landfill of Athens. In: Proceedings Sardinia 95, Fifth International Landfill Symposium, Cagliari, Italy, pp. 885–895.
Dixon, N., Jones, D.R.V., 2005. Engineering properties of municipal solid waste. Geotextiles and Geomembranes Journal 23 (3), 205–233.
Durmusoglu, E., Sanchez, M.I., Corapcioglu, Y.M., 2006. Permeability and compression characteristics of municipal solid waste. Environmental Geology 50, 773–789.
Eslami, A., Fellenius, B.H., 2004. CPT and CPTu data for soil profile interpretation: review of methods and a proposed new approach. Iranian Journal of Science and Technology, Transaction B 28 (B1), 69–86.
Eslami, A., Fellenius, B.H., 1997. Pile capacity by direct CPT and CPTu methods applied to 102 case histories. Canadian Geotechnical Journal 34, 886–904.
Ettala, M., 1987. Infiltration and hydraulic conductivity at a sanitary landfill. AquaFenn. 17, 231–237.
Fucale, E.P., 2005. Effect of Reinforcement Element on the Strength of MSW Materials. PhD thesis, University of Pernambuco, Pernambuco, Brazil (in Portuguese).
Gabr, M.A., Valero, S.N., 1995. Geotechnical properties of municipal solid waste. Geotechnical Testing Journal 18, 241–254.
Grisolia, M., Napoleoni, Q., Tangredi, G., 1995. The use of triaxial tests for the mechanical characterization of municipal solid waste. In: Proceedings of the Fifth International Landfill Symposium, Sardinia '95, pp. 761–767.
Grisolia, M., Napoleoni, Q., 1996. Geotechnical characterization of municipal solid waste: choice of design parameters. In: Proceedings of the Second International Congress on Environmental Geotechnics, Osaka, Japan, pp. 641–646.
Hinkle, R.D., 1990. Landfill site reclaimed for commercial use as container storage facility. In: Landva and Knowles (Ed.), Geotechnics of Waste Fills – Theory and Practice. ASTM STP 1070, pp. 331–344.
Hossain, M.S., Penmethsa, K.K., Hoyos, L., 2006. Permeability of municipal solid waste in bioreactor landfill with degradation. Geotechnical and Geological Engineering Journal 27, 43–51.
Jain, P., Powell, J., Townsend, T.G., Reinhart, D.R., 2006. Estimating the hydraulic conductivity of landfilled municipal solid waste using borehole permeameter test. Journal of Environmental Engineering, ASCE 132 (6), 645–653.
Jang, Y.S., Kim, Y.W., Lee, S.I., 2002. Hydraulic properties and leachate level analysis of kimpo metropolitan landfill, Korea. Waste Management 22, 261–267.
Jefferies, M.G., Davies, M.P., 1993. Use of CPTu to estimate equivalent SPT N60, American Society for Testing and Materials, ASTM. Geotechnical Testing Journal 16 (4), 458–468.
Jessberger, H.L., Kockel, R., 1993. Determination and Assessment of the Mechanical Properties of Waste. In: Sarsby, R.W. (Ed.), Waste Disposal by Landfill. Green '93, pp. 313–322.
Jessberger, H.L., 1994. Geotechnical aspects of landfill design and construction. Part 2: material parameters and test methods. Proceedings of the Institution of Civil Engineers Geotechnical Engineering 107, 105–113.
Juca, J.F.T., Cabral, J.J.P.S., Monteiro, V.E.D., Santos, S.M., Perrier Jr., G.S., 1997. Geotechnics of a municipal solid waste landfill in Recife, Brazil. In: Almeida (Ed.), Recent Developments in Soil and Pavement Mechanics. Balkema, Rotterdam, ISBN: 9054108851, pp. 429–436.
Karimpour-Fard, M., 2009. Mechanical Behavior of MSW Materials with Different Initial State under Static Loading. A Dissertation Submitted in Partial Satisfaction of the Requirements for the Degree of Doctor of Philosophy in Geotechnical Engineering – Iran University of Science and Technology (in Persian).
Kavazanjian Jr., E., Matasovic, N., Bonaparte, R., Schmertmann, G.R., 1995. Evaluation of MSW properties for seismic analysis. Geoenvironment 2000, Geotechnical Special Publication No. 46, pp. 1126–1141.
Kavazanjian Jr., E., 1999. Seismic design of solid waste containment facilities. In: Proceedings of the Eight Canadian Conference on Earthquake Engineering, Vancouver, BC, June 1999, pp. 51–89.
