Physical Characterization of Municipal Solid Waste for Geotechnical Purposes

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Abstract: A procedure to characterize municipal solid waste (MSW) for geotechnical engineering purposes is developed based on experience with waste characterization and testing. Existing MSW classification systems are reviewed briefly, and the field and laboratory waste characterization programs of two important projects are presented. Findings on the influence of the waste's physical composition on its mechanical response from these projects and recent studies of MSW are integrated to develop a waste characterization procedure for efficient collection of the relevant information on landfill operation and waste physical characteristics that are most likely to affect the geotechnical properties of MSW. A phased approach to implementation of this procedure is proposed as a best practice for the physical characterization of MSW for geotechnical purposes. The scope of the phased procedure can be adjusted to optimize the effort required to collect relevant information on a project-specific basis. The procedure includes a systematic evaluation of the moisture and organic content of MSW, because they are important factors in the geotechnical characterization of MSW.

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Introduction

Waste characterization procedures have been developed for a variety of applications. Depending on the intended application, the type of information called for in a specific procedure varies. For instance, waste characterization studies performed by the Environmental Protection Agency and various state waste management organizations [e.g., California Environmental Protection Agency (CalEPA) (2006)] often collect information for the purpose of characterizing the waste stream to facilitate studies on waste diversion, material recovery, waste processing, or conversion technologies. Geochemical characterization of waste (e.g., Piatak et al. 2004) may be performed to evaluate the type and concentration of chemicals in the waste and waste by-products that may impact the environment. Several MSW characterization systems for geotechnical purposes have been proposed since the early 1990s. These systems have been developed to collect relevant information about the waste with respect to its geotechnical response (e.g., hydraulic conductivity, shear strength, stiffness, and compressibility). Geotechnical aspects of landfill performance include the overburden pressure due to the weight of the waste mass, landfill stability under static and seismic conditions, settlement of the waste mass, performance of deep and shallow foundations on or in the waste, and dynamic response of the waste material during earthquakes.

This paper presents a phased approach to the physical characterization of municipal solid waste (MSW) for use in geotechnical engineering analyses. The recommended procedure optimizes the collection of physical information that has been shown to have a significant influence on the mechanical properties of MSW. It is recognized that the factors that influence the geotechnical properties of MSW are not fully understood. However, recent studies (e.g., Kavazanjian et al. 1999; Zekkos 2005; Zekkos et al. 2006; Dixon and Langer 2006; Zekkos et al. 2008; Bray et al. 2009) have identified a variety of factors that can significantly affect the mechanical properties of MSW. The proposed waste characterization procedure is designed to efficiently collect information on these factors as well as other potentially useful information on its physical properties. As the understanding of the physical factors influencing the mechanical response of MSW advances, modifications to the proposed characterization procedure will be required. However, the proposed procedure represents an important first step in standardizing the manner in which MSW is characterized for engineering analyses.

Background

Existing MSW Classification Systems for Geotechnical Purposes

The primary basis for many of the earliest MSW classification systems that were developed for geotechnical purposes was a dis-

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tinction between degradable and nondegradable waste constituents. For instance, Landva and Clark (1990) divided the waste constituents into organic and inorganic materials. Organic material as defined by Landva and Clark (1990) included both putrescible waste (i.e., "readily" biodegradable waste) and nonputrescible waste (i.e., "slowly" biodegradable material). Inorganic waste included both mechanically degradable and nondegradable wastes. Grisolia et al. (1995) divided MSW into three classes of waste constituents: Class A included "inert stable elements," Class B included "highly deformable elements," and Class C included "readily biodegradable elements." A drawback of the classification systems of Landva and Clark (1990) and Grisolia et al. (1995) is that various constituent categories are neither mutually exclusive nor easily distinguishable. For example, Class A in the classification system of Grisolia et al. (1995) includes soils, construction debris, and ash, whereas Class C includes small-sized (i.e., material smaller than 20 mm in dimension) degradable waste that is soil-like in physical appearance and is not easily distinguishable from Class A waste.

Dixon and Langer (2006) made a comprehensive review of published waste classification systems and found that none of these classification systems fulfilled the requirements of a rigorous classification framework. To fulfill this purpose, Dixon and Langer (2006) presented a framework for classifying waste constituents based on (1) their material type, (2) the constituent shape, (3) the constituent size, and (4) the constituent degradation potential. The classification framework of Dixon and Langer (2006) has important advantages over previous waste classification systems in that it considers a broad range of waste constituent physical and mechanical properties that appear to affect the engineering properties of the waste. However, the system of Dixon and Langer (2006) requires the careful segregation, physical description, size measurement, and testing of all waste constituents and was proposed primarily for use in research and not as a tool for use in engineering practice. Segregating, describing, measuring, classifying, and testing all waste constituents are time consuming and challenging tasks. Thus, this system is not an attractive option for use in practice, particularly if the classification scheme is to be implemented in the field.

MSW Organic Content and Moisture Content Measurements

Organic content and moisture content are two physical parameters that are widely recognized as having an important influence on the mechanical properties of geomaterials. Organic content is known to influence significantly both short-term and long-term settlement potentials. In general, a material with a higher organic content exhibits higher compressibility and lower shear strength relative to a material with a lower organic content. Moisture content impacts the consistency of fine-grained materials as well as the unit weight and the pore water suction in unsaturated materials. Moisture content may also impact settlement rate and shear strength.

The standard procedure used in geotechnical practice to evaluate moisture content and organic content of organic soils (ASTM D2974) involves drying the material at 105°C and then at 440°C to a constant mass. However, drying at 105°C may volatilize a significant portion of the organic material in some MSW. To compensate for the potential for volatilization of organic waste, many investigators recommend measuring the initial moisture content and dry weight of MSW at a temperature below 105°C. However there is no agreed upon (i.e., standardized) temperature at which to do this. There is also a lack of consensus on the size of specimen that should be tested to obtain representative results as well as on any processing (e.g., segregation of materials) that should be conducted on the MSW specimen prior to testing.

Siegel et al. (1990) reported field moisture contents on MSW from the Operating Industries, Inc. (OII) landfill measured reportedly in general accordance with ASTM D2216-80, with the exception that waste samples were dried at 60°C instead of 110°C. The samples were obtained using a 13-cm diameter acrylic tube-lined split-core barrel driven through a hollow stem auger. Gabr and Valero (1995) heated specimens at a temperature of 60°C for 24 h to evaluate the moisture content of MSW cuttings recovered from a hollow stem auger boring. However, they did not provide information on the sample size used to make their measurements. Gabr and Valero (1995) also reported measuring organic content based on ASTM D2974. They employed Method C, which calls for heating the specimen from 105 to 440°C until "the specimen is completely ashed (no change in mass occurs after a further period of heating)."

Sanchez-Alciturri et al. (1993) reported moisture contents for waste recovered from the Meruello landfill in Spain, but no information is provided on the procedure used to determine the moisture content. Coumoulos et al. (1995) reported on moisture content for the Ano Liossia landfill in Athens, Greece. The majority of the moisture content tests were performed in general accordance with ASTM D2216 by drying specimens at 110°C over a period of 18 h. However, a few tests performed by drying specimens at 60°C for 48 h were reported to yield similar results to the tests conducted at 110°C for 18 h. Each specimen's mass was approximately 1 kg (D. Zekkos, personal communication, 2008). Manassero et al. (1997) recommended evaluating MSW moisture content by heating to 55°C to avoid potential combustion of volatile material, but no recommendations on sample size or duration were made.

Zornberg et al. (1999) estimated the moisture content for MSW from a landfill in Southern California by drying 51 23-kg bucket samples and 27 1.2-kg glass jar samples at a temperature of approximately 85°C. The moisture content results from the glass jar samples showed approximately the same mean value versus depth but larger scatter than those obtained from the larger bucket samples. Gomes et al. (2005) reported on moisture content and organic content for fresh (less than three years) waste at Santo Tirso landfill (Portugal). Moisture content was obtained by drying specimens at 105°C over a period of 18 h. Gomes et al. (2005) expressed moisture content as a percentage of moist weight as opposed to dry weight. They reported that a few determinations were made at 60 and 90°C and variations in the duration of the drying period were required to obtain similar results to the tests at 105°C. Organic content was evaluated by Gomes et al. (2002) by heating the material at 450°C.

The differences in the definitions and procedures cited above for the evaluation of moisture content and organic content make comparisons of different studies difficult. A consistent procedure for the systematic evaluation of these two parameters is needed to standardize their assessment for physical characterization of MSW for geotechnical purposes.

Two Case Histories of MSW Characterization

MSW Characterization at the OII Landfill

As part of the predesign geotechnical investigation for closure of the OII landfill, a superfund site in Monterey Park, Calif., a com-

Fig. 1. Bucket auger sample recovery at the OII landfill (Geosyntec 1996)

prehensive compositional characterization program was conducted on MSW recovered from three large-diameter bucket auger borings (Geosyntec 1996). The locations of these borings as well as the location of other field tests at the OII site are provided in Matasović and Kavazanjian (1998). The three borings were advanced to depths of 33–45 m using an 840-mm diameter bucket auger (Fig. 1). In situ unit weight measurements were conducted at selected locations within the boreholes using a gravel replacement procedure modeled after the sand cone test (Matasović and Kavazanjian 1998). MSW recovered in the bucket auger was continuously logged in the field and selected samples were transported to a field laboratory for more detailed compositional characterization prior to waste specimen reconstitution for laboratory strength and compressibility testing. Fig. 1 shows waste being discharged from the bucket auger into a metal bin prior to field logging. Following field logging, the waste was either disposed of back into the landfill or placed in a high density polyethylene drum and transported to the field laboratory. Comparison of the waste recovered in the bucket auger borings to waste exposed in the wall of a 6-m deep by 6-m wide trench on the top deck of the landfill indicated that the waste recovered in the bucket augers was generally representative in size and other physical characteristics of the waste within the landfill (Geosyntec 1996).

The field logging and waste characterization system employed for the OII project was developed using the best available information at that time on the factors most likely to influence the mechanical properties of the waste. Field logging of the borings included continuous visual descriptions of the moisture level, state of compaction, state of degradation, composition (i.e., waste constituents), and apparent waste structure using the classification scheme presented in Table 1. Field characterization also included measurement of the temperature of the waste and video logging of the borehole. MSW temperature was measured immediately after the waste was discharged from the bucket to minimize tem-

Table 1. OII Landfill Field Waste Classification Scheme (Geosyntec 1996)

Moisture content			Composition
1	Dry-damp moisture levels	1	Household—paper and plastics
2	Wet moisture levels	2	Putrescible organics
3	Standing water	3	Concrete, bricks
		4	Wiring
Compaction		5	Metal
1	Slight—refuse easily falls out of bucket auger	6	Nonferrous metal
		7	Tires
2	Moderate—refuse falls out of bucket auger upon impact	8	Asphalt
		9	Soil
3	Heavy—refuse falls out of bucket auger only after being struck multiple times	10	Medical
		11	Indistinguishable
		12	Glass
		13	Other (specify)
Degradation			
1	None—newspaper very legible, no refuse discoloration		Structure
		1	Layered
2	Slight—some newspapers still legible, discoloration	2	Encapsulated
		3	Fibrous
3	Moderate—newspaper partly legible, highly discolored	4	Interlocked
		5	Indistinguishable
4	High—newspaper highly faded gray to black		

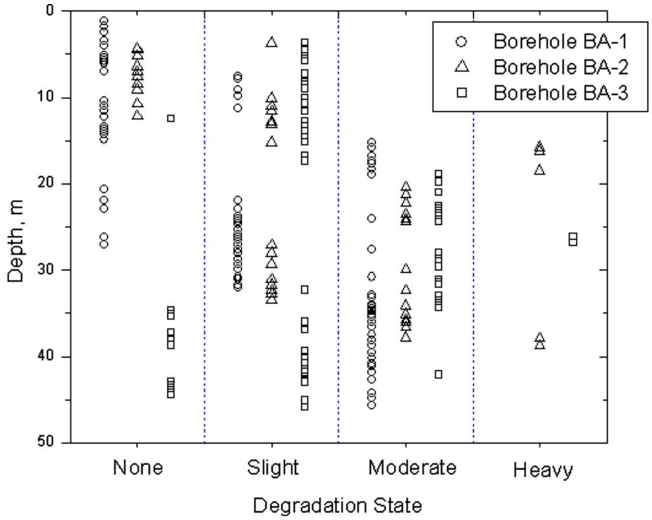

Fig. 2. Waste degradation versus depth at the OII Landfill (Geosyntec 1996)