Knochenmus, G., Wojnarowicz, M., Van Impe, W.F., 1998. Stability of municipal solid wastes. In: Sêco e Pinto (Ed.), Proceedings of the Third International Congress on Environmental Geotechnics, Lisboa, Portugal, pp. 977–1000.
Kölsch, F., 1995. Material values for some mechanical properties of domestic waste. In: Proceedings of the Fifth International Landfill Symposium in Sardinia, pp. 711–729.
Koelsch, F., Fricke, K., Mahler, C., Damanhuri, E., 2005. Stability of landfills – the Bandung dumpsite disaster. In: CISA (Hrsg.): Proceedings of the 10th International Landfill Symposium, Cagliari, Italy.
Landva, A.O., Clark, J.I., 1986. Geotechnical testing of wastefill. In: Proceedings of the 39th Canadian Geotechnical Conference Ottawa, Ontario, pp. 371–385.
Landva, A.O., Clark, J.I., 1990. Geotechnics of waste fill. In: Landva and Knowles (Eds.), Theory and Practice, STP 1070. ASTM, pp. 86–103.
Machado, S.L., Carvalho, M.F., Vilar, O.M., 2002. Constitutive model for municipal solid waste. Journal of Geotechnical and Geoenvironmental Engineering 128 (11), 940–951.
Machado, S.L., Vilar, O.M., Carvalho, M.F., 2008. Constitutive model for long term municipal solid waste mechanical behavior. Computers and Geotechnics 35 (5), 775–790.
Machado, S.L., Carvalho, M.F., Vilar, O.M., 2009. Modeling the influence of biodegradation on sanitary landfill settlements. Soils and Rocks, São Paulo 32 (3), 123–134.
Mahler, C.F., Burin, E., Oliveira, F.J.P., 1998. Reflections on the stability of a municipal sanitary landfill. In: Seco e Pinto (Ed.), Proceedings of the Third International Congress on Environmental Geotechnics. Lisbon, Portugal, pp. 83–88.
Mahler, C.F., De Lamare Netto, A., 2003. Shear resistance of mechanical biological pre-treated domestic urban waste. In: Proceedings of the Sardinia 2003, Ninth International Waste Management and Landfill Symposium, 6–10 October 2003.
Manassero, M., Van Impe, W.F., Bouazza, A., 1996. Waste disposal and containment. In: Proceedings of the Second International Congress on Environmental Geotechnics, Osaka, Japan, vol. 2, pp. 1425–1474.
Mazzucato, N., Simonini, P., Colombo, S., 1999. Analysis of block slide in a MSW landfill. In: Proceedings of the Sardinia 1999, Seventh International Waste Management and Landfill Symposium, Cagliari, Italy.
Merry, S.M., Kavazanjian Jr., E., Fritz, W., 2005. Reconnaissance of July 10, 2000, Payatas landfill failure. Journal of Performance of constructed Facilities 19 (2), 100–107.
Moore, R., Dhal. K., Yazdani, R., 1997. Hydraulic characteristics of municipal solid waste: findings of the Yolo County bioreactor landfill project. In: Proceedings of the 13th International Conference on Solid Waste Technology and Management, Philadelphia, PA, USA.
Nascimento, J.C.F., 2007. Mechanical behavior of municipal solid waste. Ms.C. thesis, University of Sao Paulo, Sao Carlos, SP, Brazil (in Portuguese).
Oliveira, D.A.F., 2002. Stability of Municipal Solid Waste Slopes. University of Brasilia, Brazil (in Portuguese).
Oweis, I.S., Smith, D.A., Ellwood, R.B., Greene, D.S., 1990. Hydraulic characterises of municipal refuse. Journal of Geotechnical Engineering 116 (4), 539–553.
Penmethsa, K.K., 2007. Permeability of Municipal Solid Waste in Bioreactor Landfill with Degradation. Ms.C. thesis, University of Texas at Arlington, USA.
Pelkey, S.A., Valsangkar, A.J., Landva, A., 2001. Shear displacement dependent strength of municipal solid waste and its major constituents. Geotechnical Testing Journal 381, 390.
Powrie, W., Hudson, A.P., Beaven, R.P., 2000. Development of Sustainable Landfill Practices and Engineering Landfill Technology, Final Report to the Engineering and Physical Sciences Research Council (Grant reference GR/L 16149).
Reddy, K.R., Hettiarachchi, H., Parakalla, N.S., Gangathulasi, J., Bogner, J.E., 2009a. Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA. Waste Management 29 (2), 952–959.