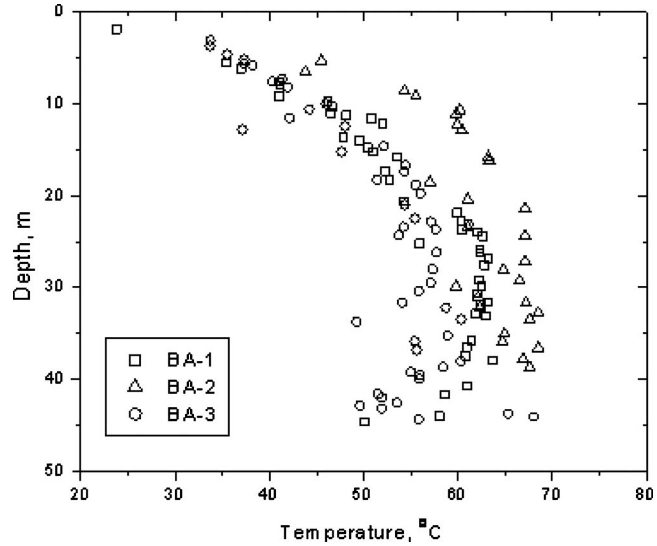

Fig. 3. Waste temperature versus depth at the OII Landfill (Geosyntec 1996)

perature loss upon discharge of the waste. Continuous video logging of each borehole was conducted using a downhole camera typically employed for oil well video logging.

The moisture level of the waste was classified in the field as either "dry" or "damp," "wet," or "standing water" (when flowing or dripping water was observed in the borehole). The assessment of the state of compaction of the waste was based on the manner in which the waste fell out of the bucket auger, with waste that fell out easily described as "loose," waste that fell out upon impact of the bucket with a hammer described as "moderate," and waste that fell out only after being struck with a hammer or jolted multiple times as "heavy." Degradation categories included "none" for waste in which newspapers were legible and there was no apparent refuse discoloration, "slight" for waste with legible newspapers and some discoloration, "moderate" for partly legible newspaper with much discoloration, and "high" for waste where newspaper was illegible, highly faded gray or black. Constituent composition categories where based on ASTM D5231, standard test method for determination of the composition of unprocessed MSW. Compositional categories used in classifying the OII landfill waste included household paper and plastics, putrescible organic matter, concrete and bricks, wiring, metal, nonferrous metal, tires, asphalt, soil, medical waste, glass, indistinguishable material, and other distinguishable items. MSW structure was described based on the condition of the waste after it was emptied from the bucket. Structure categories included "layered" when the long axes of the waste constituents were oriented in a preferred orientation, "encapsulated" when the waste was encapsulated in a soil matrix, "fibrous" when waste constituents were intertwined, "interlocked" when waste constituents were interlocked in a compact, granular type of structure, and "indistinguishable." When possible, dates were recovered from newspapers and other printed material to provide information on waste age. The field classification and temperature information were recorded on boring logs. Detailed classification information on representative samples of waste recovered from the OII landfill are presented by Matasović et al. (1998).

Graphical portrayals of field logging data were used to develop an understanding of conditions within the OII landfill waste mass. For example, moisture content versus depth charts showed that the waste in boring BA-3 was relatively dry but it contained isolated perched zones of standing water. Fig. 2, which presents degradation versus depth, shows a general trend of an increase in degradation with depth within boring BA-3, but it also shows zones of no or slight degradation that correspond to relatively dry zones at depth within this boring. The temperature profile in Fig. 3 shows temperature characteristic of anaerobic degradation (i.e., 55–70°C) at depths greater than 20 m, indicating that the technique of measuring waste temperature as it emerges from the boring is a reasonable practical method for measuring waste temperature. The compaction data from the field investigation showed a general trend of increasing compaction with depth. Except for one point representing dry waste in boring BA-2 at a depth of 16 m, one point representing dry waste from boring BA-1 at a depth of 19 m, and five points representing dry waste from boring BA-3 at depths greater than 23 m, slight waste compaction was limited to depths of less than 12 m. Heavy compaction was limited to depths greater than 23 m. The structure data recorded on waste discharged from the bucket auger were of little value, as it was classified mostly as indistinguishable. However, the video logging (Fig. 4) showed that the waste had a horizontally layered structure.

Relatively detailed characterization was conducted on samples of OII waste brought to the field laboratory for strength and compressibility testing. Based on visual assessment, a representative

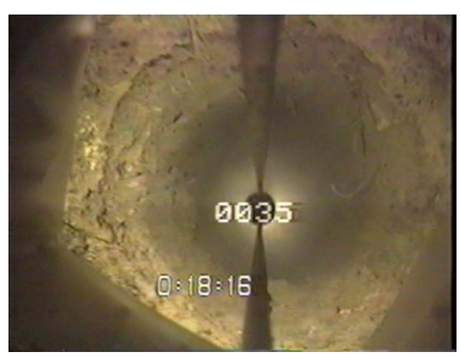

Fig. 4. View of the layered structure of the OII waste at a depth of 10.7 m

Table 2. Classification of OII Bucket Auger BA1-MV1 (Geosyntec 1996)

Constituents	% by weight
Paper	0.9
Cardboard	0.7
Plastics	5.8
Rubber	1.2
Textiles	0.7
Wood	2.3
Concrete	0
Metals	0.6
Glass	2.5
Soil and organics	84.8
Miscellaneous	0.5

Note: (1) Soil and organics are 5% gravel, 10% sand, and classify as CL in the USCS; (2) moisture content equals 21.1%.

sample of waste, typically on the order of 5–10 kg of material, was selected for more detailed characterization. The sample was then separated into the following categories: paper; cardboard; plastics; rubber; wood products; textiles; concrete; metals; glass; soil and soil-like material; and miscellaneous materials. Each constituent was weighed and the soil and soil-like material was then classified in accordance with ASTM D2488. Moisture content was measured on selected specimens of the OII waste by heating the entire specimen at a temperature of 60°C until two successive readings at least 12 h apart differed by less than 1%. Where possible, pH was measured on liquid extracted from the specimen (in all cases, the measured pH was approximately 7). It should be noted that in some cases the temperature at which the moisture content was measured was less than the in situ temperature at the location where the waste was recovered. While it is possible that the moisture content of the waste recovered from locations where the in situ temperature exceeded 60°C may have increased as it cooled, this was not considered to be a major issue. However, subsequent to this investigation the writers adopted a procedure that measures the moisture content at two different temperatures, as described in the next case history.

Waste specimens retained for laboratory testing were also classified based on comparison of the shear-wave velocity at the depth from which the sample was recovered as measured in a spectral analysis of surface wave (SASW) survey at the boring location (referred to herein as the boring value) to the mean and standard deviation shear-wave velocity at that depth from 21 SASW surveys conducted at the landfill (referred to herein as the global value) (Matasović and Kavazanjian 1998). When the boring value of the shear-wave velocity was approximately equal to the global mean value at that depth, it was designated as a medium velocity (MV) sample. Samples designated as high velocity were recovered from intervals where the boring value was equal to or greater than the mean plus one standard deviation global value at that depth. Samples designated as low velocity were recovered from intervals where the boring value was equal to or less than the mean minus one standard deviation global value at that depth.

Table 2 presents an example of the laboratory characterization of bucket auger waste sample BA1-MV1, which was recovered from a depth of 9–12 m in boring BA-1. As denoted by the MV designation, the boring value of shear-wave velocity at this depth was approximately equal to the global mean value.

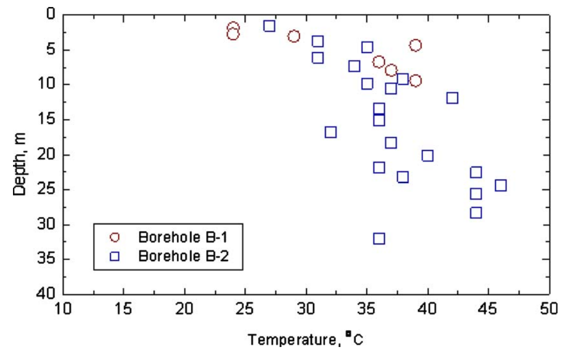

Fig. 5. Temperature measurements versus depth for the two boreholes at the Tri-Cities landfill

MSW Characterization at the Tri-Cities Landfill

As part of a collaborative research project on the static and dynamic properties of MSW, waste from the Tri-Cities landfill located in the San Francisco Bay Area was collected, characterized, and tested. The project investigated compositional influences on the static and dynamic properties of MSW. Thus, efforts were made to recover and test younger fresh waste and older more degraded waste from the Tri-Cities landfill for compositional analysis and subsequent testing.

The subsurface investigation at the Tri-Cities landfill consisted of advancing two 960-mm-diameter bucket auger boreholes to depths of 9.5 m (B-1) and 32 m (B-2) at locations selected on the basis of information on landfill operations to yield relatively young (undegraded) waste (B-1) and older (more degraded) waste (B-2). As described by Zekkos et al. (2006), during drilling operations, in situ unit weight tests were performed in the bucket auger borings using a procedure similar to the gravel replacement procedure used at the OII landfill. The recovered waste material was visually logged during drilling and bulk samples were collected for subsequent laboratory testing. The visual waste description along with the location of in situ unit weight tests and the depths from which the bulk samples were recovered were recorded on field logs similar to those used in standard geotechnical engineering investigations.

A handheld thermometer was used to measure the temperature of the waste as soon as it was removed from the borehole and brought to the surface in a similar manner as done for the OII landfill. The temperature profile developed in this manner for the Tri-Cities landfill is shown in Fig. 5. The temperature was found to increase with depth in both boreholes from 24°C near the surface to as high as 46°C at depths greater than 22 m in boring B-2. A temperature of 55°C is considered generally indicative of anaerobic decomposition, and higher temperatures are associated with aerobic decomposition. Thus, these relatively low temperatures suggest that little biological degradation was taking place in the waste at the Tri-Cities landfill at the time the measurements were taken (i.e., minimal oxygen was available to sustain aerobic decomposition and limited moisture was available to sustain anaerobic decomposition). This is consistent with the visual observations of the waste recovered from the landfill. Even the deepest waste recovered in the field investigation, which was approximately 15 years old, was generally dry and still relatively fresh, even though darker colors and more pronounced discoloration of waste constituents were observed.

Samples for large-scale laboratory testing were recovered from three depth intervals in borehole B-1 and 10 depth intervals in

Fig. 6. Processing of the waste through the 20-mm sieve

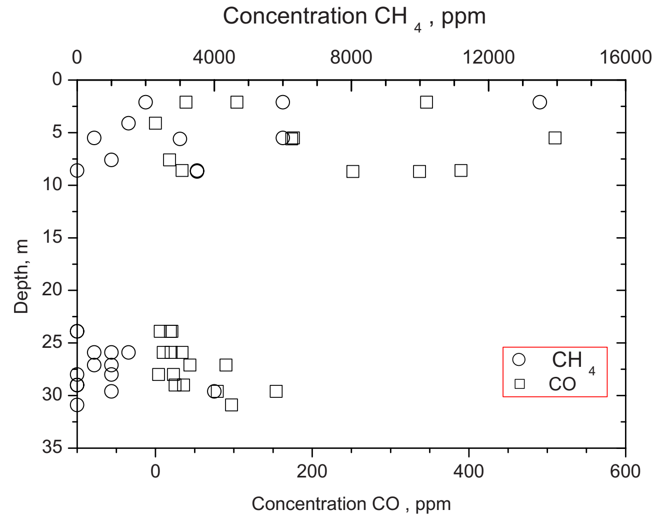

Fig. 7. Concentration of the CO and CH_4 in ppm as a function of depth for bulk samples of Tri-Cities landfill

boring B-2. Samples from each depth interval were placed in two to four 55-gal. drums to ensure that adequate material was collected for laboratory testing. A total of 39 drums were filled with waste, sealed, and marked with the date, boring number, and depth of retrieval. The drums were transported to the laboratory for subsequent characterization and laboratory testing.