Reddy, K.R., Gangathulasi, J., Parakalla, N.S., Hettiarachchi, H., Bogner, J.E., Lagier, T., 2009b. Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations. Waste Management and Research 27 (6), 578–587.
Reddy, K.R., Hettiarachchi, H., ParakallA, N., Gangathulasi, J., Bogner, J., Lagier, T., 2009c. Hydraulic conductivity of MSW in landfills. Journal of Environmental Engineering 135 (8), 677–683.
Robertson, P.K., Campanella, R.G., Gillespie, D., Grieg, J., 1986. Use of piezometer cone data. In: Clemence, S. (Ed.), Proceedings of the American Society of Civil Engineers, ASCE, In-Situ 86 Specialty Conference, Blacksburg, June 23–25, Geotechnical Special Publication GSP No. 6, pp. 1263–1280.
Sanchez-Alciturri, J.M., Palma, J., Sagaseta, C., Canizal, J., 1993. Mechanical properties of wastes in a sanitary landfill. In: Proceedings of the Green '93, Waste Disposal by Landfill, Bolton, UK, pp. 357–363.
Schmertmann, J.H., 1978. Guidelines for Cone Penetration Test, Performance and Design, Report No. FHWA-TS-78-209. US Department of Transportation, Washington, DC. p. 145.
Shank, K.L., 1993. Determination of the Hydraulic Conductivity of the Alachua County Southwest Landfill. Masters thesis, The University of Florida.
Shariatmadari, N., Machado, S.L., Noorzad, A., Karimpour-Fard, M., 2009. Municipal solid waste effective stress analysis. Waste Management 29 (12), 2918–2930.
Sharma, H.D., Reddy, K.R., 2004. Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies. Wiley, Hoboken, NJ.
Siegel, R.A., Robertson, R.J., Anderson, D.G., 1990. Slope stability investigations at a landfill in southern California. In: Clemence, S. (Ed.), Geotechnics of Waste Fills–Theory and Practice, ASTM STP 1070, X. ASTM, pp. 259–284.
Singh, M.K., Fleming, R.F., 2008. Estimation of the Mechanical Properties of MSW during Degradation in a Laboratory Compression Cell. Geo Congress 2008: Geotechnics of Waste Management and Remediation, New Orleans, Louisiana, March 9–12, pp. 200–207
Sowers, G.F., 1968. Foundation problems in sanitary landfills. Journal of the Sanitary Engineering Division, ASCE, 4, 103–116.
Stark, T.D., Eid, H.T., Evans, W.D., Sherry, P.E., 2000. Municipal solid waste slope failure. II: stability analyses. ASCE Journal of Geotechnical and Geoenvironmental Engineering, 126(5).
Towhata, I., Kawano, Y., Yonai, Y., Koelsh, F., 2004. Laboratory tests on dynamic properties of municipal wastes. In: Proceedings of the 11th Conference in Soil Dynamics and Earthquake Engineering and Third International Conference on Earthquake Geotechnical Engineering, vol. 1, pp. 688–693.
Vilar, O.M., Carvalho, M.F., 2004. Mechanical properties of municipal solid waste. Journal of Testing and Evaluation 32, 1–12.
Xie, M., Aldenkortt, D., Wagner, J.F., Rettenberger, G., 2006. Effect of plastic fragments on hydraulic characteristics of pretreated municipal solid waste. Canadian Geotechnical Journal 43, 1333–1343.
Zekkos, D.P., 2005. Evaluation of Static and Dynamic Properties of Municipal Solid Waste. A Dissertation Submitted in Partial Satisfaction of the Requirements for the Degree of Doctor of Philosophy in Geotechnical Engineering, University of California, Berkeley.
Zekkos, D.P., Bray, J.D., Kavazanjian Jr., E., Matasovic, N., Rathje, E.M., Riemer, M.F., 2006. Unit weight of municipal solid waste. ASCE Journal of Geotechnical and Geoenvironmental Engineering 132 (10), 1250–1261.

Zhan, T.L.T., Chen, Y.M., Ling, W.A., 2008. Shear strength characteristics of municipal solid waste at the Suzhou landfill, China. Engineering Geology 97 (3), 97–111.

Xiang-rong, Zhu, Jian-min, Jin, Peng-fei, Fang, 2003. Geotechnical behavior of the MSW in Tianziling landfill. Journal of Zhejiang University Science 4 (3), 324–330.