Testing conducted on the OII waste indicated that waste shear strength was roughly correlated to the amount of soil-like material in a waste specimen (Kavazanjian 2001). Furthermore, visual observations of MSW recovered in large-diameter bucket auger borings and test trenches at OII and the Tri-Cities landfill indicated that the soil-like material was less than 20 mm in dimension and most of the distinguishable waste constituents were greater than 20 mm in dimension. Therefore, the Tri-Cities waste specimens were segregated into the fraction larger than 20 mm (>20 mm) and the fraction smaller than 20 mm (<20 mm).

To separate the >20- and <20-mm fractions of MSW, a forklift was used to support the drum containing the waste in an elevated and nearly horizontal position. Two large 20-mm sieves were placed next to the drum, just below the cap of the drum. Plastic tarps were placed on the floor to collect the <20-mm fraction as waste from the drum was emptied onto the sieves, as shown in Fig. 6. Precautions were taken to monitor for harmful concentrations of gasses released by the waste material during processing of the waste. However, no harmful concentrations of gasses were detected during the waste segregation (or testing) activities. When waste segregation was completed, the relative volumes of the two fractions were estimated visually and the >20-mm fraction was visually characterized. Waste characterization forms presenting the information for each drum can be found in Zekkos (2005).

When the cap of the drum was removed, the methane (CH_4) and carbon monoxide (CO) gas levels were recorded using a handheld multigas monitor that was placed immediately next to the open cap. The recorded gas levels are shown in Fig. 7. These measurements were made for safety reasons as well as to investigate if they would provide a quantitative measure of the degree of waste degradation. Older waste at higher depths appeared to generate less CO and CH_4 than shallower fresher waste. However, these were nonstandardized measurements recorded by simply placing the multigas monitor next to the cap of the drum as soon as it was opened.

Based on the dates on legible newspapers recovered during the characterization procedure, the profile of the waste age versus depth shown in Fig. 8 was established for the two Tri-Cities borings. The waste samples retained for testing were then divided in three main classes for the purposes of the research project. Class A waste was "deep old waste" that was retrieved from borehole B-2 at depths greater than 25 m. Class B waste was "fibrous deep old waste" that was retrieved from borehole B-2 and at depth of about 29 m and was observed to include more fibrous particles in the <20-mm fraction than Class A waste. Class C waste was "shallow fresh waste" that was retrieved from boreholes B-1 and B-2 and depths of 1–10 m.

Waste samples from each class and similar depths formed a total of 11 waste sample groups (i.e., four Class A waste groups, one Class B waste group, and six Class C waste groups). Five of these sample groups were further characterized. Characterization included segregation of the >20-mm material into its constituents and geotechnical characterization of the <20-mm material. The >20-mm waste fraction included household paper, household plastics, putrescible organics, concrete and bricks, wiring, metal, nonferrous metal, tires, asphalt, medical, glass, scrap wood, and other waste products. Fig. 9 is a graphical representation of the results of the segregation of the >20-mm material for the five sample groups characterized from the Tri-Cities landfill. The total weight of each sample group varied from 60 to 320 kg. The results indicate that the predominant constituents of the >20-mm material are paper, plastic, and wood. Representative samples of these three predominant materials are shown in Fig. 10. While

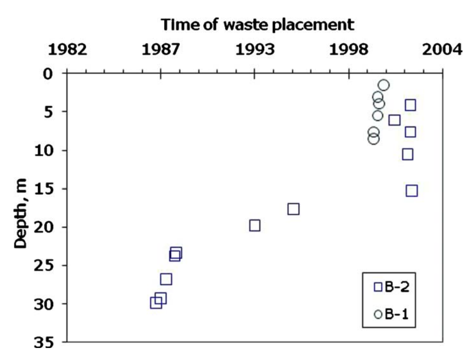

Fig. 8. Depth versus age of waste for the two boreholes at the Tri-Cities landfill

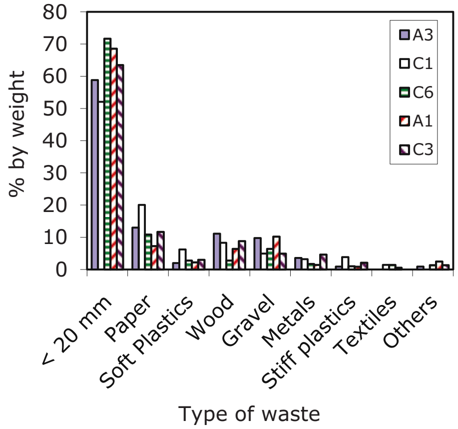

Fig. 9. Percentage by weight of the various waste types for five different waste sample groups for Tri-Cities waste

gravel represented a measurable percentage of the samples by weight because gravel is relatively heavy, it represented a negligibly small volume of the waste. The >20-mm waste material represented 25–50% of the total weight of each of the five waste sample groups.

Three of the five sample groups were selected for testing and more detailed characterization. These included the A3 waste group, retrieved from BH-2 at a depth of 25.6–26.2 m and 15 years old at the time of drilling, the C6 waste group, retrieved from BH-1 at a depth of 7.6–9.6 m and less than one year old at the time of drilling, and the C3 waste group, retrieved from BH-2 at a depth of 3.5–4.5 m and two years old at the time of drilling. The <20-mm fraction of waste material from these three sample groups was characterized using standard soil classification procedures. Dry sieve analyses of the <20-mm fraction of the three sample waste groups yielded similar results (as shown in Fig. 11), which suggest that the <20-mm material was dominated by cover soil from a consistent borrow source. The <20-mm material is a well-graded sand (*SW*) with a uniformity coefficient (C_u) of 28 and a coefficient of curvature (C_c) of 1. It should be noted that dry sieve analyses of MSW tend to underestimate the amount of fines when compared to wet sieve analyses (Gabr and Valero 1995). However, because of the organic nature of waste material, it was considered preferable to dry the material and then perform the sieve analyses rather than subject the material to the cycles of drying and wetting required to perform a wet sieve analysis. Moisture content of the <20-mm waste material was measured using an oven temperature of 55°C. The specimen was heated at this temperature until it had dried to a constant mass as indicated by a change in mass of less than 1% between two consecutive readings taken 12 h apart. The <20-mm fraction had moisture contents of about 12% for the A3 and C6 waste groups and about 23% for the C3 group. The samples were subsequently heated to 105°C until dried to constant mass. The additional material loss upon heating from 55 to 105°C for the <20-mm fraction using approximately 1–2 kg of material was 0.5–2% for all specimens of the Tri-Cities waste.

Organic content was measured as the percentage of material loss upon heating from 105 to 440°C using a muffle furnace. Due to the size of the furnace, the specimens used to evaluate the organic content weighed only about 50 g each. Larger specimen sizes would be preferable if a suitable furnace was available. To compensate for the small sample size, the <20-mm material was thoroughly homogenized, and two samples of the homogenized material were tested every time. As shown in Fig. 12, the two tests typically yielded relatively consistent values of organic content. The organic content of the <20-mm fraction of sample group A3 was estimated to be between 13 and 23%. The organic content of the <20-mm fraction of the sample Group C6 was estimated to be between 11 and 13%. The organic content of the <20-mm material of the C3 waste group was estimated to be between 17 and 27%.

The >20-mm material fraction appeared to have generally higher mass loss than the <20-mm fraction upon heating to 55°C. For example, in sample Group A3, the mass loss of the >20-mm material upon heating to 55°C was measured to be about double that of the <20-mm material (i.e., 24 and 12.5%, respectively). For the C3 waste group the mass loss at 55°C of the >20-mm fraction was also higher than the mass loss of the <20-mm fraction (i.e., 31 and 23%, respectively). No clear trends were observed between the age of the waste and the mass loss on heating.

The small size of the muffle furnace did not allow the evaluation of the organic content of representative samples of the >20-mm material. Thus, only some limited tests were conducted on small samples of individual waste constituents. The mass loss at 440°C for wood and paper was estimated to be 84 and 60%, respectively. Thus, the measured organic content (as well as the moisture content) will be significantly affected by the composition of the waste sample being tested. As an example, if the tested A3 sample included the paper, plastic, and wood inclusions, the measured organic content would be significantly higher than the organic content measured for the <20-mm fraction only. For example, the organic content of a sample that included 60% <20-mm material, 20% paper, and 20% wood would be approximately 40% as opposed to the values of 13–23% measured for the <20-mm fraction only. In addition, the organic content of the >20-mm constituents is not of the same nature as the organic content of the <20-mm material. Thus, it is preferable that the various constituents of the waste material be tested separately. Similar discrepancies arise in the evaluation of the MSW mois-

Fig. 10. View of the primary waste constituents of the >20-mm fraction for Tri-Cities waste: wood, paper, and plastic (from left to right)

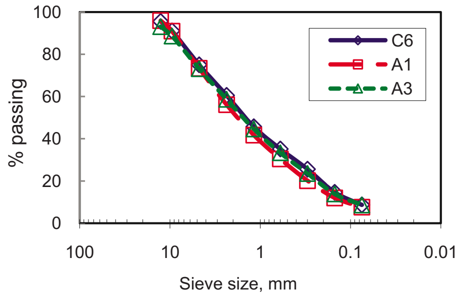

Fig. 11. Dry sieve analyses of finer than 20-mm fraction for Tri-Cities waste

ture content. Because standard procedures have not yet been established, it is essential that the amount and type of waste material tested be reported when values of the moisture and organic content are provided.

Recommended MSW Physical Characterization Procedure

Overview

The cumulative experience of the waste characterization activities performed at the OII landfill (Geosyntec 1996) and the Tri-Cities landfill (Zekkos 2005) combined with recommendations from previous waste characterization programs can be integrated to develop a standardized procedure for characterizing MSW for geotechnical purposes. The recommended geotechnical characterization procedure includes four phases:

- Phase 1—Collection and review of available information.
- Phase 2—Field characterization.
- Phase 3—Primary geotechnical characterization.
- Phase 4—Secondary geotechnical characterization.

In Phase 1, available information regarding waste sources, the history of waste placement, and landfill operations is collected. In Phase 2, qualitative compositional information is collected in the field for relatively large amounts of waste material and selected quantitative field information is also collected. In Phases 3 and 4, detailed compositional information is collected on smaller amounts of waste material selected from the recovered material. Depending on the engineering objectives of the characterization activities, different emphasis may be given to each of the four phases. Detailed recommendations for each of the waste characterization phases are provided in the following sections.

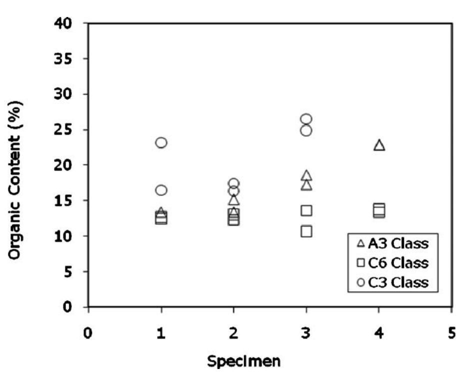

Fig. 12. Organic content for A3, C6, and C3 sample groups for Tri-Cities waste for the <20-mm-sized waste specimens

Phase 1: Collection and Review of Available Information

In this first phase of the proposed MSW characterization procedure, information about the waste received at the landfill, the history of landfill development, and the landfill operations are collected. For landfills that have been operational for many years, a wealth of valuable information of this type may be available. This information should be collected and evaluated prior to the initiation of subsequent studies. The collected information may include details on the type of waste the landfill has historically received, types of waste excluded from the landfill, the amount of waste placed on a yearly basis, periodic aerial photos and topographic maps showing waste elevation, and information on landfill operations. Relevant information on landfill operations includes waste placement procedures, areas of the landfill dedicated to specific waste types, wet weather operations areas, daily and interim cover placement, containment system details, leachate and gas management procedures, and surface water management practices. Sources of this information include interviews with current and former landfill staff, landfill permitting and design documents, previous studies performed at the landfill, and landfill records on the amount and type of waste delivered to the landfill as well as any records of waste material encountered during the installation of the gas collection system. Annual (or periodic) landfill topographic surveys or aerial photos, when available, may also help establish the waste placement history of the site.

Information on waste sources and daily and interim cover placement are of particular importance in terms of waste composition. Regional studies on the composition of residential and commercial waste streams may be useful with respect to identification of waste sources and evaluation of typical waste composition. Information from operations personnel on daily and interim cover placement is also invaluable. However, in obtaining landfill operations information, care should be taken to make sure that the quantity measures employed by the operation's personnel are defined. For example, in reporting initial waste density, operators generally report refuse quantities only, without including daily cover quantities, and in citing daily and interim cover soil quantities operators generally report volume ratios as opposed to the engineering practice of reporting weight ratios (Kavazanjian 2001). Operational information is also valuable in identifying if there are designated areas for specific types of waste (e.g., ash, asbestos waste, or construction debris) and if changes in disposal practices have occurred during the life of the landfill. Other relevant information on landfill operational practices include any preprocessing conducted prior to waste placement, the means and amount of compaction during waste placement, and the type of soil (or alternative material) used for daily and interim cover.

Information on leachate and surface water management at the facility is also important. In particular, leachate recirculation practices may have an impact on the moisture content and state of degradation of the waste. The presence of a liner and a leachate collection and removal system may also have an impact on the presence of the leachate and the rate of waste decomposition. Surface water management practices may also impact the amount of water that will percolate in the waste mass. Finally, permitting documents and previous engineering reports, including design and construction quality assurance reports, may include valuable information on the history, construction, and operation of the landfill.

Phase 2: Field Characterization

Based on the information collected in Phase 1, locations at the landfill for subsurface investigation are selected. Depending on the objectives of the project, areas where the waste is most representative of the MSW placed at the landfill or areas with MSW and subsurface conditions (e.g., perched leachate) that would be of particular concern (e.g., to evaluate stability) are identified. Noninvasive testing such as SASW surveys (Kavazanjian et al. 1996) and electrical resistivity surveys or other geophysical measurements may be used to evaluate stiffness, moisture content, and spatial variability, depending on the project objectives. Downhole seismic velocity surveys (e.g., conventional downhole or suspension logging surveys) have also been performed for waste characterization purposes at MSW landfills. However, these are "point-specific" surveys generally conducted to evaluate properties for engineering analyses, and they are not well suited for broad areal surveys for characterization purposes due to their cost. If borings are to be performed, large-diameter (i.e., 750–900-mm-diameter) bucket auger borings are preferable to get representative data on larger waste constituents (this type of drilling equipment is typically employed for the construction of landfill gas collection wells). Test pits allow excavation of shallow waste and observation of waste structure.

During field investigations, visual descriptions of the predominant constituents of the recovered waste, moisture level, and state of degradation versus depth are recorded. The moisture level, state of degradation, and compositional categories in Table 1 provide a basis for these visual descriptions (although it is now suggested that separate moisture level classifications of dry or damp be used). Representative bulk samples of waste materials may be collected for Phases 3 and 4 characterization activities as warranted by the project objectives. The bulk waste samples should be placed in sealed drums to preserve the moisture content during transportation and storage. Storage time before testing should be minimized.

Dates from legible newspapers, magazines, or other documents recovered during sampling should be recorded and combined with the waste placement information from Phase 1 to develop a waste placement chronology. Field characterization should capture observed changes in waste texture, color, composition, degradation, and moisture content as well as the presence of flowing or standing leachate in the boring or test pit. Temperature measurements of the waste, made within the bulk waste as soon as safely possible, may also provide useful information regarding waste decomposition. Additional field investigation activities may include large-scale in situ unit weight tests (e.g., Zekkos et al. 2006) and video logging (e.g., Geosyntec 1996).

Phase 3: Primary Geotechnical Characterization

MSW samples selected for more detailed characterization should be transported to a well-ventilated open area either in a laboratory or a secure location at the landfill for Phases 3 and 4 characterization activities. For geotechnical characterization, the MSW should be separated into >20- and <20-mm waste fractions. Large 20-mm sieves are preferable for this task due to the large volume of waste material typically involved in waste characterization activities.

Segregation into >20- and <20-mm waste fractions is recommended because there is a significant difference in the nature of the <20- and the >20-mm fractions of typical MSW. The <20-mm fraction is typically soil-like in nature (i.e., includes significant amounts of daily cover soil and inorganic debris as well as fine waste inclusions), whereas, the >20-mm material consists primarily of waste generated at the source. The >20-mm MSW fraction is likely to include mostly plastics, paper, and wood, even though significant variations may exist between landfills in different regions as well as within a landfill. Segregation of the <20- and >20-mm fractions is also advantageous because the <20-mm material can be characterized with typical soil mechanics testing equipment and procedures, whereas the >20-mm material is relatively easy to segregate by hand and categorize visually.

The delineation between the >20- and <20-mm waste fractions has also been shown to be valuable in understanding the properties of the waste material. Waste with lower amounts of >20-mm material (e.g., when large quantities of daily soil cover or other soil materials are used) has significantly higher unit weight than waste with higher amounts of >20-mm material primarily due to the low unit weight of the fibrous constituents of the >20-mm fraction (Zekkos et al. 2006). Also, the unit weight of waste with high amounts of >20-mm material is found to increase significantly with overburden stress, while the increase in unit weight with overburden stress of MSW rich in <20-mm (such as the OII landfill) may be negligible (Zekkos et al. 2006). Waste with a higher amount of >20-mm material will typically exhibit higher shear strength (Bray et al. 2009) if the fibrous waste constituents are mobilized during shearing. The compressibility of waste will also, in general, increase with an increase in >20-mm material (Kavazanjian et al. 1999). Finally, the dynamic properties of MSW have been shown to be significantly affected by the amount of >20-mm material (Zekkos et al. 2008). As the amount of >20-mm material increases, the small strain shear modulus reduces, and the volumetric threshold strain increases indicating linear dynamic properties over a wider strain range [i.e., less reduction in shear modulus and lower material damping at large strains (Zekkos et al. 2008)]. These changes in the dynamic properties can have significant impact on the seismic response of landfills (Athanasopoulos-Zekkos et al. 2008).

After the sample is segregated into <20- and >20-mm fractions, the relative volumes of the two waste fractions are estimated visually and the weights of the two fractions are measured. Additional information is collected about the composition, age, moisture content, and degradation of these fractions. For the >20-mm fraction this information may include:

- A more detailed qualitative description of the composition of the >20-mm fraction based on the waste constituents identified in Table 1.
- Additional information on the age of waste from magazines, newspapers, or other documents if legible.
- Quantification of the state of waste degradation based on the four levels of degradation in Table 1.
- Visual characterization of the moisture level of the waste as dry, damp, or wet.

Due to the difficulty in separating and characterizing the >20-mm material, collection of additional information on the >20-mm fraction beyond visual classification is deferred to Phase 4.

Phase 4: Secondary Geotechnical Characterization

In Phase 4, the >20-mm material is segregated into its constituents and the <20-mm material is characterized using conventional geotechnical classification procedures. Performing moisture content and organic content tests of the <20-mm material is relatively easy to do and yields potentially useful information, so it should normally be done. In many cases, manually separating the >20-mm material into its constituents may not be worth the effort. However, characterization may be valuable because recent studies on synthetic waste indicate that the type of waste inclusions can have a major impact on the mechanical properties of MSW (Athanasopoulos et al. 2008). During the >20-mm segregation process, <20-mm material which was "trapped" within the larger fraction should be separated as much as practical and added to the <20-mm material. The weight of each of the >20-mm constituents is measured to quantify the composition of the waste sample by weight. Although the size of the fibrous materials may influence the properties of MSW, there is a paucity of data to confirm this. Therefore, while this information may be valuable for research purposes (e.g., Langer 2005; Dixon and Langer 2006), tracking the variability in the sizes of the fibrous materials within the MSW is not justified in engineering practice at this time.

The <20-mm material can be characterized using traditional geotechnical classification procedures, including sieve analysis, moisture content, organic content, and Atterberg limits. Moisture content should be measured by heating to a temperature of 55°C until a constant mass is achieved. Constant mass is achieved when the weight of the sample changes by less than 1% between two consecutive readings taken 12 h apart.

It is recommended that organic content be defined as the ratio of the weight of the specimen lost at 440°C according to the ASTM D2974 procedure to the weight of the material upon heating until constant mass of the same specimen at a temperature of 55°C. For comparison purposes with conventional geotechnical practice, it may be desirable to make an intermediate measurement of the weight of the specimen at 105°C. A large enough mass of material will need to be tested so that it is considered representative of the waste sample. The representative mass may depend on the size of the original sample. If the sample size is too small to ensure that it is representative, multiple samples should be tested to evaluate the variability of the organic content among different samples. Detailed documentation of the composition of the sample that is tested for moisture and organic content should accompany the reported values.

With respect to the Phase 4 geotechnical characterization, after the waste is segregated into the <20- and >20-mm fractions, the moisture content and the dry mass of the >20-mm fraction may have to be evaluated separately for each constituent. As large furnaces that can heat material to 440°C are typically not available in geotechnical laboratories, it may be necessary to heat samples of each constituent of the >20-mm fraction separately and then calculate a weighted average organic content. Even if a large muffle furnace is available and larger quantities of the >20-mm material can be tested, it may be preferable to test constituents separately so that the loss of mass of each constituent is identified. Furthermore, due to the inherent variability of MSW, it is recommended that at least two representative samples be heated at 440°C to determine organic content. Measurement of the pH of any free liquid that can be extracted from the waste may also be desirable. Finally, if a more quantitative measure of the state of waste degradation is required, the proposal of Hossain et al. (2003) to quantify degradation based on the ratio of cellulose plus hemicellulose to lignin may be employed on the <20-mm fraction of MSW.

Conclusion

Based on existing MSW classification systems and experience in waste characterization at the OII and Tri-Cities landfills, a recommended procedure for the physical characterization of MSW for geotechnical engineering purposes has been developed. The four phase characterization procedure is designed to capture the characteristics of MSW that may have a major influence on its mechanical properties. Qualitative data collected in Phase 1 of this procedure include information on waste origin, landfill operational procedures (e.g., waste processing and placement procedures), climatic conditions, and waste age. While it is difficult to quantify the direct effects of these parameters on the engineering properties of MSW at the present time, this information is relatively easy to collect, is expected to play a role in the MSW properties, and may prove valuable in the future. Furthermore, this information may prove useful in qualitatively assessing the spatial variability of the waste.

Phase 2 of the proposed procedure involves field characterization of the waste, including the recovery of bulk samples for Phase 3 and Phase 4 characterizations. The use of large-diameter (at least 750-mm) bucket auger boreholes is recommended for recovery of bulk samples at depth to minimize comminuting of larger waste particles. Visual characterization of the recovered waste should be performed as described in the paper, with the intent to capture the important characteristics of in situ waste composition. Field activities may also include geophysical exploration, in situ unit weight tests, and video logging of the boreholes.

The most important aspect of Phase 3 characterization is the separation of the recovered waste into the >20-mm fraction, which is largely waste materials, and the <20-mm fraction, which is largely soil-like material. Testing on reconstituted waste specimens has shown that the percentage of <20-mm material in the waste has a significant effect on MSW unit weight, shear strength, stiffness, and material damping during cyclic loading, and testing of synthetic waste suggests that the nature of the >20-mm material has also a significant effect on MSW mechanical response. Phase 3 includes segregation, weighing, and visual description of the >20-mm material to provide this critical information.

Phase 4 testing can provide useful quantitative data, such as moisture content; however, some laborious parts of Phase 4 testing may not be considered necessary for all projects. In many cases, manually separating the >20-mm material into its constituents may not be worth the effort. In Phase 4, the <20-mm material is characterized using conventional geotechnical soil testing procedures, including grain size analysis, plasticity index, and, if desired, conventional geotechnical soil testing methods. Moisture content and organic content of both the <20-mm material and the >20-mm material are measured in Phase 4 using a temperature of 55°C for the moisture content determination and a temperature of 440°C to determine organic content. Detailed examination of the >20-mm material is also performed.

Many unanswered questions about the factors that most affect the mechanical properties of MSW remain. The proposed characterization procedure is likely to be refined as new insights on the mechanical response of MSW are garnered. However, the proposed system is designed to capture the key aspects of waste composition that are believed to influence the geotechnical properties of the MSW at the present time. Furthermore, the recommended procedure is designed to optimize the time and effort required to collect the most relevant information that governs the geotechnical properties of MSW.

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